Encompassing Quantum Electronics, Photonics, Optics, an exhibition and tutorials.

→ 3 – 6 September 2012
Durham University, Durham, UK

→ www.photon.org.uk

IOP’s premier event in optics and photonics
FORTHCOMING INSTITUTE CONFERENCES
AUGUST 2012 – JULY 2014

2012

10–11 September
Magnetic Tight Binding
Institute of Physics, London, UK
Organised by the IOP Computational Physics Group

20–21 September
A Celebration of the 50th Anniversary of the Diode Laser
University of Warwick, Coventry, UK
Organised by the IOP Quantum Electronics and Photonics and Semiconductor Physics Groups

8–9 November 2012
Complex Molecules at Surfaces II (CMAS-2)
Institute of Physics, London, UK
Organised by the IOP Thin Film and Surfaces Group

26–27 November
Biomolecular Thermodynamics
Institute of Physics, London, UK
Organised by the IOP Biological Physics Group

17–18 December
Topical Research Meetings on Physics: Quantum technologies: taking concepts through to implementations
Institute of Physics, London, UK

2013

16–18 January
AFPAc 2013 - 12th Anglo-French Physical Acoustics Conference
Villa Clythia, Fréjus, France
Organised by the IOP Physical Acoustics Group

17–18 January
Ferroelectrics UK 2013
University of Sheffield, Sheffield, UK
Organised by the IOP Materials and Characterisation Group

6–8 March
Adaptive Quantum Computation 2013
Institute of Physics, London, UK
Organised by the IOP Quantum Optics, Quantum Information, Quantum Control Group

25–28 March
The 40th IOP Annual Conference on Plasma Physics
University of York, York, UK
Organised by the IOP Plasma Physics Group

25–28 March
Interdisciplinary Surface Science Conference (ISSC-19)
East Midlands Conference Centre, Nottingham, UK
Organised by the IOP Thin Films and Surfaces Group

7–10 April
IOP Nuclear Physics Group Conference 2013
University of York, York, UK
Organised by the IOP Nuclear Physics Group

10–12 April
Dielectrics 2013
University of Reading, Reading, UK
Organised by the IOP Dielectrics Group

24–25 June
Physics of Emergent Behaviour: from Molecules to Individuals
The Grand Hotel, Brighton, UK
Organised by the IOP Biological Physics Group

8–12 July
International Conference on Neutron Scattering (ICNS2013)
Edinburgh International Conference Centre, Edinburgh, UK

3–6 September
Electron Microscopy and Analysis Group Conference 2013 (EMAG)
University of York, York, UK
Organised by the IOP Electron Microscopy and Analysis Group

4–6 September
PR’13: International Conference on Photorefractive Effects, Materials and Devices
The Winchester Hotel, Winchester, UK
Organised by the IOP Optical Group and the IOP Quantum Electronics and Photonics Group

9–11 September
Physical Aspects of Polymer Science
University of Sheffield, Sheffield, UK
Organised by the IOP Polymer Physics Group

16–18 September
Sensors & their Applications XVII
Rixos Libertas, Dubrovnik, Croatia
Organised by the IOP Instrument Science and Technology Group

16–19 September
EuroDisplay 2013 (33rd International Display Research Conference)
Imperial College London, London, UK
Organised by the IOP Optical Group and Society for Information Display

18–20 November
High-speed imaging for dynamic testing of materials and structures – 21st DYMAT Technical Meeting
Institute of Physics, London, UK
Organised jointly by the IOP Applied Physics and Technology Division and DYMAT Association

2014

21–25 July
ICSOS 11: 11th International Conference on the Structure of Surfaces
University of Warwick, Coventry, UK
Organised by the IOP Thin Films and Surfaces Group

See www.iop.org/conferences for a full list of IOP one-day meetings.

The conferences department provides a professional event-management service to the IOP Groups and Divisions and supports bids to bring international physics events to the UK.

Institute of Physics,
76 Portland Place, London W1B 1NT, UK
Tel +44 (0)20 7470 4800
E-mail conferences@iop.org
Web www.iop.org/conferences
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Welcome to Photon12

Dear Colleagues

Photon12 is conference organised by the Optics and Photonics Division of the Institute of Physics and is the seventh in the biennial series of conferences that actually began in a far-sighted way in 2000. By using both the words optics and photonics we deal with light in both a classical way and the quantisation routes. This means that the conference embraces a lot of photon-based technologies such as laser science and computational physics. Indeed, a whole range of areas is covered, including nonlinearity, a complete menu of quantum effects and also nanophotonics and metamaterials that have received such a lot of attention over the last decade. Technically the Photon12 conference is formulated in a style first demonstrated in Cardiff in 2002, emerging then as the largest UK optics event of that year. The biennial series has maintained this profile so Photon12 looks forward to welcoming over 300 participants from 27 different countries.

In the same way as its predecessors, Photon12 is organised as a set of exciting co-located, interlocked, meetings and represents the whole of the UK Optics and Photonics community, ranging from learned societies to special interest groups. They provide a single forum and involve over 320 papers under the umbrella of four very distinguished plenary lectures. This is all in parallel with an exciting exhibition of scientific instruments, equipment and techniques. All of these conference characteristics explain why Photon12 is such a dominant meeting. The four beautiful plenary lectures are the famous Rank lecture about seeing really small objects with light, presented by Professor Sir John Pendry, an encouraging perspective on biomedical imaging, presented by Professor Pavone, from Florence, Italy, a fascinating discussion about engineered quantum systems by Professor Milburn from Queensland, Australia and an exciting perspective from the Optics and Photonics Division prize-winner, Professor Jonathan Knight, on the spread of a new generation of optical fibres across the globe. All of this adds up to a superb meeting and, even though the Divisions is in the IOP infrastructure are being reorganised we can see that Photon12 will lead on immediately to Photon14. The latter, building upon Photon12, will continue to demonstrate just how important to Society, and alive, developments in Photonics are today.

I very much hope that you will enjoy Photon12, not only in terms of its presentations but also by getting engaged with the wonderful exhibition. I must thank everybody who has offered sponsorship to the meeting and worked so hard to get it into its current shape. I am absolutely certain that you will have a great time in Durham and, as is always the case, conferences are a vital opportunity to meet up to meet up with friends and collaborators. This event will be no exception.

With very best wishes

Professor Allan Boardman, Conference Chair
# Oral programme

## Sunday 2 September

<table>
<thead>
<tr>
<th>Time</th>
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<tr>
<td>16:00</td>
<td>Calman Learning Centre reception, Derman Christopherson (CLC406) and Kingsley Barrett (CLC407)</td>
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<tr>
<td>19:00</td>
<td>Registration and drinks reception</td>
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## Monday 3 September

<table>
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<tr>
<th>Time</th>
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<tr>
<td>08:30</td>
<td>Calman Learning Centre reception</td>
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<tr>
<td></td>
<td>Registration</td>
</tr>
<tr>
<td>09:15</td>
<td>Arnold Wolfendale lecture theatre (CLC013)</td>
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<tr>
<td></td>
<td>Welcoming remarks by the Photon12 Local Chair</td>
</tr>
<tr>
<td></td>
<td>Professor Gordon Love, Durham University, UK</td>
</tr>
<tr>
<td></td>
<td>Welcome to Photon12</td>
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<tr>
<td></td>
<td>Professor Tom McLeish FRS, Durham University, UK</td>
</tr>
<tr>
<td>09:30</td>
<td>Chair: Professor G Love, Durham University, UK</td>
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<tr>
<td></td>
<td>The Rank Lecture</td>
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<tr>
<td></td>
<td>Inside the Wavelength - seeing really small objects with light</td>
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<tr>
<td></td>
<td>Professor Sir John Pendry FRS, Imperial College London, UK</td>
</tr>
<tr>
<td>10:15</td>
<td>Calman coffee area, Derman Christopherson (CLC406) and Kingsley Barrett (CLC407)</td>
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<tr>
<td></td>
<td>Refreshments</td>
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<tr>
<td>Time</td>
<td>Session</td>
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</tr>
<tr>
<td>10.45</td>
<td>(invited) Active and adaptive optics: principles and applications</td>
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<tr>
<td>11.15</td>
<td>Adaptive optics for light sheet microscopy</td>
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<tr>
<td>11.30</td>
<td>Wavefront sensing and adaptive optics in high resolution microscopy</td>
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<td>Microfabricated ion trap chips for quantum technologies</td>
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<td></td>
<td>Computational quantum walks</td>
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<td></td>
<td>The scattering properties of spherical particles coated with epsilon near zero (ENZ) materials</td>
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<tr>
<td>11.45</td>
<td>Femtosecond laser direct write waveguides using adaptive optics: beam shaping and aberration correction</td>
</tr>
<tr>
<td></td>
<td>Bosonic and fermionic quantum walk dynamics in waveguide arrays</td>
</tr>
<tr>
<td>12.00</td>
<td>Interferometric metrology using reprogrammable binary holograms</td>
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<td>New trends in laser ablation-induced high-order harmonic generation</td>
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<tr>
<td>Time</td>
<td>Session</td>
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<tr>
<td>12.30</td>
<td>Rosemary Cramp lecture theatre (CLC202)</td>
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<td>13.30</td>
<td>Arnold Wolfendale lecture theatre (CLC013)</td>
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<td>Rosemary Cramp lecture theatre (CLC202)</td>
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<td>Ken Wade lecture theatre (CLC203)</td>
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<td>Dawson lecture theatre (D110)</td>
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<td>Arnold Wolfendale lecture theatre (CLC013)</td>
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<td>13.45</td>
<td>Rosemary Cramp lecture theatre (CLC202)</td>
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<td>Rosemary Cramp lecture theatre (CLC202)</td>
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<td>Rosemary Cramp lecture theatre (CLC202)</td>
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<td>Ken Wade lecture theatre (CLC203)</td>
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<td>Ken Wade lecture theatre (CLC203)</td>
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<td>Dawson lecture theatre (D110)</td>
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<td>Arnold Wolfendale lecture theatre (CLC013)</td>
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<td>Rosemary Cramp lecture theatre (CLC202)</td>
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<td>Ken Wade lecture theatre (CLC203)</td>
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<td>Ken Wade lecture theatre (CLC203)</td>
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<td>Dawson lecture theatre (D110)</td>
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<td>Rosemary Cramp lecture theatre (CLC202)</td>
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<td>15.00</td>
<td>Rosemary Cramp lecture theatre (CLC202)</td>
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<tr>
<td>15.15</td>
<td>Rosemary Cramp lecture theatre (CLC202)</td>
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<tr>
<td>Time</td>
<td>Imaging systems (invited)</td>
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<tr>
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<tr>
<td>15.45</td>
<td>Bayesian localization microscopy reveals nanoscale podosome dynamics S Cox, King's College London, UK</td>
</tr>
<tr>
<td>16.15</td>
<td>Interrogating 3D structure of optically deformed suspensions A Kirby, Durham University, UK</td>
</tr>
<tr>
<td>16.30</td>
<td>Analysis of aberrations in STED microscopy D Burke, University of Oxford, UK</td>
</tr>
<tr>
<td>16.45</td>
<td>Image processing for spinning-disk, wide-field optical sectioning microscopy L Fafchamps, Imperial College London, UK</td>
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<td>17.00</td>
<td>Optical eigenmode imaging M Mazilu, University of St Andrews, UK</td>
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<tr>
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<tr>
<td>17.15</td>
<td>Arnold Wolfendale lecture theatre</td>
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<td>Rosemary Cramp lecture theatre</td>
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<td>(CLC202)</td>
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<tr>
<td>19.00</td>
<td>Poster session I, exhibition and</td>
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<tr>
<td></td>
<td>buffet reception</td>
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<tr>
<td>18.30</td>
<td>Rosemary Cramp lecture theatre</td>
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<td></td>
<td>(CLC202)</td>
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<tr>
<td>19.00</td>
<td>Calman Learning Centre reception</td>
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<td></td>
<td>Coaches depart to Durham Castle</td>
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<td>(please note coaches for return journey are not organised)</td>
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<tr>
<td>19.30</td>
<td>Durham Castle</td>
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<td>21:00</td>
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<tr>
<td>08.30</td>
<td>Calman Learning Centre reception&lt;br&gt;Registration</td>
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<tr>
<td>09.00</td>
<td><strong>Arnold Wolfendale lecture theatre (CLC013)</strong>&lt;br&gt;Chair: Professor M Neil, Imperial College London, UK&lt;br&gt;(plenary) <strong>Biophotonics: perspectives in biomedical imaging</strong>&lt;br&gt;Professor Francesco Pavone, University of Florence, Italy</td>
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<tr>
<td>09.45</td>
<td><strong>Earth Sciences, ES228/229/230/231</strong>, Derman Christopherson (CLC406) and Kingsley Barrett (CLC407)&lt;br&gt;Exhibition and refreshments</td>
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<p>| 10.15 | <strong>Optical biosensing and bioimaging</strong>&lt;br&gt;Chair: P Borri, Cardiff University, UK&lt;br&gt;(invited) <strong>Optical resonator biosensors</strong>&lt;br&gt;F Vollmer, Max-Planck-Institut fuer die Physik des Lichts, Germany |
| 10.30 | <strong>Advances in THz technology I</strong>&lt;br&gt;Chair: S Hadjiloucas, The University of Reading, UK&lt;br&gt;(invited) <strong>Kinetic inductance detectors for THz imaging and spectroscopy</strong>&lt;br&gt;P Mauskopf, Arizona State University, USA |
|       | <strong>Quantum information III</strong>&lt;br&gt;Chair: V Kendon, University of Leeds, UK&lt;br&gt;Observation of Hong Ou Mandel interference as a function of Berry's phase&lt;br&gt;A Laing, University of Bristol, UK |
|       | <strong>Analysis of detector performance in a GigaHertz clock rate quantum key distribution system</strong>&lt;br&gt;R Collins, Heriot-Watt University, UK |
| 10.45 | <strong>Organic distributed feedback biosensor</strong>&lt;br&gt;A-M Haughey, University of Strathclyde, UK&lt;br&gt;Measurements of THz pulse delay in sooty flames&lt;br&gt;K Ozanyan, The University of Manchester, UK |
|       | <strong>High efficiency near field microwave quantum key distribution</strong>&lt;br&gt;B Varcoe, University of Leeds, UK&lt;br&gt;Nonparaxial refraction laws for spatial solitons at cubic-quintic material interfaces&lt;br&gt;E McCoy, University of Salford, UK |
| 11.00 | <strong>Random-access spectral imaging</strong>&lt;br&gt;P Kelleher, University of Glasgow, UK&lt;br&gt;THz nanodevices based on layered superconductors&lt;br&gt;S Savel'ev, Loughborough University, UK&lt;br&gt;An experimental demonstration of quantum digital signatures&lt;br&gt;P Clarke, Heriot-Watt University, UK&lt;br&gt;Continuous-wave intra-cavity Optical Parametric Oscillator&lt;br&gt;L C Heering, University of St Andrews, UK |</p>
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<th>Presenter and Affiliation</th>
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</thead>
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<td>Arnold Wolfendale lecture theatre</td>
<td>High-speed light-sheet microscopy for imaging 3D behaviour during Dictyostelium Discoideum development&lt;br&gt; E Rozbicki, University of Dundee, UK</td>
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<tr>
<td></td>
<td>Rosemary Cramp lecture theatre (CLC202)</td>
<td>Tuneable monolithically integrated photonic THz heterodyne system&lt;br&gt; K Balakier, University College London, UK</td>
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<tr>
<td></td>
<td>Ken Wade lecture theatre (CLC203)</td>
<td>Entanglement detection in hybrid optomechanical systems&lt;br&gt; G De Chiara, Queen’s University Belfast, UK</td>
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<td></td>
<td>Dawson lecture theatre (D110)</td>
<td>Locking of laser cavity solitons&lt;br&gt; G-L Oppo, University of Strathclyde, UK</td>
</tr>
<tr>
<td>11.30</td>
<td>Versatile volumetric imaging by oblique plane microscopy&lt;br&gt; S Kumar, Imperial College London, UK</td>
<td>Deeper insight into material optical properties extraction procedure from THz TDS in a transmission mode&lt;br&gt; O Sushko, Queen Mary, University of London, UK</td>
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<td>Quantum probes for complex systems: applications to quantum simulations&lt;br&gt; S Maniscalco, Heriot-Watt University, UK</td>
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<td>(invited) Bright polariton solitons in semiconductor microcavities&lt;br&gt; D Krizhanovskii, University of Sheffield, UK</td>
</tr>
<tr>
<td>11.45</td>
<td>Quantum dot nano-thermometry for optofluidic devices&lt;br&gt; D Choudhry, Heriot-Watt University, UK</td>
<td>THz torch technologies for 21st century applications&lt;br&gt; F Hu, Imperial College London, UK</td>
</tr>
<tr>
<td>12.00</td>
<td>Earth Sciences, ES228/229/230/231, Derman Christopherson (CLC406) and Kingsley Barrett (CLC407)</td>
<td>Lunch and exhibition</td>
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<td>12.30</td>
<td>Rosemary Cramp lecture theatre (CLC202)</td>
<td>Biophotonics Chair: M Dickinson, The University of Manchester, UK</td>
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<tr>
<td>13.30</td>
<td>Tutorial II: Vikings in shades: navigating by skylight polarization&lt;br&gt; M Dennis, University of Bristol, UK</td>
<td>Advances in THz technology II Chair: K Ozanyan, The University of Manchester, UK</td>
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<td>(invited) Ultra-low-noise FIR imaging arrays for space science&lt;br&gt; S Withington, University of Cambridge, UK</td>
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<td>Quantum coherent control II Chair: K Weatherill, Durham University, UK</td>
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<td>(invited) Sub-wavelength resonance imaging and robust addressing of atoms in an optical lattice&lt;br&gt; P Jessen, University of Arizona, USA</td>
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<td>Nonlinear photonics II Chair: W Firth, University of Strathclyde, UK</td>
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<td>Characterisation of cross-phase modulation in a hydrogenated silicon optical fibre&lt;br&gt; P Mehta, Optoelectronics Research Centre, UK</td>
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<td>Four-wave mixing and cascaded nonlinearity yielding low-noise high-brightness tunable ultrashort pulses&lt;br&gt; P Mosley, University of Bath, UK</td>
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<tr>
<td>13.45</td>
<td>(invited) Controlling polarisation: Achromatic waveplates and omnidirectional reflectors in nature&lt;br&gt; N Roberts, University of Bristol, UK</td>
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</tr>
<tr>
<td>Time</td>
<td>Title</td>
<td>Speaker</td>
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<tr>
<td>14.15</td>
<td>Higher-order aberrations in the human eye cause task-specific degradations to visual performance: a comparison between letter recognition and reading</td>
<td>L Young</td>
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<tr>
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<td>Frequency agile THz source based on Parametric generation</td>
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<td>Periodically-poled materials for the parametric generation of THz radiation</td>
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<td>An integrated photonic atom chip</td>
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<tr>
<td>14.30</td>
<td>Tracking ophthalmic drugs in the eye using a confocal fluorescence instrument</td>
<td>K Buttenschoen</td>
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<td>Intracavity terahertz parametric oscillator for stand-off spectroscopy applications</td>
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<td>Atomic motion in the evanescent field of tapered optical fibers</td>
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<tr>
<td>14.45</td>
<td>Correlative fluorescence and label-free optical microscopy of model lipid membranes</td>
<td>C McPhee</td>
</tr>
<tr>
<td>15.00</td>
<td>Heart-stopping moments with zebrafish: real-time optical synchronization for precision imaging and intervention in the beating heart</td>
<td>J Taylor</td>
</tr>
<tr>
<td>15.15</td>
<td>Earth Sciences, ES228/229/230/231, Derman Christopherson (CLC406) and Kingsley Barrett (CLC407)</td>
<td>Exhibition and refreshments</td>
</tr>
<tr>
<td>15.45</td>
<td>Advanced optical microscopy techniques</td>
<td>Chair: M Neil, Imperial College London, UK</td>
</tr>
<tr>
<td></td>
<td>(invited) Advances in fluorescence super-resolution biplane FPALM and STED microscopy</td>
<td>J Bewersdorf</td>
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<td></td>
<td>(invited) Footprint imaging by guided path tomography</td>
<td>Chair: K Weir, Imperial College London, UK</td>
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<tr>
<td></td>
<td>(invited) Quantum information processing by coherent control of Rydberg atoms</td>
<td>Chair: A Sinclair, National Physical Laboratory, UK</td>
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<td></td>
<td>(invited) Squeezing light into the nanometer scale: quantum plasmonics</td>
<td>Chair: M Fujiwara, Hokkaido University &amp; Osaka University, Japan</td>
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<tr>
<td></td>
<td>Nanophotonics and plasmonics I</td>
<td>(invited) Quantum coherent control II</td>
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<tr>
<td>Time</td>
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<td>Speaker</td>
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<tr>
<td>16.15</td>
<td>Structured illumination design and polarisation effects in super resolution microscopy</td>
<td>K O'Holleran, National Physical Laboratory, UK</td>
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<td>Analysis of array waveguide grating based interrogation of fibre Bragg gratings for dynamic strain measurement</td>
<td>W MacPherson, Heriot-Watt University, UK</td>
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<td>Overcoming decoherence in the collapse and revival of spin Schrödinger-cat states</td>
<td>M Everitt, Loughborough University, UK</td>
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<td>16.30</td>
<td>Analysis of array waveguide grating based interrogation of fibre Bragg gratings for dynamic strain measurement</td>
<td>W MacPherson, Heriot-Watt University, UK</td>
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<td>Overcoming decoherence in the collapse and revival of spin Schrödinger-cat states</td>
<td>M Everitt, Loughborough University, UK</td>
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<td>Range-resolved optical fibre interferometry for quasi-distributed dynamic strain sensing</td>
<td>T Kissinger, Cranfield University, UK</td>
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<td>Tissinger, Cranfield University, UK</td>
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<td>Coupling of silicon nanocrystals and plasmonic nanostructures</td>
<td>E Massa, Imperial College London, UK</td>
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<tr>
<td>16.45</td>
<td>Single source multimodal D-CARS/TPF/SHG microscopy of lipids in living mammalian cells</td>
<td>I Pope, Cardiff University, UK</td>
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<td>C Di Napoli, Cardiff University, UK</td>
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<td>THz coherent control in Rydberg states in silicon</td>
<td>E Bowyer, University of Surrey, UK</td>
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<td>M Tanner, Heriot-Watt University, UK</td>
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<tr>
<td>17.00</td>
<td>Ultra high resolution single-mode fibre-optic distributed Raman thermometer using superconducting nanowire single-photon detectors</td>
<td>M Tanner, Heriot-Watt University, UK</td>
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<td>THz coherent control in Rydberg states in silicon</td>
<td>E Bowyer, University of Surrey, UK</td>
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<td>M Tanner, Heriot-Watt University, UK</td>
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<tr>
<td>17.15</td>
<td>Quantitative CARS and D-CARS study of model lipid droplets</td>
<td>C Di Napoli, Cardiff University, UK</td>
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<td>C Di Napoli, Cardiff University, UK</td>
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<td>POF based moisture and pH sensor in soils for e-agriculture applications</td>
<td>P Scully, The University of Manchester, UK</td>
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<tr>
<td>17.15 – 19.00</td>
<td>Non-linear ultrasound modulated optical tomography with laser speckle detection</td>
<td>H Ruan, The University of Nottingham, UK</td>
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<td>POF based moisture and pH sensor in soils for e-agriculture applications</td>
<td>P Scully, The University of Manchester, UK</td>
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<td>Controlling tamm plasmon polariton states in organic microcavities</td>
<td>I Iorsh, Durham University, UK</td>
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<td>Exhibitors drink reception and poster session II</td>
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<td>exhibiting, ES228/229/230, Derman Christopherson (CLC406) and Kingsley Barrett (CLC407)</td>
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**Notes:**
- The schedule includes presentations on various topics in optics and photonics.
- Speakers and institutions are listed for each presentation.
- The locations of the presentations are indicated in parentheses.
- The schedule includes times, topics, and speakers for presentations across different lecture theatres.
### Wednesday 5 September

**08.30**  
*Calman Learning Centre reception*  
Registration

**09.00**  
*Arnold Wolfendale lecture theatre (CLC013)*  
Chair: Professor G Buller, Heriot-Watt University, UK  
(Plenary) Quantum optomechanics: an engineered quantum system  
Professor Gerard Milburn, University of Queensland, Australia

**09.45**  
*Earth Sciences, ES228/229/230/231, Derman Christopherson (CLC406) and Kingsley Barrett (CLC407)*  
Exhibition and refreshments

<table>
<thead>
<tr>
<th>Time</th>
<th>Session</th>
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</table>
| 10.15 | **Optical tweezing and micromanipulation**  
Arnold Wolfendale lecture theatre (CLC013)  
Chair: M Dickinson, The University of Manchester, UK  
(invited) Light driven toy models to study hydrodynamic synchronization at the micron scale  
R Di Leonardo, National Research Council of Italy, Italy |
| 10.15 | **Optical diagnostics in engineering**  
Rosemary Cramp lecture theatre (CLC202)  
Chair: R Groves, Delft University of Technology, The Netherlands  
(invited) Infra-red imaging in experimental mechanics  
J Barton, University of Southampton, UK |
| 10.15 | **Quantum optics I**  
Ken Wade lecture theatre (CLC203)  
Chair: W Langbein, Cardiff University, UK  
(invited) Cavity optomechanics: exploring the coupling of light and micro- and nanomechanical oscillators  
T Kippenberg, EPF Lausanne, Switzerland |
| **11.00** | **Silicon and carbon photonics**  
Dawson lecture theatre (D110)  
Chair: R Kelsall, University of Leeds, UK  
(invited) Integrating plasmonics with silicon photonics  
A Chelnikov, CEA-LETI, France |

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<tr>
<th>Time</th>
<th>Session</th>
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| 10.45 | **Overcoming polarisation issues in circularly polarised conical refraction optical tweezers**  
Frequency-division multiplexing in interferometric planar Doppler velocimetry  
J Bledowski, Cranfield University, UK  
C McDougall, University of Dundee, UK |
| 10.45 | **Modelling, fabrication and measurement of 3-D photonic crystal defect layer in woodpile structures**  
Y-L D Ho, University of Bristol, UK |
| **11.00** | **Optical binding in motion: symmetry breaking and periodic motion in optically trapped particle arrays**  
Development of tunable diode laser spectroscopy sensor systems for line-of-sight measurement of water vapour in aero engine exhaust plumes  
J Taylor, Durham University, UK  
J Bain, University of Strathclyde, UK |
| **11.00** | **Nano-fabricated solid immersion lenses registered to single emitters in diamond**  
L Marseglia, University of Ulm, Germany  
L Marseglia, University of Ulm, Germany |
| **11.00** | **(invited) High performance optical modulators in silicon**  
G Reed, University of Southampton, UK |
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<th>Time</th>
<th>Session</th>
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<th>Speaker(s)</th>
<th>Institution(s)</th>
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<tbody>
<tr>
<td>11.15</td>
<td>Optically trapped nanowires as sensitive force probes</td>
<td>Rosemary Cramp lecture theatre (CLC202)</td>
<td>S Hanna, University of Bristol, UK</td>
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<td>Y Wang, University of St Andrews, UK</td>
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<td>InGaN LED pumped polymer laser explosive sensor</td>
<td>Ken Wade lecture theatre (CLC203)</td>
<td>Interference of independent, telecom wavelength, heralded single photons from PCF and PPLN based sources</td>
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<td>A McMillan, University of Bristol, UK</td>
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<td>NARROW LINWIDTH SILICON NANO LIGHT SOURCE AT TELECOMMUNICATION WAVELENGTHS</td>
<td>Dawson lecture theatre (D110)</td>
<td>A Shakoor, University of St Andrews, UK</td>
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<td>11.30</td>
<td>Non-spherical optically trapped probes: design, control and applications</td>
<td>Rosemary Cramp lecture theatre (CLC202)</td>
<td>Automated analysis of the thermal distribution of jet engine components from thermal paints using optical techniques and principal component analysis</td>
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<td>B Russell, The University of Manchester, UK</td>
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<td>Two-dimensional quantum walks of correlated photons in 3-dimensional waveguide optics</td>
<td>Ken Wade lecture theatre (CLC203)</td>
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<td>D Fry, University of Bristol, UK</td>
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<td>Designing optimised lateral tapers for integrated silicon photonics</td>
<td>Ken Wade lecture theatre (CLC203)</td>
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<td>L Lever, University of Leeds, UK</td>
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<td>11.45</td>
<td>VALOR: Vertical Acoustic Levitation with increased Optical Routing</td>
<td>Rosemary Cramp lecture theatre (CLC202)</td>
<td>The effective use of Doppler LIDAR in wind power applications</td>
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<td>P Clive, SgurrEnergy Ltd, UK</td>
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<td></td>
<td>Silicon as a platform for integrated quantum photonics</td>
<td>Ken Wade lecture theatre (CLC203)</td>
<td>3D photonic quantum interferometry</td>
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<td>C Vitelli, Sapienza Università di Roma, Italy</td>
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<td>1300 nm wavelength InAs quantum dot photodetector grown on silicon</td>
<td>Ken Wade lecture theatre (CLC203)</td>
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<td>L Sandall, University of Sheffield, UK</td>
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<td>12.00</td>
<td>Evaluation of the feasibility of a non-dispersive UV detection technique for measurement of gaseous formaldehyde</td>
<td>Ken Wade lecture theatre (CLC203)</td>
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<td>J J Davenport, Cranfield University, UK</td>
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<td>1300 nm wavelength InAs quantum dot photodetector grown on silicon</td>
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<td>L Sandall, University of Sheffield, UK</td>
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<td>12.15</td>
<td>Earth Sciences, ES228/229/230/231, Derman Christopherson (CLC406)</td>
<td>Rosemary Cramp lecture theatre (CLC202)</td>
<td>Lunch and exhibition</td>
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<td>and Kingsley Barrett (CLC407)</td>
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<tr>
<td>12.30</td>
<td>Rosemary Cramp lecture theatre (CLC202)</td>
<td>Rosemary Cramp lecture theatre (CLC202)</td>
<td>Tutorial III: Cool things to do with lasers</td>
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<td>13.30</td>
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<td>I Hughes, Durham University, UK</td>
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<td>13.45</td>
<td>(invited) Controlled deformation of emulsion droplets with ultralow interfacial tensions using optical tweezers</td>
<td>Arnold Wolfendale lecture theatre (CLC013)</td>
<td>M Mazilu, University of St Andrews, UK</td>
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<td>(invited) Single artificial atom optical dispersive bistability</td>
<td>Ken Wade lecture theatre (CLC203)</td>
<td>T Kippenberg, EPF Lausanne, France</td>
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<td>(invited) Optics with electron beams in plasmonic metamaterials</td>
<td>Dawson lecture theatre (D110)</td>
<td>K MacDonald, University of Southampton, UK</td>
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<tr>
<td>14.15</td>
<td>Aerosol coalescence dynamics in optical traps</td>
<td>Arnold Wolfendale lecture theatre (CLC013)</td>
<td>D McGloin, University of Dundee, UK</td>
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<td></td>
<td>A machine learning approach to fringe-location identification</td>
<td>Rosemary Cramp lecture theatre (CLC202)</td>
<td>F Sawaf, Delft University of Technology, The Netherlands</td>
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<td></td>
<td>Cavity-photon controlled coherent coupling of quantum dots</td>
<td>Ken Wade lecture theatre (CLC203)</td>
<td>W Langbein, Cardiff University, UK</td>
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<td></td>
<td>Strong field enhancement of periodically-arrayed gap-mode nanoantennas</td>
<td>Dawson lecture theatre (D110)</td>
<td>K Sakai, Hokkaido University, Japan</td>
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<td>14.30</td>
<td>Optical shield: measuring turbid fluids’ viscosity with optical tweezers</td>
<td>Arnold Wolfendale lecture theatre (CLC013)</td>
<td>M Lee, University of Glasgow, UK</td>
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<td></td>
<td>Quantum statistics of surface plasmon polaritons in metallic stripe waveguides</td>
<td>Ken Wade lecture theatre (CLC203)</td>
<td>M Tame, Imperial College London, UK</td>
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<td></td>
<td>Interference of strong and weakly radiating modes of nanostructures</td>
<td>Dawson lecture theatre (D110)</td>
<td>F Papoff, University of Strathclyde, UK</td>
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<tr>
<td>14.45</td>
<td>Optical pulling of liquid droplets</td>
<td>Arnold Wolfendale lecture theatre (CLC013)</td>
<td>S A Ellingsen, Norwegian University of Science and Technology, Norway</td>
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<td></td>
<td>Optimization of Tilt Scanning Interferometry in tomographic imaging and profilometry</td>
<td>Rosemary Cramp lecture theatre (CLC202)</td>
<td>P Ruiz, Loughborough University, UK</td>
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<td></td>
<td>Maximising and detecting the dimensionality of bipartite orbital-angular-momentum entanglement</td>
<td>Ken Wade lecture theatre (CLC203)</td>
<td>D Giovannini, University of Glasgow, UK</td>
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<td></td>
<td>Spaser spectroscopy</td>
<td>Dawson lecture theatre (D110)</td>
<td>A Dorofeenko, Institution of the Russian Academy of Sciences, Russia</td>
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<tr>
<td>15.00</td>
<td>Extraction of membrane proteins from single cancer cells using holographic optical traps</td>
<td>Arnold Wolfendale lecture theatre (CLC013)</td>
<td>J Phillips, Imperial College London, UK</td>
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<td>An investigation into the accuracy of optical vortex metrology</td>
<td>Rosemary Cramp lecture theatre (CLC202)</td>
<td>V Beyer, Heriot-Watt University, UK</td>
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<td>Tailored orbital angular momentum correlations via pump-shaping</td>
<td>Ken Wade lecture theatre (CLC203)</td>
<td>D Giovannini, University of Glasgow, UK</td>
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<td>A novel technique for measuring absorption and scatter in metallic nanoparticle colloids</td>
<td>Dawson lecture theatre (D110)</td>
<td>R Hewins, Queensland University of Technology, Australia</td>
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<tr>
<td>15.15</td>
<td>Earth Sciences, ES228/229/230/231, Derman Christopherson (CLC406) and Kingsley Barrett (CLC407)</td>
<td>Exhibition and refreshments</td>
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<td>Time</td>
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<td>15:45</td>
<td>T. Denz, University of Münster, Germany</td>
<td>(Invited) Trends in optical micromanipulation: tailored light fields meet nanocontainers &amp; absorbing particles</td>
<td>Rosemary Cramp lecture theatre (CLC202)</td>
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<tr>
<td>16:00</td>
<td>C. Denz, University of Münster, Germany</td>
<td>Calibration of optical surface topography measuring instruments using the transfer function</td>
<td>Ken Wade lecture theatre (CLC203)</td>
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<td></td>
<td>R. Leach, National Physical Laboratory, UK</td>
<td>Direct determination of purity and fidelity for single-photon states</td>
<td>Dawson lecture theatre (D110)</td>
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<tr>
<td>16:15</td>
<td>L. Wright, University of Oxford, UK</td>
<td>Trends in optical micromanipulation: tailored light fields meet nanocontainers &amp; absorbing particles</td>
<td>Fringe Analysis Special Interest Group (FASIG): Techniques and application</td>
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<td></td>
<td>R. Leach, National Physical Laboratory, UK</td>
<td>Metrology of thin films using interferogram analysis techniques</td>
<td>Quantum optics theory</td>
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<td></td>
<td>D. Towers, University of Leeds, UK</td>
<td>Calibrating optical surface topography measuring instruments using the transfer function</td>
<td>Chair: J. Rarity, University of Bristol, UK</td>
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<tr>
<td>16:30</td>
<td>G. Gibson, University of Glasgow, UK</td>
<td>A compact holographic optical tweezers system</td>
<td>Nanophotonics and plasmonics III</td>
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<td></td>
<td>D. Towers, University of Leeds, UK</td>
<td>Metrology of thin films using interferogram analysis techniques</td>
<td>Chair: J. Bayu</td>
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<td></td>
<td>J. Jeffers, University of Strathclyde, UK</td>
<td>Detecting nothing</td>
<td>(Invited) Efficient coupling of ultrathin tapered fibers with nanoemitters and microsphere resonators</td>
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<tr>
<td>16:45</td>
<td>A. Jeorrett, University of Strathclyde, UK</td>
<td>Optical tweezers at high pressure</td>
<td>M. Fujiwara, Hokkaido University &amp; Osaka University, Japan</td>
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<td>T. D. Nguyen, Heriot-Watt University, UK</td>
<td>Measurement of the hygroscopic expansion coefficient of Ethylene Vinyl Acetate using wavelength scanning interferometry</td>
<td>Quantum optics theory</td>
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<td>E. Eleftheriadou, University of Strathclyde, UK</td>
<td>Super-optimal coherent state amplification without quantum resources</td>
<td>Chair: J. Bayu</td>
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<td>B. Patton, University of Oxford, UK</td>
<td>Femtosecond phase-resolved microscopy of plasmon dynamics in individual gold nanospheres</td>
<td>(Invited) Efficient coupling of ultrathin tapered fibers with nanoemitters and microsphere resonators</td>
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<tr>
<td>17:00</td>
<td>S. Casabella, The University of Manchester,</td>
<td>Optical immobilisation techniques applied to Raman analysis of individual cancer cells</td>
<td>Metal-glass nanocomposites for optical storage of information</td>
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<td>UK</td>
<td>A widefield, two laser, interferometer</td>
<td>A. Abdolvand, University of Dundee, UK</td>
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<td>17:15</td>
<td>Free time</td>
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<td>18.00</td>
<td>Calman Learning Centre reception</td>
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<td>Coaches depart for Conference dinner</td>
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<td>19.00</td>
<td>Newcastle Football Club</td>
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<td>Conference dinner</td>
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<td>Poster prize presentation and Conference speech by Professor Allan Boardman</td>
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Thursday 6 September

08.30  *Calman Learning Centre reception*  
Registration

09.00  **Arnold Wolfendale lecture theatre**  
Chair: Professor A Boardman, University of Salford, UK  
IOP Optics and Photonics Division Prize winner  
(plenary) Superfibre - how a new generation of optical fibres is spreading across the globe  
Professor Jonathan Knight, University of Bath, UK

09.30  Calman coffee area, Derman Christopherson (CLC406) and Kingsley Barrett (CLC407)  
Refreshments

<table>
<thead>
<tr>
<th>Time</th>
<th>Session</th>
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<tr>
<td>10.00</td>
<td><strong>Arnold Wolfendale lecture theatre</strong></td>
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<td>Optical vortices, polarization, coherence and non-Gaussian beams I</td>
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<td></td>
<td>Chair: M Dennis, University of Bristol, UK</td>
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<td>(invited) Atomic size OAM electron beams as tools for characterization and</td>
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<td>manipulation of nanoparticles J Verbeeck, University of Antwerp, Belgium</td>
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<td>Rosemary Cramp lecture theatre (CLC202)</td>
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<td>Fibre optics and wave guidelines I Chair: J Knight, University of Bath, UK</td>
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<td></td>
<td>(invited) Si slow light photonic crystals: four wave mixing and on-chip quantum interference J Rey, University of St Andrews, UK</td>
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<td>Ken Wade lecture theatre (CLC203)</td>
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<td>Quantum dots I: colloidal quantum dots Chair: J Smith, University of Oxford, UK</td>
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<td></td>
<td>(invited) Electron-hole wavefunction engineering as a tool to control the</td>
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<td>exchange interaction in CdSe/CdS nanocrystals: towards novel quantum light</td>
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<td>sources G Raino, IBM Research, Switzerland</td>
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<td>Dawson lecture theatre (D110)</td>
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<td></td>
<td>Optical and quantum metrology I Chair: G Buller, Heriot-Watt University, UK</td>
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<td></td>
<td>(invited) Frontiers in photon-counting R Hadfield, Heriot-Watt University, UK</td>
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<td></td>
<td>10.30 Twisted photons and twisted electrons - theory and experiment</td>
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<td></td>
<td>S Lloyd, University of York, UK</td>
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<td></td>
<td>Axial tamm plasmons R Abram, Durham University, UK</td>
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<td></td>
<td>Ultrafast transient absorption spectroscopy of HgTe quantum dots A Al-Otaify, The University of Manchester, UK</td>
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<td></td>
<td>Waveguide integrated quantum photonics: superconducting single-photon detectors and autocorrelators D Sahin, Eindhoven University of Technology, The Netherlands</td>
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<td>10.45 Detecting the azimuthal and radial content of Laguerre Gaussian beams M Mazilu, University of St Andrews, UK</td>
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<td>Tunable slow light in nonlinear electro-optic materials C Deng, University of Münster, Germany</td>
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<td>Spin-flip limited exciton zero-phonon line dephasing in CdSe colloidal quantum dots P Bori, Cardiff University, UK</td>
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<td>Nano-optical measurements of novel superconducting single photon detector designs R Heath, Heriot-Watt University, UK</td>
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*Note: All sessions are in the *Calman Learning Centre*. Registration starts at 08.30.
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<thead>
<tr>
<th>Time</th>
<th>Session Title</th>
<th>Presenters/Institutions</th>
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<tbody>
<tr>
<td>11.00</td>
<td>Electron vortex propagation in magnetic fields</td>
<td>C Greenshields, University of Glasgow, UK</td>
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<td>Rosemary Cramp lecture theatre (CLC202)</td>
<td>Ken Wade lecture theatre (CLC203)</td>
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<td>Multi-pixel detector for photon-correlation measurements in position, transverse momentum and intermediate bases for an extended field of view</td>
<td>Dawson lecture theatre (D110)</td>
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<td></td>
<td>11:00 Electron vortex propagation in magnetic fields</td>
<td>C Greenshields, University of Glasgow, UK</td>
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<td></td>
<td>Passive Q-switched mode-locking in a Ytterbium doped bismuthate planar waveguide laser</td>
<td>R Mary, Heriot-Watt University, UK</td>
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<td>Optical properties of graded-alloy colloidal nanocrystal quantum dots</td>
<td>J Fill, University of Oxford, UK</td>
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<td></td>
<td>11.15 Singularimetry - probing chiral surfaces with optical vortices</td>
<td>Y Ren, Heriot-Watt University, UK</td>
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<td>Tm:YAG waveguide laser fabricated by ultrafast laser inscription</td>
<td>Measuring optical frequency ratios in 171Yb+ to study fundamental physics</td>
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<td>J Goette, Max-Planck-Institute for the Physics of Complex Systems, Germany</td>
<td>L Johnson, National Physical Laboratory, UK</td>
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<td>Attractive biexciton interaction energies in CdSe/CdTe/CdS Type II colloidal dots</td>
<td>M Cadirci, The University of Manchester, UK</td>
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<td>11.30 Calman coffee area, Derman Christopherson (CLC406) and Kingsley Barrett (CLC407)</td>
<td>Refreshments</td>
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<td></td>
<td>Optical vortices, polarization, coherence and non-Gaussian beams II</td>
<td>Fibre optics and wave guidelines II</td>
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<td>Chair: M Padgett, University of Glasgow, UK</td>
<td>Chair: G Buller, Heriot-Watt University, UK</td>
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<td></td>
<td>Measuring the orbital angular moment with custom refractive optical elements</td>
<td>Silica hollow-core photonic crystal fibres with selective bandgaps in the 2 to 3.6µm mid-infrared region</td>
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<td>M Lavery, University of Glasgow, UK</td>
<td>Chair: R Oulton, University of Bristol, UK</td>
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<td></td>
<td>(Invited) Measuring the orbital angular moment with custom refractive optical elements</td>
<td>R Menchon-Enrich, Universitat Autònoma de Barcelona, Spain</td>
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<td>12.00</td>
<td>12:00 Adiabatic passage and spectral filtering of light in CMOS-compatible silicon oxide integrated rib waveguides</td>
<td>R Menchon-Enrich, Universitat Autònoma de Barcelona, Spain</td>
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<td></td>
<td>Characterisation of a long period grating refractive index profile through correlation analysis</td>
<td>R Nazir, Imperial College London, UK</td>
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<td></td>
<td>Understanding exciton-phonon interactions in driven quantum dots</td>
<td>Observation of spatial correlated photon pairs in position and momentum with an electron multiplying CCD camera</td>
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<td>A Nazir, Imperial College London, UK</td>
<td>F Izdebski, Heriot-Watt University, UK</td>
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<td></td>
<td>12:30 The Pearcey Beam</td>
<td>The Pearcey Beam</td>
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<td></td>
<td>J Ring, University of Bristol, UK</td>
<td>Characterisation of a long period grating refractive index profile through correlation analysis</td>
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<td>Chair: G Buller, University of Glasgow, UK</td>
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<td></td>
<td>(Invited) Measuring the orbital angular moment with custom refractive optical elements</td>
<td>A Greilihx, Technische Universität Dortmund, Germany</td>
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<td>12.45</td>
<td>Arnold Wolfendale lecture theatre</td>
<td>Experimental investigation of anomalous behaviour of a phase perturbed random optical field</td>
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<td>Rosemary Cramp lecture theatre</td>
<td>Direct integration of electro-optically tunable waveguide Bragg gratings in lithium niobate by femtosecond laserwriting</td>
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<td>Ken Wade lecture theatre (CLC203)</td>
<td>Electro-elastic control of self-assembled InGaAs quantum dots</td>
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<td>Dawson lecture theatre (D110)</td>
<td>Measuring protein concentration with entangled light in an opto-fluidic chip</td>
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<td>13.00</td>
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<td>Conservation and quantization of photon angular momentum in non-uniformly polarized beams</td>
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<td>Ultrafast laser inscription of low loss mid-infrared waveguides in polycrystalline ZnSe</td>
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<td>Spectroscopy of charge tunable quantum dots at telecom wavelengths</td>
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<td>Practical photon number detection using electric field-modulated silicon avalanche photodiodes</td>
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<td>13.15</td>
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<td>Multi-beam interference from lensed multicore fibre probes</td>
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<td>(invited) Quantum dot resonance fluorescence: progress and outlook</td>
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<td>Kilometre range single-photon depth imaging system at 1560 nm wavelength</td>
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13.45 Close of conference. A packed lunch will be available to collect from the Calman coffee area on departure.
Poster programme

Poster session I – Monday 3 September 2012
Location: Derman Christopherson (CLC406) and Kingsley Barrett (CLC407)

Active and adaptive optics

P.01 - Performance evaluation of a liquid crystal based 3D autostereoscopic display
J F Algorri, Carlos III University, Spain

P.02 - Measurement of the M2 laser propagation factor using a liquid lens
S Hall, National Physical Laboratory, UK

P.03 - Femtosecond microfabrication using an adaptive optics addressed microlens array
P Salter, University of Oxford, UK

Advances in imaging and displays

P.04 - Low noise InAs electron avalanche photodiodes for imaging applications
P Ker, University of Sheffield, UK

Biophotonics

P.05 - Phase sensitive-optical low coherence reflectometry for bio-sensing applications
A-F Obaton, LNE, France

P.06 - Light-sheet tomography for in vivo imaging of arabidopsis root
Z Yang, University of Dundee, UK

P.07 - Optical designs to improve opto-electronic neural stimulation with micro-LED arrays
L Chaudet, Imperial College London, UK

P.08 - Nanothermometry: quantum dots for temperature sensing in biological environments
W T Ramsay, Heriot-Watt University, UK

P.09 - Cavity Enhanced Absorption Spectroscopy (CEAS) as a detection technique for microfluidic devices
R Gupta, The University of Manchester, UK

P.10 - Catadioptric micro-optics
C Saunter, Durham University, UK

P.11 - Novel nanotechnologies for multiple spatially and temporally resolved live single cell membrane sampling and analysis
D Wylie, Imperial College London, UK

Diffractive optics

P.12 - Design and fabrication of transmissive and reflective diffractive optical components for mass replication
A Waddie, Heriot-Watt University, UK
Optical tweezing and micro-manipulation

P.13 - Optical control of microparticle morphology in the liquid phase
A Payne-Dwyer, Durham University, UK

P.14 - Measuring the interaction between Uvr proteins and DNA using an optically-controlled force probe
M Pollard, STFC Rutherford Appleton Laboratory, UK

P.15 - Optical trapping with optical spirals containing orbital angular momentum
S Anand, University of Dundee, UK

P.16 - Arduino controlled optical tweezers
R Henderson, University of Dundee, UK

P.17 - Optical red blood cell sorting
P O’Mahoney, University of Dundee, UK

P.18 - Expanding the toolbox for optical manipulation of metal nanoparticles with holographic optical tweezers
G Gibson, University of Glasgow, UK

P.19 - Microsoft Kinect interface for controlling holographic optical manipulation
C McDonald, University of Dundee, UK

P.20 - Acousto-optically generated potential energy landscapes: potential mapping using colloids under flow
M Juniper, University of Oxford, UK

P.21 - Single aerosol trapping with an annular beam
R D Dear, University of Oxford, UK

Silicon and carbon photonics

P.22 - Electronic structure and optoelectronic properties of strained Ge nanowires with different orientations
O Aldaghri, University of Leeds, UK

P.23 - Photonic crystal cavity based cascaded modulators and demodulators for a WDM system
K Debnath, St Andrews University, UK

P.24 - Density matrix modelling of Ge/GeSi quantum cascade terahertz lasers
Z Ikonic, University of Leeds, UK

P.25 - Incandescent emission from graphene films
L Lawton, University of Exeter, UK

P.26 - Room temperature 2 micron fluorescence from Tm3+ doped silicon thin film
M Murray, University of Leeds, UK

P.27 - Group IV photonic devices and modulation predictions
M Nedelijkovic, University of Surrey, UK

P.28 - Charge transport efficiency in Ge/Si single-photon avalanche diodes
N Pilgrim, University of Leeds, UK
Advances in laser science

P.29 - Excess noise induced by optical feedback in 6.1-um quantum cascade lasers under well-defined conditions
K Tsushima, Ritsumeikan University, Japan

P.30 - Graphene based Q-switched thulium-doped fibre lasers at 2 micron
C Ye, Xiamen University, China

P.31 - Direct measurement of the junction temperature of a DFB laser diode used in tunable diode laser spectroscopy
A Asmari, Cranfield University, UK

P.32 - The increase of the output power value of gas ion lasers in presence of noble gas additions
W Kaminski, Warsaw University of Technology, Poland

Metamaterials and cloaking

P.33 - Maxwell's fishpond
P Kinsler, Imperial College London, UK

Nanophotonics and plasmonics

P.34 - Homogenous silver-glass nanocomposite
S Wackerow, University of Dundee, UK

P.35 - Light backscattering in plasmonic films for enhanced gas and vapour sensing
M Lobet, University of Namur, Belgium

P.36 - Optics of nanometer-scale structures
T Kudykina, University Ukraina, Ukraine

P.37 - A columnar thin film as a surface-plasmonic-polaritonic optical sensor
S S Jamaian, The University of Edinburgh, UK

P.38 - Polarization-resolved absorption and scattering microspectroscopy of individual silver nanoparticles
P Borri, Cardiff University, UK

P.39 - Polarization-degenerate quantum dot emission in photonic crystal cavities
A Thijssen, University of Bristol, UK

P.40 - Balanced detection for interferometry with a noisy source
E Robinson, University of Bristol, UK

P.41 - Enhancement of radiation from dielectric waveguides using resonant plasmonic coreshells
R Fernandez-Garcia, Imperial College London, UK

P.42 - Cross resonant antennas for controlling emission polarization of organic emitters
R Fernandez-Garcia, Imperial College London, UK

P.43 - Plasmonic photovoltaics: new concepts for absorption enhancements in III-V solar cells
N Hylton, Imperial College London

P.44 - Silicon-based plasmonic coupler
R Thomas, University of Leeds, UK

P.45 - Optimised plasmonic structures for thin film solar cells
A Powell, University of Oxford, UK
P.46 - Collective effects in 2D spaser lattices
A Zyablovsky, Institute for Theoretical and Applied Electromagnetics, Russia

Nonlinear photonics

P.47 - Two-colour spatial optical solitons: new stability analyses for off-axis propagation
C Bostock, University of Salford, UK

P.48 - Helmholtz dark spatial solitons in waveguides with defocusing saturable materials
C Bostock, University of Salford, UK

P.49 - Optical manipulation of BEC momentum states via non-normality
F Papoff, University of Strathclyde, UK

P.50 - Control of response of exciton polariton confined in GaAs thin films by controlling pump and probe pulses
O Kojima, Kobe University, Japan

P.51 - Effect of phase, amplitude and spacing on neighboring soliton pulses
A Antwiwaa, SRM University, India

P.52 - Spatiotemporal soliton formation in arrays of silicon waveguides
A Gorbach, University of Bath, UK

P.53 - Energy shedding during nonlinear focusing of optical beams for sub-diffraction imaging
C Travis, University of Strathclyde, UK
Poster session II - Tuesday 4 September 2012
Location: Derman Christopherson (CLC406) and Kingsley Barrett (CLC407)

**Advances in terahertz technology**

**P.01** - A theoretical framework for chemometric analysis of amorphous materials  
S Hadjiloucas, The University of Reading, UK

**P.02** - Quasi-optical antenna phase measurements using homodyne detectors  
S Hadjiloucas, The University of Reading, UK

**P.03** - A 1-port de-embedding technique for quasi-optical measurements of characteristic impedance in waveguides with applications to microspectroscopy and antenna characterization  
S Hadjiloucas, The University of Reading, UK

**P.04** - Compressive three-dimensional (3D) terahertz imaging  
Y Shen, University of Liverpool, UK

**P.05** - Double bosonic stimulation of THz radiative transitions  
M Kaliteevski, Durham University, UK

**Fibre optic and wave guidelines**

**P.06** - Comparative studies of the Thulium and Erbium doped from 1480-1650 nm with different host materials as optical fiber amplifiers  
O Mahran, Alexandria University, Egypt

**Fibre optic sensors**

**P.07** - Long term stability of fibre Bragg gratings embedded in polymeric structures using additive layer manufacturing technology  
R J Maier, Heriot-Watt University, UK

**P.08** - The development of a POF based distributed sensor and its application to environmental monitoring  
M Benyezzar, The University of Manchester, UK

**P.09** - Optical fibre cantilever sensors fabricated using ps-laser machining  
J Li, Heriot-Watt University, UK

**Optical and quantum metrology**

**P.10** - Quantum metrology with fibre sources  
B Bell, University of Bristol, UK

**P.11** - Towards single photon avalanche diode detectors using narrow bandgap InAs  
S Butera, Heriot-Watt University, UK

**P.12** - High-resolution single-photon spectroscopy at telecom wavelengths  
C Fitzpatrick, National Physical Laboratory, UK

**P.13** - Uncooled GaSb/InAs type II superlattice photodiode for radiation thermometry  
M Hobbs, University of Sheffield, UK
P.14 - FPGA based flexible instrumentation for photon counting and time tagging
R Nock, University of Bristol, UK

P.15 - Temporal variation of residual amplitude modulation in electro-optic phase modulators
J Sathian, Queensland University of Technology, Australia

Optical diagnostics in engineering

P.16 - Comparative analysis of digital demodulation approaches in Optical Coherence Tomography
P Liu, Delft University of Technology, the Netherlands

P.17 - Characterization of tablet coatings using infrared optical coherency tomography
C Li, University of Liverpool, UK

Singularities, optical vortices, polarization, coherence and non-Gaussian beams

P.18 - Angular momentum of quasimonochromatic Gaussian beam
K Kharytonovat, Chernivtsi National University, Ukraine

P.19 - Testing of the angular position- Orbital Angular Momentum uncertainty relationship based on entropy
R Aspden, University of Glasgow, UK

P.20 - Control of the amplitude and polarisation distributions of focussed high NA beams using holograms on spatial light modulators
J Clegg, Imperial College London, UK

P.21 - A novel method for generating electron vortex beams
F Trindade, University of Glasgow, UK

P.22 - Intensity and phase profile measurements of vortex beams at millimetre wavelengths
S Maccalli, The University of Manchester, UK

Location: Earth Sciences, ES228/229/230/231

Quantum coherent control

P.23 - Energy sharing in the two-electron attosecond streak camera
H Price, University College London, UK

P.24 - 2D Holographic optical lattices for single atoms manipulation
L Beguin, Institut d’Optique, France

P.25 - Reduced-density-operator description of single-photon and multi-photon processes in quantized many-electron systems
V Jacobs, Naval Research Laboratory, USA

P.26 - Dynamics of correlations in the fermi problem
M Borrelli, Heriot-Watt University, UK

P.27 - Strange change of CsCdCl₃ excitation spectra with temperature
R Demirbilek, Yıldız Technical University, Turkey

P.28 - Excitation and emission spectra of CsMgCl₃, CsMgBr₃ and CsMgI₃
A Celik Bozdoğan, Yıldız Technical University, Turkey

P.29 - Enhancement of collective atomic recoil lasing by electromagnetically induced transparency
J Mckelvie, University of Strathclyde, UK
P.30 - Nonlinear dynamics of Bose-Einstein condensates in optical cavities
M Diver, University of Strathclyde, UK

P.31 - Spatial opto-mechanical structures in cold atomic gases
E Tesio, University of Strathclyde, UK

P.32 - An optical isolator using atomic vapour in the hyperfine paschen-back regime
M Zentile, Durham University, UK

Quantum dots
P.33 - Photon correlation spectroscopy of ZnO Quantum Dots - a tool for investigating size dispersions and inter-particle forces
M Shortell, Queensland University of Technology, Australia

Quantum information
P.34 - Quantum measurement with chaotic apparatus
M Everitt, Loughborough University, UK

P.35 - Polaractivation of noisy optical quantum channels
L Gyongyosi, Budapest University of Technology and Economics, Hungary

P.36 - Transmission of classical information over zero-capacity optical quantum channels
L Gyongyosi, Budapest University of Technology and Economics, Hungary

P.37 - Programmable beamsplitters and complete memory retrieval: towards applications in quantum information science
K Reim, ETH Zurich, Switzerland

P.38 - A stable diode laser for quantum-coherent control and entanglement of 88Sr+ ions in a 3D microfabricated ion trap
J Thom, National Physical Laboratory, UK

P.39 - Direct optical experimental verification of Yang-Baxter equation
G L Long, Tsinghua University, China

Quantum optics
P.40 - Quantum-classical crossover of a field mode
M Everitt, Loughborough University, UK

P.41 - Super-optimal coherent state amplification without quantum resources
E Eleftheriadou, University of Strathclyde, UK

P.42 - Tapered distributed feedback pillar cavity in diamond
M Taverne, University of Bristol, UK

P.43 - Photon pair quantum interference with 2x2 multimode interference devices
D Fry, University of Bristol, UK

Structured optical materials
P.44 - Helmholtz spatial solitons and oblique propagation in coupled-waveguide arrays
E McCoy, University of Salford, UK
P.45 - A hidden sector photon search using photonic band gap structures
N Woollett, Lancaster University, UK, and Cockcroft Institute, UK
Plenary speaker biographies

IOP Optics and Photonics Division Prize Winner

Professor J C Knight, University of Bath, UK

Jonathan Knight is in the Department of Physics at the University of Bath. He obtained his PhD at Cape Town for work on cylindrical microlasers. He did postdoctoral research at the École Normale Supérieure in Paris (working on high-Q whispering-gallery-mode resonators) and at the Optoelectronics Research Centre in Southampton. Whilst at Southampton he worked with colleagues Philip Russell and Tim Birks to design and fabricated the first photonic crystal optical fibre, in which light was guided by an array of air holes in glass. Since moving to Bath in 1995 he has established and run a state-of-the-art fabrication complex for novel optical fibres, achieving a number of breakthroughs but most notably demonstrating low-loss guidance in an air-core fibre. He was a co-founder of the Bath spin-out company BlazePhotonics in 2001 and has worked closely with Fianium Ltd. in developing supercontinuum sources over the last few years. He is currently Head of the Department of Physics at Bath and is formerly Director of the Centre for Photonics and Photonic Materials. He is a Fellow of the Optical Society of America, is a frequent invited speaker at conferences on optics and photonics and has an h-index of 57.

Professor G Milburn, University of Queensland, Australia

Gerard Milburn obtained a PhD in theoretical Physics from the University of Waikato in 1982 for work on squeezed states of light and quantum nondemolition measurements. He is currently an Australian Research Council Federation Fellow at the University of Queensland and Director of the new Australian Research Council Centre of Excellence in Engineered Quantum Systems.

Gerard Milburn is a Fellow of the Australian Academy of Science and The American Physical Society.

He has worked in the fields of quantum optics, quantum measurement and stochastic processes, atom optics, quantum chaos, mesoscopic electronics, quantum information and quantum computation, and most recently in quantum nanomechanics and superconducting circuit QED.

He has published four books. Together with Dan Walls he published one of the first texts on Quantum Optics (Springer 1994), recently updated with a new edition (Springer, 2008), and two non technical books on quantum technology and quantum computing (Schroedinger’s Machines, Allen and Unwin, 1996; The Feynman Processor, Allen and Unwin 1998).

His new book, coauthored with Howard Wiseman, "Quantum Measurement and Control!" was published by Cambridge University Press, last year.

Professor F Pavone, University of Florence, Italy

Francesco Saverio Pavone is directing a research group working in the field of biophotonics on single molecule biophysics, microscopy imaging-spectroscopy techniques, biomedical imaging, laser manipulation of bio-samples.

In particular, he is developing new microscopy techniques for high resolution and high sensitivity imaging, and for laser manipulation purposes. These techniques have been applied both for single molecule biophysics, single cell imaging and optical manipulation. Tissue imaging is another research area developed, where non-linear optical techniques have been applied for skin and neural tissue imaging. Recently, In-Vivo imaging apparatus have been developed and applied to animal and humans.

Pavone is authors of many internationals papers and editor of international books. He has more than 50 invited talk and he is editors of international journals. He coordinates several European projects and he has organized international congresses; he is also director of the international PhD program at LENS.
John Pendry is a condensed matter theorist. He has worked at the Blackett Laboratory, Imperial College London, since 1981. He has worked extensively on electronic and structural properties of surfaces developing the theory of low energy diffraction and of electronic surface states. Another interest is transport in disordered systems where he produced a complete theory of the statistics of transport in one dimensional systems. In 1992 he turned his attention to photonic materials and this project culminated in the proposal in 2000 for a “perfect lens” whose resolution is unlimited by wavelength. These concepts have stimulated further theoretical investigations and many experiments which have confirmed the predicted properties. More recently in 2006, in collaboration with David Smith at Duke University, he has proposed a recipe for a cloak that can hide an arbitrary object from electromagnetic fields. Several realisations of this concept have been built some operating at radar and others at visible wavelengths.
Plenary speaker abstracts

The Rank Lecture

Inside the Wavelength – seeing really small objects with light

J Pendry
Imperial College London, UK

Light, though our eyes, gives us the most direct means of observing the world. Using a microscope we can see many objects invisible to the naked eye, but even the microscope has its limitations: it is impossible with a conventional microscope to resolve anything smaller than the wavelength of light. Typically this sets a resolution limit of about 0.5 microns. To do better than this and to “get inside the wavelength” scientists have been seeking a deeper understanding of light and its component electric and magnetic fields. We can now give a theoretical prescription for the perfect lens that has no limits to resolution. I shall report on recent progress and describe some experiments that bring light to an intense focus very much smaller than the free space wavelength.

Biophotonics: perspectives in biomedical imaging

F Pavone
University of Florence, Italy

An introductory part will be dedicated to describe the most popular biomedical imaging techniques using photons, ranging from linear to non-linear imaging approaches. A more detailed description will be devoted to discuss about laser imaging in the near infrared and visible. Finally, a few examples of laser imaging on different biological samples and organs will show how new photonics tools will be useful in the near future in clinics to perform early diagnosis or follow up of therapies.

Quantum optomechanics: an engineered quantum system

G Milburn
The University of Queensland, Australia

The emerging field of quantum optomechanics combines quantum optics and new fabrication techniques to control the quantum state of macroscopic mechanical resonators. These systems are an example of a new kind of engineered quantum system in which supra-atomic, hybrid systems are engineered to have the desired quantum functionality. They have application to metrology and sensing and may enable new experiments at the quantum-classical boundary. I will give an overview of this new field and discuss some specific models. These include a single photon optomechanics, quantum entanglement in optomechanical networks and quantum-limited readout of phonon jumps.
In the decade since the telecom crash, optical fibre science and technology has defied predictions by renewing itself as a vibrant research area. As a result, fibres are making massive and sometimes surprising inroads into a range of application areas. Some notable advances have been in areas like few-moded fibres, photonic crystal fibres, hollow core fibres, photonic bandgap fibres and plasmonic fibres. Simultaneous development of improved pump sources have enabled a new range of fibre-based light sources, including high power fibre lasers, ultrafast fibre laser systems, and supercontinuum systems and frequency combs, which offer high powers, high energies and controllable spectral profile, with high-mode-purity optical fibre delivery taken for granted. This is leading to a profound change in the perception of laser sources as they become embedded into a range of user-oriented products for industrial and biomedical applications. Incorporating novel or traditional fibres in applications relies on ways to integrate them, and developments in fibre processing, splicing and tapering are resulting in new devices like fibre-based gas cells and mode processors for astrophotonics. Just as the technologies originally developed for telecommunications have resulted in the current “glory days” for fibre optic research, so current telecom interests in multi-core fibres and multimode transmission promise to drive applications in other areas in the future. The talk will describe the core developments in fibre optics over the last decade, illustrated with examples from the areas listed above, and how these and current developments may drive further progress in this exciting research area.
Invited speaker biographies

Dr M Atature, University of Cambridge, UK
Topic: Quantum dots

Mete Atature is currently the Head of Atomic, Mesoscopic and Optical Physics Group at the University of Cambridge. He received his Bachelor of Science degree in 1996 from Bilkent University Physics Department in Turkey. Then, he joined the Quantum Imaging Laboratory at Boston University for his PhD studies. From 2002 to 2007, he worked as a Postdoctoral Fellow in the Quantum Photonics Group at ETH Zurich. He joined the Cavendish Laboratory in June 2007 as a Lecturer and was promoted to a Readership in 2011. Current research efforts in his group are focused on solid-state quantum information and nanoscale quantum metrology using semiconductors and diamond. Mete Atature is an elected Fellow of IoP since 2011.

Professor D Bagnall, University of Southampton, UK
Topic: Structured optical materials

Professor Darren Bagnall is Head of the Nano Group in the department of Electronics and Computer Science, at the University of Southampton. His research is currently focused on the application of nanomaterials and nanostructures to photovoltaic devices. Prof. Bagnall’s research career began as a PhD student at Salford University, where he worked on "CulnSe2 thin films for photovoltaic applications". With post-doctoral positions at Strathclyde University, Tohoku University and Riken (Japan) he developed interest in II-VI compounds and demonstrated the world’s first ZnO based room temperature laser. Since joining the University of Southampton, in 1999, Prof. Bagnall has pursued research based on silicon photonics and silicon photovoltaics. In particular he has explored nanostructured metamaterials and plasmonic systems including; planar chiral metamaterials, and biomimetic and plasmonic systems for photovoltaics. Professor Bagnall’s research is currently funded by the UK EPSRC "Supergen" program and he is an International Collaborator on the NEDO/METI 'Cool Earth 50' Innovative Photovoltaics Technology (2008) with AIST, Japan. He is a member of the IoP and IET and sits on the UK Solar Energy Society committee and is an associate editor for the Solar Energy Journal.

Professor J Barton, University of Southampton, UK
Topic: Optical diagnostics in engineering

Professor Dulieu-Barton has worked in experimental mechanics and non-destructive testing since 1989 and has published more than 230 papers on these topics. She received a BSc in Mechanical Engineering in 1988 from the University of Salford and a PhD from the University of Manchester in 1993. Currently she is a Professor of Experimental Mechanics in the School of Engineering Sciences at the University of Southampton. Professor Barton’s primary research interest is in imaging. Applications include: damage analysis of composite/ sandwich/ textile materials, crack-tip stress studies and small scale full-field experimental stress analysis. Professor Dulieu-Barton is a Fellow of the UK Institute of Physics and a Chartered Mechanical Engineer. She was the Editor-in-Chief of the international journal for experimental mechanics, Strain, and is now its Associate Editor. She has numerous roles with the Institute of Physics (IOP) including chairman of the Applied Physics and Technology Division. She is also past chairman of the British Society for Strain Measurement (BSSM), a founder member of the UK Forum for Applied Mechanics and UK representative and interim president of the European Association for Experimental Mechanics (EURASEM). In 2007 she won the EURASEM’s Robert Hooke award for Experimental Mechanics. She is also the Chairman of the US-based Society for Experimental Mechanics Thermal Methods Division.
Dr J Bewersdorf, Yale University, USA

Topic: Advances in imaging and displays

Joerg Bewersdorf studied physics in Freiburg and Heidelberg, Germany, interrupted by an exchange year at the University of Glasgow, UK. After his doctoral and postdoctoral work with Stefan Hell at Leica Microsystems and the Max Planck Institute for Biophysical Chemistry in Goettingen, Germany, he worked for 4 years at The Jackson Laboratory in Bar Harbor, Maine, as a Research Scientist. Since 2009 he is an Assistant Professor at Yale in the Department of Cell Biology with a secondary affiliation to the Department of Biomedical Engineering.

Dr. Bewersdorf’s interests lie in the development and application of super-resolution techniques to image cellular structures that are below the diffraction limit and inaccessible to conventional microscopy. He has more than 10 years of experience in super-resolution fluorescence microscopy, in particular 4Pi microscopy, fluorescence photoactivation localization microscopy (FPALM/PALM), STED microscopy, and 3D particle tracking.

Professor D Burton, Liverpool John Moores University, UK

Topic: Fringe Analysis Special Interest Group (FASIG)

Prof David Burton has for a number of years worked in the field of optical metrology. His work has covered such diverse areas as; classical interferometry, both classical and digital holographic interferometry, structured light systems and fibre optic sensors. He is particularly known for his contribution to the early development of the Fourier Transform fringe phase measurement techniques and, along with various colleagues, the development of many of the most successful, and widely used, phase unwrapping algorithms in deployment today. His software techniques for the phase analysis of structured light systems have seen application in fields as diverse as; industrial manufacture, medicine and cultural heritage.

The author of over 80 journal papers in pretty well all of the leading journals dealing with optical metrology he has supervised nearly 40 PhD students. Currently he is the Professor of Engineering Science at Liverpool John Moores University and Director of the General Engineering Research Institute at that university - a world class centre for research in optics, laser processing and advanced manufacturing technology.

Recently Prof Burton has been applying his knowledge gained through 30 years research in optical measurement into small scale applications and has developed new methods and models for the study of the mechanics of living cells. But in his paper at this event he will be drawing on his experience to exam the maturity of e state-of-the-art in fringe phase analysis systems from a wide range of workers in the field and asking the question, is this technology fully fit for applications yet, or do we still have significant problems to research?

Professor S Chavez-Cerda, INAO optics, Mexico

Topic: Computational physics

Sabino Chávez-Cerda, after receiving his PhD in 1994 from Imperial College, UK, has been at INAOE, Mexico, where he is a full professor since 2004. Dr. Chávez-Cerda is well-known for his work on the alternative traveling waves theory to Bessel beams. His theoretical approach explains in a simple and physically intuitive way their controversial features. This theory also led to the discovery of Mathieu and transverse parabolic beams, two other types of non-diffracting beams, and can be extended to describe all the apparently odd observed propagation features of Airy beams, a different class of non-diffracting beams. Some of his research works have featured in the Best in Optics list in OSA’s Optics and Photonics News and Physical Review Focus. His main research interests is to apply theoretical techniques (analytical and numerical) to study the spatio-temporal propagation and diffraction of optical beams in dispersive linear and nonlinear media. The aim is to understand the physics of these phenomena and to study potential applications to photonics devices and optical computing components.
Dr A Chelnokov, CEA-Leti, France
Topic: Silicon and carbon photonics
Alexei Chelnokov is now a chief scientist of the Optronics Dépt, CEA Leti Minatec (Grenoble, France), after having headed the Silicon Photonics Lab of the CEA Leti. He was educated at A.F. Ioffe Physico-Technical Institute (St.-Petersbourg, Russia) and has worked successively at Ioffe Institute, CNRS Institute of fundamental electronics (Orsay, France), Corning Inc. (France), with short stays with Polaroid Corp (MA, USA) and Thomson LCR (France). His research interests concern optoelectronic devices for tele- and data-coms, solid-state lighting, silicon photonics, photonic crystals, integrated nano-optics and plasmonics. He has published over 50 journal papers, over 50 conference presentations, and co-authored two books.

Ms S Cipiccia, University of Strathclyde, UK
Topic: Ultrafast and attosecond optics
Silvia Cipiccia studied Nuclear Physics at the University degli studi di Perugia in Italy doing her Master Degree on “The study of the behavior at low temperature of irradiated silicon particle detectors”. After working experiences in different fields which include magnetic confinement fusion at ENEA in Frascati, Silvia did her PhD at the University of Strathclyde in the Alpha-X group lead by Prof. Dino Jaroszynski on “Compact Gamma-ray Sources Based on Laser-Plasma Wakefield Accelerator”. Silvia is currently research associate at the University of Strathclyde, she is working on development and application of radiation sources based on laser-plasma wakefield accelerators.

Dr Christopher Chunnilall, National Physical Laboratory, UK
Topic: Optical and quantum metrology
Dr Christopher Chunnilall is an expert in optical radiation metrology, and is a Senior Research Scientist at the National Physical Laboratory (NPL), the UK’s National Measurement Institute. He received his Ph.D. from King’s College London and has worked at NPL since 1995. His research interests are in optical measurement for the photon counting regime and the scattering of light from materials. The first area covers the characterisation of single and entangled photons, photon counting detectors, and developing measurements to meet the needs of technologies and applications based on the production, manipulation, and detection of single and entangled photons. The latter area involves realising measurement scales for the reflection, transmission and scattering of light from materials.

Mr T Coenen, AMOLF, The Netherlands
Topic: Nanophotonics and plasmonics
Coenen studied chemistry and physics at the University of Utrecht, where he graduated in 2010 after doing a research project at the FOM Institute AMOLF in Amsterdam on the development of angle-resolved cathodoluminescence imaging spectroscopy (ARCIS). He is currently working as a graduate student at AMOLF. His studies focus on probing the optical properties of metallic and dielectric nanostructures using cathodoluminescence spectroscopy.

Dr Animesh Datta, University of Oxford, UK
Topic: Quantum information
Dr. Animesh Datta obtained his PhD from the University of New Mexico in 2008, working with Prof. Carl Caves on the role of quantum entanglement in mixed-state quantum quantum computation. He explored the significance of correlations beyond quantum entanglement, such as quantum discord in providing quantum enhancements in
computation and communication, and also developed the theory of nonlinear quantum metrology. He is presently in the Physics Department at the University of Oxford, where he works on the nature of quantum correlations, quantum metrology, quantum communications and quantum effects in biological light-harvesting complexes.

Professor C Denz, University of Münster, Germany

Topic: Fast and slow light

Cornelia Denz received her PhD from Darmstadt University of Technology, Germany. In 1992 she received the Lise Meitner-Award, and in 1999 the Adolf-Messer-Award for her work in optical neural networks and nonlinear dynamic phase contrast microscopy, respectively. Since 2001, she is a full professor, holding the chair for applied physics, and head of the nonlinear photonics group at Münster University, Germany, leading a group of about 25. She is an author of more than 150 publications, three books, and numerous book chapters. Cornelia Denz’ main research interests are on the application of nonlinear optics and photonics in information technology and life sciences. Other interests include nonlinear photonic X(2) and X(3) lattices, slow and fast light, solitons, vortices, optical holographic tweezers and manipulation, and novel organic photonic materials. Cornelia Denz is a fellow of the Optical Society of America and the European Optical Society.

Professor R Di Leonardo, Università di Roma "La Sapienza", Italy

Topic: Trapping and manipulation

Roberto Di Leonardo is a researcher for the National Research Council of Italy in Rome. He has been working on glass transition, off-equilibrium dynamics and soft matter using scattering techniques and numerical simulations. In 2005 he starts working with holographic tweezers as a research associate at Glasgow University. Back in Italy in 2006, he mainly concentrates on applications of holographic tweezers to dynamical problems at the micron scale, where the combination of low Reynolds number hydrodynamics, Brownian motion, and colloidal interactions gives rise to a rich variety of peculiar phenomena. More recently he became interested in active matter, from the microhydrodynamic aspects of bacterial swimming to the off-equilibrium statistical mechanics of concentrated bacterial suspensions.

Dr M Farsari, IESL-FORTH, Greece

Topic: Ultrafast and attosecond optics

Dr. Maria Farsari is a Researcher at the Institute of the Electronic Structure and Laser, Foundation for Research and Technology-Hellas, where she joined in 2003. Her main research interests are multi-photon lithography, laser-based fabrication of 2D and 3D micro and nano structures and materials processing using ultrafast lasers.

Dr. Farsari received her undergraduate degree in 1992 from the Physics Department, University of Crete and her PhD in 1997 from the Physics Department, University of Durham, UK. After graduating, she worked as a postdoctoral research fellow at the Universities of Durham and Sussex and as a Senior Optical Scientist for the security company DeLaRue Holographics. She was a founding member of the Dublin-based company Xsil Ltd.

Professor W Firth, University of Strathclyde, UK

Topic: Nonlinear photonics

Willie Firth has been at Strathclyde since 1985 as Professor in Physics, and founded its Computational, Nonlinear and Quantum Optics group. He has published well over 200 papers, mainly in the theory of lasers, optical pattern formation, and dissipative solitons. He is a Fellow of IOP, OSA and the RSE.
Dr M Fujiwara, Hokkaido University and Osaka University, Japan

Topic: Nanophotonics and plasmonics

Dr. Masazumi Fujiwara received his doctoral degree in 2008 from Osaka City University for his work on coherent light-matter interactions in biological complexes including organic dyes and photosynthetic pigment-protein complexes. In 2009, he was appointed to assistant professor in the laboratory of Prof. Shigeki Takeuchi at Research Institute for Electronic Science (RIES), Hokkaido University. He is currently working on quantum optics and cavity QED of solid-state atomic systems (e.g. quantum dots and diamond NV centers) in nanophotonic structures (e.g. microresonators and fiber tapers). His research interests cover the exploration of fundamental physics of coherent light-matter interactions using these nanophotonic architectures and its applications to quantum information science, optical sensing and biological science.

Dr E Ginossar, University of Surrey, UK

Topic: Quantum optics

Eran Ginossar graduated in Physics BSc from Tel-Aviv University, Israel, 1996. During his graduate studies at the Weizmann Institute of Science, Rehovot, he worked on Coulomb blockade effects in mesoscopic disordered quantum dots and later on extending the theory of optical spin orientation of direct gap semiconductors to include the fluctuations of the light and of the spins. After receiving his PhD in 2008 he moved to Yale University as a postdoctoral researcher working mainly on the physics of circuit quantum electrodynamics, a field that is rapidly progressing towards creating devices for quantum information processing. Additional topics of interest include interaction effects in mesoscopic systems, quantum optics and computer simulations of open quantum systems. Eran has joined the Department of Physics and the Advanced Technology Institute at the University of Surrey in 2011. He is a Fellow of the EPSRC.

Dr A Greilich, TU Dortmund, Germany

Topic: Quantum dots

Alex Greilich graduated from Nowgorod State University, Russia with BSc degree in 1999 and obtained my MSc degree at TU Dortmund University, Germany in 2003. After short stay at University of Chile in Santiago de Chile at the Center for Mathematical Modeling followed by the work at the Max-Plank Institute for Molecular Physiology, Germany he have obtained my PhD degree at the TU Dortmund University in 2007 in the group of Professor Manfred Bayer. Next two years Greilich have spent in the same group continuing my work on coherent optical control in semiconductor quantum dots. Second postdoc stay 2009-2011 was spent in the group of Dr. Daniel Gammon at Naval Research Laboratory in Washington, USA, where he was involved into creation and realization of optical control of two entangled electron and hole spins, confined in quantum dot molecules. In 2012 Greilich was awarded with the Walter-Schottky-Prize for the year 2012 from German Physical Society for the studies on coherent properties and control of spins. Currently he has 35 publications that were cited about 740 times and archived h-index of 14.

Dr R Hadfield, Heriot-Watt University, UK

Topic: Optical and quantum metrology

Dr Robert Hadfield is an expert in infrared single photon detectors based on superconducting materials. He received his PhD from the University of Cambridge, UK in 2003 for work on nanoscale superconducting devices. He spent four years as a postdoctoral guest researcher at the US National Institute of Standards and Technology in Boulder, Colorado. He implemented superconducting nanowire single-photon detectors into practical systems for use in
quantum cryptography experiments over record distances. He joined Heriot-Watt University as a Royal Society University Research Fellow in 2007 and was promoted to Reader in Physics in 2009. His research team is pursuing the development of next generation superconducting detectors and their implementation in new photon-counting applications. He has published over 50 peer-reviewed papers, 11 as first author, including a major topical review for Nature Photonics.

Dr K Hampson, University of Bradford, UK
Topic: Active and adaptive optics
Dr Karen Hampson completed her PhD in optical physics at Imperial College in 2004. During this time she developed an adaptive optics system to investigate the effect of monochromatic aberrations on the focusing control, and visual acuity, of the human eye. Since 2005, she has continued working in the field of adaptive optics as a postdoctoral researcher at Bradford School of Optometry and Vision Science at the University of Bradford. She has developed several systems for the eye. Her current work is developing the first binocular adaptive optics system with dynamic convergence control.

Dr M Hawkeye, University of Cambridge, UK
Topic: Nanophotonics and plasmonics
Biography unavailable

Dr A Jesacher, Innsbruck Medical University, Austria
Topic: Diffractive optics
Dr. Alexander Jesacher is a researcher at the Division of Biomedical Physics at Innsbruck Medical University. During his PhD research he has mainly worked with spatial light modulators in the fields of holographic optical trapping and microscopy. After his PhD he joined the Scanning Optical Microscopy group at the Department of Engineering Science in Oxford, where he worked on adaptive optical techniques for microscopy and laser micro-fabrication in the years 2008/09. In 2010 he has taken up a position at Innsbruck Medical University, where he now works on projects that involve the integration of dynamic optical elements in CARS microscopy and lensless imaging applications.

Professor P Jesson, University of Arizona, USA
Topic: Quantum coherent control
Dr. Poul S. Jessen is a Professor and Chair of Quantum Information and Control in the College of Optics at the University of Arizona. He received his PhD in Physics from the University of Aarhus in 1993, for research done with Dr. W. D. Phillips at the US National Institute of Standards and Technology. His research interests lie at the intersection of quantum optics and quantum information science, and currently include quantum control and measurement of single and collective atomic spins, quantum control of atoms in optical lattices, and atom-light quantum interfaces based on optical nanofiber traps. Dr. Jessen is a fellow of the American Physical Society and a member of the Optical Society of America.
**Professor A Jha, University of Leeds, UK**

Topic: Advances in laser science

Animesh Jha (FInstP) obtained his PhD in Materials Science in 1984 from the Imperial College of Science, Technology and Medicine, after which he pursued his career in infrared glasses and their optical properties at the University of Sheffield. Before joining the University of Leeds as a Reader in March 1996, he was lecturer at Brunel for 7 years where he continued research on IR Glasses for lasers and amplifiers in collaboration with ORC, Southampton. At Leeds, he established novel photonic materials and devices research, and continued extensive UK (Aston, Cambridge, Heriot-Watt, Manchester, Sheffield, St. Andrews) and overseas (Milano, NRL in US, CGCRI in India) collaborations for expanding novel photonic devices research. Twice he was recipient of the DTI’s SMART Awards with NORTEL Networks in 1999 and 2000 for broadband fibre amplifier engineering, Basic Technology Award from RCUK in Nov 2005 and the Yorkshire Concept Award for Innovation in March 2010.

Novel Photonic Materials and Devices research at Leeds focusses on optical fibres, thin films, bulk glasses and glass-ceramics, and waveguide engineering for visible, near-IR and mid-IR applications. Engineering of novel nanoscale composites using ultrafast pulsed lasers is one of the thrust areas for optoelectronic, energy devices and biomedical materials engineering. Some of our key collaborative achievements are: in ultra-broadband Er-doped waveguide and fibre devices (Politecnico di Milano and Cambridge), 2 µm fibre, bulk and waveguide lasers (Manchester, St. Andrews, Heriot-Watt), glass-semiconductor integrated devices (Sheffield), mid-IR and nonlinear waveguides (Heriot-Watt).

AJ frequently speaks as invited and keynote speakers at major conferences and promotes interdisciplinary culture of research in “laser-matter interaction” leading to novel materials and devices for engineering applications. He has published widely (more than 275 papers) in prestigious optics, physics and materials journals. Currently his research focusses on two main areas- applications of novel optical devices for critical diseases for point-of-care and thin-film silicon devices for energy harvesting.

**Dr M Keller, University of Sussex, UK**

Topic: Quantum information

Dr Matthias Keller is a senior lecturer in Atomic, Optical and Molecular physics in the Department of Physics and Astronomy at the University of Sussex. He received his PhD in 2004 for his work with Prof. H. Walther at the Max Planck Institute for Quantum Optics (Germany) on cavity QED with trapped ions. His work has been awarded in 2005 with the Otto-Hahn medal from the Max-Planck society (Germany). In 2005 he joined the Ion Trap Cavity-QED group at Sussex as a Leopoldina Fellow. After the end of his fellowship in 2007 he became a Lecturer in Atomic Molecular and Optical Physics at the University of Sussex.

His research interest is cavity QED with ions with a focus on the development of ion-photon quantum interfaces and the photon mediated entanglement of ions. Additionally, he investigates trapped molecular ions.

**Dr T Kippenberg, Laboratoire de Photonique et de Mesure Quantique (LPQM), Switzerland**

Topic: Quantum optics

Prof. Dr. habil. Tobias J. Kippenberg (EPFL). Tobias J. Kippenberg obtained his PhD at Caltech (2004) and lead from 2005-2009 an independent Max Planck Junior Research Group at the MPI of Quantum Optics in Germany. His research interests are centered around ultra high Q microcavities; notably the use as sources of optical frequency combs and the study of their optomechanical properties, notably mechanical laser cooling and mechanical quantum measurements. He obtained his Habilitation in 2009 from the LMU Munich. In 2008 he was appointed Assistant Professor at EPFL and is since 2010 Associate Professor at EPFL. He has accumulated more than 3500 citations, and has a Hirsch-Index (N papers cited N times) of 29. Tobias J. Kippenberg has moreover gained several prizes including, EFTF Young Investigator Award (2011), The Fresnel Price of the European Physical Society (2009)
Helmholtz Price for Metrology (jointly with Dr. Holzwarth) in 2009 [for invention of the monolithic frequency comb] and the European Union Contest for Young Scientists (1996). He has given more than 110 invited talks at international conferences.

**Dr D Krizhanovskii, University of Sheffield, UK**

**Topic: Nonlinear Photonics**

Dr Krizhanovskii graduated from Moscow State University with MSc degree in 2001 and obtained his PhD degree at the Institute of Solid State Physics, Chernogolovka, Russia in 2004. He then joined the group of Professor Maurice Skolnick at the University of Sheffield, where during 2004-2007 he investigated spin properties of excitons in GaAs based semiconductor quantum dots and polariton properties in GaAs semiconductor microcavities. In 2007 he was awarded EPSRC Advanced Research Fellowship to investigate quantum and classical properties of nonequilibrium polariton condensates. His major achievements include the demonstration that polariton condensates have long temporal coherence, the demonstration of the major role of interactions, the observation of 2D to 1D condensate transition in a periodic potential and the demonstration of vortex phenomena in polariton condensates. He has published about 50 papers in reputable physics journals.

**Mr M Lavery, University of Glasgow, UK**

**Topic: Singularities, optical vortices, polarization, coherence and non-Gaussian beams**

Martin Lavery graduated from Bachelor’s degree in Physics in 2009, and is now working towards his Ph.D. in the Optics group at the University of Glasgow.

The main focus of his work has been to develop an efficient methods to distinguish between each of the possible integer values of orbital angular momentum that a photon can carry. In collaboration with the University of Leiden and the University of Durham, he developed a new approach to measure this OAM through the design of two freeform passive optical elements, which allow the twist to be converted into spatial location and then be easily detected using widely available photon detection systems.

Martin is continuing to develop the effectiveness of the technique and implement it in novel ways within the fields of optical communications and quantum optics.

**Professor Richard Leach, National Physical Laboratory, UK**

**Topic: Fringe Analysis Special Interest Groups (FASIG)**

Professor Richard Leach is a Principal Research Scientist at the National Physical Laboratory in the UK and a visiting professor at Loughborough University. He obtained a PhD in Surface Metrology from University of Warwick in 2000. He has been with NPL since 1990 and has current research interests in surface topography measurement, micro-coordinate metrology and computed tomography. Richard is on the Council of euspen, the Board of MANCEF, the IoN Advisory Board and several international standards committees. He has over 150 publications including two textbooks. Richard is a Fellow of the Institute of Physics and the Institute of Nanotechnology.

**Professor P Mauskopf, Arizona State University, USA**

**Topic: Advances in terahertz technology**

*Biography unavailable*
Dr D Pawlak, Institute of Electronic Materials Technology, Poland

Topic: Metamaterials and cloaking

Dorota Anna Pawlak (DAP) is a materials scientist. She received her PhD (1999) in chemistry and her habilitation (2011) in physicochemistry of solid state, both from the University of Warsaw. She worked for 2 years at the Institute of Materials Research, Sendai, Japan. She currently holds a professorship position at the Institute of Electronic Materials Technology (ITME). She has created a group of young scientists aiming at developing novel materials and novel technologies to be used in such fields as metamaterials, plasmonics and energy systems. DAP coordinates the efforts of FP7 EU Collaborative project ENSEMBLE: ENgineered SEIf-organised Multi-component structures with novel controllable Electromagnetic functionalities. The project includes 7 Partners from 6 EU countries (including UK). She is a laureate of highly competitive projects: TEAM project from the Foundation for Polish Science, and Maestro project from the National Science Centre in Poland. She is president-elect of the Polish Society of Crystal Growth.

Dr G Raino, IBM Research - Zurich, Switzerland

Topic: Quantum dots

Gabriele Rainò graduated as an electrical engineer in 2005, at the Politecnico of Turin, Italy. The topic of his research was the study of the optical properties of quantum dot MCLEDs operating at 1.3 μm. Then, he moved to the National Nanotechnology Laboratory, Lecce-Italy, where he received the Ph.D degree in 2008, under the supervision of Prof. Cingolani. The activity mainly dealt with the experimental investigation of carrier dynamics in nanostructured materials (InAs quantum dots, GaSb-based quantum wells and superlattices) and laser characterization. In September 2008, he joined the Exploratory Photonics group at IBM-Research, Zurich, where he is currently working on both organic and inorganic nanostructured materials for novel photonic devices.

Professor G Reed, University of Southampton, UK

Topic: Silicon and carbon photonics

Graham Reed, BSc, PhD, FIEE, CEng, is Professor of Silicon Photonics at the University of Southampton, UK. He has recently joined Southampton from the University of Surrey, where he was Professor of Optoelectronics, and was Head of the Department of Electronic Engineering from 2006 to 2012.

Reed is a pioneer in the field of Silicon Photonics, and acknowledged as the individual who initiated the research field in the UK. He established the Silicon Photonics Research Group at the University of Surrey in 1989. The Group have provided a series of world leading results since its inception, and are particularly well known for their work on silicon optical modulators. For example, the Group produced the first published design of an optical modulator with a bandwidth exceeding 1 GHz, and were the first to publish the design of a depletion mode optical modulator, which is now a technology standard device. More recently the team were responsible for the first all-silicon optical modulator operating at 40Gb/s with a high extinction ratio (10dB), as well as a second modulator design (also operating at 40Gb/s) that operates close to polarization independence. They have now reported the first device operating at 50 Gb/s.

Reed is a regular invited and contributing author to the major Silicon Photonics conferences around the world. He has served on numerous international conference committees, and has also chaired many others. To name but two, he has been co-chair, of the Silicon Photonics symposium at Photonics West since it was first established in 2006, and in 2011 he was co-chair of the prestigious Silicon Photonics conference, IEEE Group IV Photonics, held at the Royal Society in London, the latter being the most well supported conference in the history of the event. He is currently a member of 5 international conference committees, and has published over 250 papers in the field of Silicon Photonics.
Ms I Rey, St Andrews University, UK
Topic: Fast and Slow Light
Isabella Rey graduated (with honours) in Engineering Physics from the Politecnico di Torino, Torino, Italy, in 2006, and received a Master (with honours) in Engineering Physics from the Politecnico di Torino in 2008. During her last year of studies she spent six months in the Microphotonics group at St Andrews University writing her final thesis about Raman scattering in silicon channel and photonic crystal waveguides. She is currently working toward completion of her Ph.D. in the Microphotonics Group at St Andrews University. Her research interests include active functionalities and slow light in silicon photonic crystal waveguides, with focus on tunable delay and stimulated Raman scattering.

Professor N Roberts, University of Bristol, UK
Topic: Biophotonics
Dr Nicholas Roberts is a BBSRC David Philips Research Fellow in the School of Biological Sciences at the University of Bristol. He received his PhD from the University of Manchester for research on the optics of liquid crystals, and has since held two other research fellowships from the Leverhulme Trust and the EPSRC. He has worked extensively overseas, spending time at the Universities of Victoria and Queens in Canada and UMBC in the USA. He currently conducts his experimental field work out on the Great Barrier Reef in Australia.
Dr Roberts’ research interests lie within the area of sensory biology, with a specific focus on the fields of visual ecology and biological optics. In particular, he works on polarization vision in a variety of invertebrate and vertebrate species, optical and biophysical mechanisms that allow animals to control the polarization of light and molecular adaptations in visual pigments from animals that live in the deep-sea. He has developed several new microscopy techniques including imaging microspectrophotometry.

Professor M Saffman, University of Wisconsin, USA
Topic: Quantum coherent control
Mark Saffman was educated at Caltech and the University of Colorado at Boulder. He has 30 years of experience in industrial and academic research and development working in the areas of optical diagnostics for fluids and plasmas, experimental atomic physics, quantum and nonlinear optics, and quantum information processing. He has made notable contributions to light scattering instrumentation, optical solitons and pattern formation, sources of entangled light, and quantum computing. His research team was the first to demonstrate a quantum CNOT gate between two trapped neutral atoms, and the deterministic entanglement of a pair of neutral atoms. He is currently developing scalable neutral atom processors using arrays of trapped alkali atoms.

Dr P Scully, The University of Manchester, UK
Topic: Fibre optic sensors
Research interests: Photonic sensing for environmental, chemical and biological monitoring using polymer photonic materials and devices, and laser nanostructuring of polymer and metallic materials. Low cost, rugged sensors have been developed for environmental, chemical and biological monitoring, for applications such as biofouling and scaling, algal growth, pH, particle concentration, turbidity, fluid flow, strain and water toxicity.

Current & Recent Projects:
1. Laser microstructuring of polymers for optical devices
2. Biocompatible polymer coatings for biosensors
3. MATINOES: Novel Organic-Inorganic Materials in Opto-Electronic Systems for the Monitoring and Control of Bio-
Processes
4. HYPER: Installation permitting guidance for hydrogen and fuel cells stationary applications
5. AQUA-STEW "Water Quality Surveillance Techniques for Early Warning by Interface Sensors".
6. CLOOPT "On-line measurement for preventing fouling when closing industrial process water circuit".

Teaching experience: Undergraduate and postgraduate courses in Applied Physics, Optical Science and Technology, Electronic Engineering and Chemical Engineering. Currently Module Leader for MSc Module Optical Instruments (15 credits) and Second Year Systems Measurement (10 Credits).

Dr A Travis, Microsoft Corporation, USA
Topic: Advances in imaging and displays
Adrian Travis was a lecturer at Cambridge University for twenty years until 2007, researching the display of 3D and virtual images. He found a way of projecting images through slab waveguides which allows control of the position and direction from which rays leave a flat panel. This may enable a flat panel computer interface which acts like a digital window so in 2007 his small research team moved to Microsoft in the USA for whom Travis continue to do research.

Dr J Verbeeck, University of Antwerp, Belgium
Topic: Coherence, polarisation and non-gaussian beams
Dr. Jo Verbeeck received his PhD from the EMAT laboratory at the University of Antwerp in 2002. He specializes in transmission electron microscopy both in terms of state of the art experiments as well as in depth theoretical research involving coherence aspects and inelastic electron scattering. He authored over 90 papers in international peer reviewed journals and received the Ernst Ruska award for electron microscopy in 2011 for his work on the quantification of EELS spectra and electron vortex beams. He successfully produced electron vortices in the electron microscope and used their peculiar properties to detect magnetic information in EELS. He is currently leading an ERC starting grant project to further explore the potential and properties of such electron vortex beams.

Professor F Vollmer, Max-Planck-Institut fuer die Physik des Lichts, Germany
Topic: Biophotonics
Frank Vollmer obtained his PhD in ‘Physics & Biology’ from the Rockefeller University, NYC in 2004. He then became leader of an independent research group at the Rowland Institute at Harvard University where he was appointed Rowland Fellow from 2004 to 2009.

In 2010 he joined the Wyss Institute for Bio-Inspired Engineering at Harvard University as a Scholar-in-Residence. In 2011 he was appointed group leader of a Max Planck Research Group at the Max Planck Institute for the Science of Light in Erlangen, Germany. Since 2011 he is also appointed Associate Biologist at Brigham and Women’s Hospital in Boston, USA where he runs a satellite laboratory.

Frank Vollmer is interested in inventing, constructing and using light fields for the study of biological systems. During his PhD thesis he demonstrated the use of resonant light fields in high-Q microsphere cavities (whispering gallery modes) for sensitive label-free molecularlevel detection. Ever since he continued improving and applying this technique towards the goal of single molecule detection and analysis as well as towards integration in hand-held chip-scale biosensors and lab-on-chip devices. As a Rowland Fellow he demonstrated the detection of single Influenza A virus particles using microsphere resonators. Furthermore, he introduced the concept of disordered photonic crystal structures to obtain Anderson-localized light fields that can be used in detection as well as for ‘designing’ random lasers. His Laboratory of Biophotonics & Biosensing at the Max Planck Institute remains
focused on these broad research directions but also explores related topics such as laser-induced flow fields (optofluidics for lab-on-chips), next generation graphene- and metamaterials-based biosensors, biolasmonics as well as application of quantum optics in biodetection. He developed and teaches the course 'Physics of Biosensing' and is a mentor at the IMPRS School of Optics. Since 2011 he is also leading the efforts of his satellite laboratory located at Brigham & Women's Hospital where he explores clinical diagnostics using optical microcavities.

Frank Vollmer has published over 23 papers with a total of more than 1000 citations, has been awarded a Rowland Junior Fellowship as well as a Max Planck Research Group and is holding O-visa status for exceptional researchers in the USA. He is associate Editor Optics Express (OSA Journal) and recently received NIH-R01 grant award for constructing highthroughput put biosensors. He also holds an external appointment as Associate Biologist and Instructor in Medicine (PI) at Brigham and Women's Hospital in Boston, USA.

Dr A Ward, Rutherford Appleton Laboratory, UK

Topic: Optical tweezing and micro-manipulation

Dr Andy Ward is the facility manager for the Optical Tweezers and Raman Microscopy Laboratory at the Central Laser Facility, STFC. In this role Dr Ward has collaborated with over 25 academic user groups to apply laser trapping and laser spectroscopy techniques to scientific fields as diverse as colloid science, aerosol physics and the life sciences.

Dr Ward received his PhD from the University of Bristol, studying the growth kinetics of polymer latex preparations using dynamic light scattering. His past research interests include the synergic effects of surfactants at interfaces (Unilever Port Sunlight Laboratories), the wettability behaviour of crude oil (University of Bristol), and the formulation of reactive microemulsions (DERA, Porton Down). Currently he has specific research interests in studying the chemistry of optically levitated, micron-sized, aerosol particles and the deformation behaviour of emulsion systems with ultralow interfacial tensions.

Professor S Withington, University of Cambridge, UK

Topic: Advances in terahertz technology

Stafford Withington is the Head of the Detector and Optical Physics Group at the Cavendish Laboratory, University of Cambridge, and a member of the Kavli Institute for Cosmology. He is a Professorial Fellow of Downing College Cambridge, and a Visiting Professor in the School of Physics and Astronomy at the University of Oxford. Stafford was recently a Visiting Fellow at All Souls College Oxford. For many years Stafford has developed advanced instrumentation for submillimetre-wave and far-infrared astronomy (3mm-30um), and currently holds formal research agreements with a number of international space agencies developing ultra-low-noise imaging technology for space telescopes. Stafford leads one of the world’s foremost laboratories, including device processing clean rooms, for developing advanced superconducting sensor technology. His own interests include the electromagnetic modelling of partially coherent optical systems, energy absorption processes in materials, non-equilibrium superconductivity, ultra-low-noise device physics, and heat transport and thermal fluctuation noise in low-dimensional systems.
Professor M Zepf, Queen’s University Belfast, UK

Topic: Ultrafast and attosecond optics

M. Zepf is currently holds a joint appointment at the Queen’s University Belfast and the University of Jena. He is Director of Research of the Centre for Plasma Physics at Queen’s University Belfast and member of the directorate at the Helmholtz Institute in Jena.

He has been a member of staff at QUB since 2001 and previously worked at Imperial College and the University of Oxford, where he obtained his D.Phil.
Invited speaker abstracts

Monday 3 September

Active and adaptive optics
Active and adaptive optics: principles and applications
K Hampson
Bradford University, UK

In conventional optical systems the components are rigid and their properties, such as refractive index, are fixed. However in active and adaptive optical systems, at least one of the components can change its properties. The most common dynamic components are mirrors that are deformed by an array of actuators, and liquid crystal devices that change their refractive index. Active optics is commonly used in telescopes. The mirrors are deformed to account for distortions in the mirrors themselves, due to temperature changes for example. In adaptive optics systems the dynamic element/elements are updated at a faster rate, and used to compensate for effects external to the instrument. Applications include correcting for the effects of turbulence on image quality in ground based telescopes and correcting for the effects of the eye’s aberrations on high resolution retinal imaging. In this talk the principles of active and adaptive optics, the current state of the art technology, and their applications, will be discussed.

Quantum information I
Interfacing ions and photons at the single quantum level
M Keller, H Takahashi, E Brama, A Riley-Watson and W Lange
University of Sussex, UK

The complementary benefits of trapped ions and photons as carriers of quantum information make it appealing to combine them in a joint system. Ions provide low decoherence rates, long storage times and high readout efficiency, while photons travel over long distances. To interface the quantum states of ions and photons efficiently, we use calcium ions coupled to an optical high-finesse cavity via a Raman transition.

For strong ion-cavity coupling, deterministic transfer of quantum states between ions and photons is possible. Each basis state of the ion is linked with one polarization mode of the cavity. Through a partially transparent cavity mirror, a freely propagating photon is generated which can be used to distribute quantum information, for example to entangle distant ions in a network of multiple quantum nodes. Ion-cavity systems can also be employed to create entanglement between ions trapped in the same cavity. This is most efficiently achieved through the exchange of virtual photons, which requires the coupling strength to exceed the cavity damping rate significantly. For moderate coupling, quantum entanglement may be generated probabilistically. Ions coupled to two orthogonally polarized cavity modes are projected to an entangled state upon detection of photons emitted from the cavity with different polarization.

The realization of these schemes requires the development of novel techniques to combine ion traps with miniature optical cavities, as the strength of the ion-photon coupling increases with shrinking cavity mode volume. We are presently testing three different setups, optimized for the respective interaction regimes mentioned above.
Metamaterials and cloaking

Bottom-up manufacturing methods for metamaterials and plasmonic materials

D Pawlak, M Gajc, A Klos, B Surma, K Bienkowski, K Sadecka and A Stefanski

Institute of Electronic Materials Technology, Poland

In recent years, novel research areas have been developed in the fields of photonics, metamaterials and nanoplasmonics. By utilizing the ideas developed in these research areas and using specially-designed materials, unusual electromagnetic properties such as artificial magnetism, negative refractive index, cloaking and squeezing photons through subwavelength holes have been demonstrated. These novel fields need new material fabrication techniques, especially bottom-up approaches such as self-organization. Two novel bottom-up manufacturing methods will be presented based on: (i) directional solidification of eutectic composites and (ii) doping dielectric matrices with plasmonic nanoparticles. Eutectics are simultaneously monolithic and multiphase materials forming self-organized micro/nanostructures, which enable: (i) the use of various component materials including oxides, semiconductors, metals, (ii) the generation of a gallery of geometrical motifs and (iii) control of the size of the structuring, often from the micro- to nanoregimes. On the other hand, the novel method of physical doping of dielectric matrices with nanoparticles utilizing directional solidification may provide three-dimensional nanoplasmonic materials enabling doping with nanoparticles of various chemical composition, various size and shape, as well as co-doping with other chemical agents. In both cases we apply one of the crystal growth methods - the micro-pulling down method - to create the material. Materials with plasmonic resonances at visible and IR wavelengths will be presented, as well as their influence on photoluminescence properties of the optically active materials. Our new approach may lead to novel manufacturing solutions for photonic applications in areas such as metamaterials, plasmonics, as well as photovoltaics and photoelectrochemical applications.

Ultrafast and attosecond optics I

Coherent attosecond x-ray pulses arising from the interaction of intense laser pulses with solids

M Zepf

Queen's University Belfast, UK

Relativistic laser plasma interactions provide a range of non-linear processes through which intense laser radiation can be converted to attosecond XUV and X-ray pulses.

To date, two dominant processes have been identified to operate in the reflected direction. The relativistic oscillating mirror or ROM process and the Coherent Wake Emission or CWE. Such processes produce broad spectra with a sufficiently well defined phase structure to allow the production of isolated attosecond pulses.

Recently coherent synchrotron emision (CSE) is also predicted to arise for the correct interaction conditions, whereby the coherence arises from the fact that electron bunches have a spatial extent on the nm-scale. We present recent experimental and simulation data demonstrating CSE for the first time.
**Imaging and displays technology**

**Looking out of a display with a wedge waveguide**  
A Travis  
Microsoft Corporation, USA

Displays are a long way from the digital equivalent of a white-board or else a notice-board on which can be pinned many laser-printed documents. For such high resolution, it may be easier to transmit data across the screen optically than fight the high stray capacitance of display rows and columns. It would help to see where the user is looking so that we need only display data where it is needed and so that we do not waste power by sending rays where there is no eye to see them. A wedge-shaped sheet of acrylic can let us see out of a liquid crystal display as if from a point deep behind and lets us control what each eye sees. By linking two such displays, we may be able to digitize the experience of looking through a window.

**Computational physics**

**Computational physics of nondiffracting beams**  
S Chavez-Cerda  
INAEO Optics, Mexico

The nondiffracting Bessel beams were first studied using diffraction integrals that could not account for the total of the physical characteristics of the beams. Later, having introduced the propagating conical waves approach based on the differential wave equation helped to understand their physics and propose other families of this class of beams, the Mathieu and transverse parabolic (Weber). In this talk we will present physical and computational aspects needed to study the propagation of all the nondiffracting beams included the Airy beams.

**Structured optical materials**

**Light-trapping in photovoltaic devices**  
D Bagnall  
University of Southampton, UK

Over the last number of years we have carried out comprehensive study of both antireflection and light-trapping schemes with particular attention to the use of nanostructured materials and application to thin film silicon solar cells. In antireflection, we have studied antireflective coatings, micron-scale texturing, sub-wavelength biomimetic textures as well as plasmonic antireflection effects. In studying light-trapping we have examined textured transparent conducting oxides (TCOs), dielectric gratings, dielectric scattering, and plasmonic scattering by a wide variety of metal nanoparticle types in a wide variety of conditions.

In this presentation we will provide an overview of our understanding of photon management in solar cells built from our own experiments and from the now extensive literature. We will discuss the pros and cons of the most promising antireflection schemes, as well as outline the main principles and limits to light-trapping. While the jury is still out on plasmonics it is clear that the best devices will exploit sub-micron textures for A/R at the front of devices and efficient dielectric or plasmonic scattering mechanisms. Although it seems likely that methods will emerge that can take light-trapping beyond the Yablonovitch “limit” this has to be achieved without significant additional cost on device production.
Ultrafast and attosecond optics II

Radiation sources based on laser-plasma wakefield accelerators

S Cipiccia
University of Strathclyde, UK

The laser-plasma wakefield accelerator is a novel concept that has some advantages over conventional particle accelerators. The ponderomotive force of a high intensity laser beam focused into plasma generates a plasma density wake. Injected electrons surf these waves and accelerate to very high energies over extremely short distances. Plasma as an accelerating medium provides unprecedented accelerating gradients, in excess of 1 GeV/cm, a thousand times higher than in conventional accelerators. The electron beams produced by a laser-plasma accelerator have ultra-short bunch length (1-3 fs), low emittance (few p mm mrad), low energy spread (<1 %), which could potentially make them suitable for driving a compact free-electron laser. Moreover the plasma itself can act as a very compact wigglar and while electrons accelerate they can undergo a slow transverse betatron oscillation and emit femtosecond duration pulses of synchrotron-like radiation in the range of 10s of keV. We will show that the betatron motion can be resonantly enhanced by the presence of the co-propagating laser pulse in the plasma accelerating structure and lead to a dramatic increase in the oscillation amplitude leading to the emission or radiation in excess of hundreds of keV and extending to several MeV photon energies. This combined accelerator-radiator system is a very compact, high brilliance, femtosecond duration pulsed gamma-ray source that could have many potential applications.

Direct fs laser writing: principles and applications

M Farsari, I Sakellari, E Kabouraki, D Gray, C Fotakis, M Vamvakaki, A Pikulin and N Bityurin
IESL-FORTH, Greece

We present a new method for increasing the resolution of direct fs laser writing by multiphoton polymerization, based on quencher diffusion. This method relies on the combination of a mobile quenching molecule with a slow laser scanning speed, allowing the diffusion of the quencher in the scanned area and the depletion of the multi-photon generated radicals. We use this method to fabricate dielectric, metallic and quantum-dot doped photonic crystals and we show that the results are comparable to those produced by direct laser writing based on stimulated-emission-depletion microscopy, the method considered today as state-of-the-art in 3D structure fabrication. Finally, we model the quencher diffusion and we show that radical inhibition is responsible for the increased resolution. Finally, we discuss applications of Direct fs Laser Writing in Photonics, Metamaterials, and Biomedical Implants.

Imaging systems

Bayesian localization microscopy reveals nanoscale podosome dynamics

S Cox1, E Rosten2, J Monypenny1, T Jovanovic-Talisan3, D Burnette3, J Lippincott-Schwartz3, G Jones1 and R Heintzmann4

1Kings College London, UK, 2University of Cambridge, UK, 3National Institute of Health, UK, 4University of Jena, Germany

High resolution optical microscopy methods have pushed the resolution of fluorescence microscopes below the Abbe limit. One class of methods, localization microscopy, builds up a high resolution image from the localized positions of many single fluorophores. It is highly desirable to maximise the information extracted from the data for a given light dose, and speed up data acquisition. Here we present a new method which allows localization data to be extracted from wide field images of a live cell sample labeled with a standard fluorescent protein. Our method
allows the use of data with overlapping fluorophores, and the use of information from bleaching events, blinking events, and changes due to fluorophores being added or removed by the cell. We carried out imaging on a standard widefield microscope at 37°C, illuminated by a xenon arc lamp. A sequence of images is taken at high frame rate (around 50 frames/second), and the data is modeled as arising from a number of fluorophores. Since we model the whole dataset we are able to pick up fluorophore reappearances, even in non-adjacent frames. Thus we are able to use all the photons collected from a fluorophore to improve its localization. This Bayesian analysis of bleaching and blinking data (3B analysis) method allows us to perform localization microscopy with a spatial resolution of 50 nm and a temporal resolution of 4 s on cytoskeletal structures called podosomes in living cells expressing an mCherry fusion of a truncated talin construct.

**Diffractive optics**

**Liquid crystal spatial light modulators as versatile diffractive optical elements**

A Jesacher, S Bernet, M J Booth, P Salter and M Ritsch-Marte

1Innsbruck Medical University, Austria, 2University of Oxford, UK

Spatial light modulators (SLMs) are miniaturized liquid crystal displays that allow computer-controlled wavefront shaping with high spatial resolution. With pixel sizes in the range of only 10 micrometer, they represent a versatile dynamic phase diffractive optical element. Profiting from commercial display technology they have seen a rapid development in the last decade and find nowadays a broad field of applications in optics.

The talk gives a brief introduction to dynamic wavefront shapers such as SLMs and deformable mirrors and focuses on specific applications such as aberration correction and beam shaping in laser micro-fabrication, microscopic imaging, optical trapping and digital holography.

**Quantum information II**

**A compact entanglement distillery**

A Datta, L Zhang, J Nunn, N Langford, A Feito, M Plenio and I Walmsley

1University of Oxford, UK, 2Vestas Technology, Denmark

I will discuss a new paradigm of storing and processing quantum information in the same physical space. As an example, I will introduce a new scheme for continuous-variable entanglement distillation that requires only linear temporal and constant physical or spatial resources. Distillation is the process by which high-quality entanglement may be distributed between distant nodes of a network in the unavoidable presence of decoherence. Known versions of this protocol scale exponentially in space and doubly exponentially in time. Our optimal scheme therefore provides exponential improvements over existing protocols. It uses a fixed-resource module—an entanglement distillery—comprising only four quantum memories of at most 50% storage efficiency and allowing a feasible experimental implementation. Tangible quantum advantages are obtainable by using existing off-resonant Raman quantum memories outside their conventional role of storage.
Advances in laser science

Recent developments in 2 µm mid-IR lasers using novel tellurite and germanate glasses

A Jha

University of Leeds, UK

The mid-IR near 2 µm is a spectroscopically-rich region for many applications in Physics and Astronomy, sensing and surgical applications, and a strategically important wavelength for engineering of solid-state sources for applications longer than 2 µm.

Although many high power CW fibre devices using Tm³⁺ and Ho³⁺ doping in silica have been demonstrated[1], the apparent high linear loss in silica limits the longer wavelength operation, which is where mid-IR transmitting tellurite (TeO₂) and germanium oxide (GeO₂) devices can play significant role by enabling highly efficient mid-IR 2 µm devices.

I will present and discuss the results on CW, Q-switched, mode-locked lasers developed in collaboration with the Universities at Manchester, St. Andrews, and Heriot-Watt. In the first section, I will focus on the fibre based spectroscopy and CW results using Tm³⁺/Ho³⁺/Yb³⁺ doped tellurite fibre lasers operating around 2 µm range and, demonstrate the engineering of high slope efficiency laser cavities using Tm³⁺-doped and Ho³⁺-doped devices, showing 76% and 62% values, respectively[2,3]. The latter laser was also mechanically Q-switched using a chopper to produce ~100 ns pulses with up to 4.4 µJ energies at 2.1 µm.

Based on the successes of fibre lasers, our collaborative research demonstrated 2 µm CW lasers in bulk tellurite and GeO₂ glasses. With optimal doping of Tm³⁺ in tellurite and GeO₂ bulk glasses, the slope efficiencies of 30 to 50% were demonstrated using pump at 800 nm. The CW bulk glass cavity was then engineered for mode-lock operation, in which the short pulses of 435 fs duration ~ 2 µm were generated[4]. CW lasing in fs-laser inscribed waveguides was also demonstrated[5].

Tuesday 4 September

**Optical biosensing and bioimaging**

**Optical resonator biosensors**
F Vollmer
Max-Plank-Institut fuer die Physik des Lichts, Germany

Optical resonator biosensors are emerging as one of the most sensitive microsystem biodetection technology that does not require amplification or labeling of the analyte. I will give an overview of the exciting possibilities provided by this highly sensitive technique for molecular diagnostics, nanoparticle detection and manipulation. I will then talk about the prospects of boosting sensitivity with plasmonic nanoantennas - bringing label-free single molecule detection within reach.

**Advances in THz technology I**

**Kinetic inductance detectors for THz imaging and spectroscopy**
P Mauskopf
Arizona State University, USA

Photons interacting with superconducting films can break apart so-called ‘Cooper pairs’ and change the ratio of paired to unpaired charge carriers and in turn change the complex surface impedance of the film.

This is similar to the creation of electron-hole pairs in a semiconductor but the superconducting gap energy is orders of magnitude smaller and therefore can be used to detect lower energy photons. The reactive part of the surface impedance of a superconducting film consists of a fixed geometric or magnetic inductance plus a variable kinetic inductance. The change in kinetic inductance can be measured by configuring the superconducting film as a microwave resonator and monitoring the resonant frequency. This type of detector is called a microwave kinetic inductance detector (MKID). MKIDs can be easily fabricated in large arrays with individual pixels designed to have different resonant frequencies allowing an entire array to be read out using frequency division multiplexing with a small number of microwave cables. MKIDs have demonstrated photon noise limited performance in the laboratory and in prototype astronomical instruments. I will describe the development of new instruments for THz imaging and spectroscopy using MKIDs for both scientific and industrial applications.

**Nonlinear photonics I**

**Solitonic lasers**
W J Firth, T Ackemann, G-L Oppo, P V Paulau
University of Strathclyde, UK

Solitons are self-localised waves for which dispersive broadening is balanced by a nonlinear narrowing effect (e.g. Kerr effect). In optics, soliton pulses are familiar from fibre optics, and provided the motivation for the first "soliton laser" in 1984 [1]. It used a fibre section in a coupled-cavity geometry to generate sech-like mode-locked pulses. Real laser cavities are lossy, so one needs gain-loss as well as dispersion-linearity matching. Such double-balance systems typically support so-called "dissipative solitons" [2].
Since diffraction in space acts like dispersion in time, one could envisage a "spatial soliton" laser, with a sech, rather than gaussian, beam profile. Again gain-loss balance is required: broad-area semiconductor lasers have recently been configured to generate multiple independent dissipative solitons [3]. The individual solitons can be switched on or off independently, so that these systems can be considered as arrays of independently controllable microlasers.

More generally, any pulse or beam with nonlinearly-determined width might be called solitonic. and I will review the history and present status of various kinds of solitonic laser, with emphasis on the spatial domain. I will discuss models of such lasers, the simplest requiring only cubic nonlinearity, with linear frequency-selective feedback to provide stability [4]. Among the interesting phenomena exhibited by such systems are spontaneous soliton motion, vortex solitons, frequency-locking of solitons to form coherent structures, and coexistence (and interaction) of two different types of stable soliton. I will discuss these and other features of solitonic laser physics, with a view to practical implementation and possible exploitation.


**Bright polariton solitons in semiconductor microcavities**

D Krizhanovskii1, M Sich1, D Skryabin2, E Cerda3, K Biermann3, R Hey3, P Santos3, M Skolnick1

1University of Sheffield, UK, 2University of Bath, UK, 3Paul-Drude-Institut Berlin, Germany

Microcavity polaritons are hybrid interacting light-matter particles, which exhibit interesting phenomena, like superfluidity, parametric scattering and spontaneous condensation. Here we report observation of propagating bright polariton solitons. The solitons are supported by repulsive Coulomb polariton-polariton interactions and polariton negative effective mass at large wavevectors. Therefore, there is a direct analogy between solitons in atom condensates and strongly coupled microcavities. However, unlike solitons known in atom BECs, they are nonequilibrium and rely on a balance between losses and external pumping. The solitons can be switched on and off on a picosecond timescale using an external pulsed probe beam. Moreover, c3 nonlinearity supporting soliton propagation is much stronger for polaritons than for photons in weakly coupled structures, thus much weaker pump powers are required to sustain soliton propagation. Therefore, solitons have further benefits for the information processing over the light only solitons in semiconductor cavity lasers and potentially can be useful for development of ultrafast all-optical digital circuits.

**Biophotonics**

**Controlling polarisation: Achromatic waveplates and omnidirectional reflectors in nature**

N Roberts

University of Bristol, UK

Animals have evolved a remarkable diversity of biophotonic structures to control light, from multilayer reflecting structures in butterfly scales, to waveguide optics in some invertebrate eyes, to broadband image focussing mirrors in the eyes of deep-sea fish. However, animals are not only able to control the flow of light, but in several cases, control and manipulate the polarization of light as well.
In this talk I will discuss two of our recent discoveries. The first is how several species of stomatopod, commonly called mantis shrimps, have evolved an optical mechanism to produce an achromatic quarter-wave plate in the photoreceptor cells of their eyes. Remarkably, the achromaticity is approximately a factor of 3 better than the best current man-made sub-wavelength grating devices and extends across the whole visible range. Secondly, we have uncovered the first biological omnidirectional reflector in the sides of silvery fish. For mid-water pelagic fish, a polarisation neutral structure increases the reflectivity over all angles of incidence and provides a real advantage in background matching camouflage. In the context of biomimetic inspiration, this biological mechanism of omnidirectionality is novel, and has design advantages over currently manufactured synthetic reflectors.

**Advances in THz technology II**

*(invited)* Ultra-low-noise FIR imaging arrays for space science

S Withinghton and D J Goldie

University of Cambridge, UK

SPICA is a joint Japanese Space Agency – European Space Agency (JAXA-ESA) mission to place a Far-Infrared (200-30μm) Space Telescope at Lagrange Point 2. Its 3.25m primary mirror will be cooled to 5K to eliminate thermal background radiation from losses in the optics, and it will use superconducting imaging arrays cooled to 50mK to achieve single-pixel NEPs of order $10^{-19}$ WHz$^{1/2}$. The cameras will be the most sensitive imaging systems every built, enabling the Universe to be observed at times when galaxies were first forming. In the talk I will outline the SPICA mission, and describe the work we have been doing together with colleagues at the Space Research Institute of the Netherlands (SRON) to realise the ultra-low-noise imaging technology needed. Each imaging pixel comprises a MoAu Transition Edge Sensor and a β-phase Ta absorber on a suspended 200nm SiN membrane. The whole assembly is placed behind a few-mode (typically 15) infrared light pipe. These individual pixels are assembled into arrays of 1849, 1156, and 324 pixels for the three spectral bands that cover the whole 200-30μm range. The arrays are then cooled to 50 mK, and read out using a superconducting multiplexer. My talk will focus on the physics of the devices, and the noise mechanisms that determine sensitivity. I will also consider the challenges of measuring accurately the optical and noise characteristics of detectors that saturate with power loadings of only 10W. To conclude I will indicate how phononic thermal engineering of the micromachined SiN support legs might lead to yet higher levels of performance and increased on-chip functionality.

**Quantum coherent control I**

Sub-wavelength resonance imaging and robust addressing of atoms in an optical lattice

P Jessen$^1$, J Lee$^1$, E Montano$^1$ and I Deutsch$^2$

$^1$University of Arizona, USA, $^2$University of New Mexico, USA

Schemes for quantum computation and simulation in optical lattices generally assume that atoms can be accessed independently at each lattice site. To meet this challenge, we have developed a resonance imaging and addressing protocol that circumvents the need for high resolution optics and lends itself to implementing robust, high fidelity quantum gates. The basic idea is to superimpose on the trapping lattice a long-period “addressing” lattice that induces site-dependent frequency shifts between qubit states in the atomic ground manifold. Resonant microwave pulses can then be used to initialize atoms at specific sites in the trapping lattice, and subsequent pulses can be applied in a spatially shifted addressing lattice to image them with resolution below 200nm. Composite pulses can be designed to implement a given single-qubit gate with high fidelity within a desired range of frequency shifts, and the identity outside it. When matched to the distribution of frequency shifts in the trapping lattice, this allows us to perform the gate on a target site without affecting its neighbors, and to do so reliably even in the presence of small
errors in the position and intensity of the addressing lattice. Using randomized benchmarking, we experimentally measure an average fidelity of 97% for a collection of such addressable gates.

**Advanced optical microscopy techniques**

*Advances in fluorescence super-resolution biplane FPALM and STED microscopy*

J Bewersdorf  
Yale University, USA

The last two decades have seen a revolution in high-resolution imaging techniques. By optically switching fluorescent molecules on and off, the classical diffraction limit of light has been overcome. Instead of ~250 nm spatial resolution in far-field optical microscopy, 25 nm or better are now achievable.

In stimulated emission depletion (STED) microscopy, a ring-shaped laser focus stimulates emission from fluorophores excited by a conventional laser focus. The fluorophores are depleted from their excited state and fluorescence is essentially switched off. Signal from spontaneous fluorescence can therefore only originate from the center of the ring where STED intensities are negligible. Increasing the STED intensity can narrow down the remaining fluorescent area to diameters of 25 nm and smaller.

Fluorescence Photoactivation Localization Microscopy (FPALM) utilizes the random on and off switching of single fluorophores. Individual molecules are localized sequentially and by combining the obtained molecule positions, an image representing the fluorophore distribution is created. Recently, we have expanded FPALM imaging to three-dimensional (3D) imaging by simultaneous multiplane detection.

I will present recent results on combining total internal reflection with STED microscopy and other advances with our custom-built STED setup. Additionally, I will present our latest results of our development and application of Biplane FPALM.

J.B. declares financial interest in Vutara Inc., a start-up company producing a fluorescence microscope utilizing 3D particle localization.

**Fibre optics sensors**

*Footprint imaging by guided path tomography*

P Scully, N Nurgiyatna, J Vaughan, P Wright, C Brown Wilson, P Fiadzomor and K Ozanyan  
The University of Manchester, UK

In earlier work on Photonic Guided Path Tomography, we introduced the principle of imaging surface deformation, by four-projection measurements of transmission through strategically placed grooved plastic optical fibres on a flexible surface with a soft foam underlay. Hough transform-based centre-of-mass imaging from data acquired with small area demonstrators using four-fibre crossing points have been reported. In this work, targeting the dynamic imaging of human footprints, we show results from small area prototypes using only three tomographic projections with only two fibres crossing at any one point, reducing the bending-induced background which is not object-specific.

Reconstructions of bare feet and shoes footprints have been implemented with two small area demonstrators – with grooved and un-grooved plastic optical fibres to exhibit the effect of grooving for applications related to relatively hard surfaces, such as high-duty carpets. The measurements are taken with red LEDs and photodiodes on each line integral and images are reconstructed using the iterative Landweber technique. The results are discussed in terms of
the capability of such imaging technology to study variations in gait and walking patterns, as well as the footprint of a human body lying in various positions.

Quantum coherent control II
Quantum information processing by coherent control of Rydberg atoms
M Saffman
University of Wisconsin, USA

Neutral atoms are attractive candidates for quantum information processing due to their stability and weak interaction with the environment.

The challenge of implementing a strong and controllable two-atom interaction was recently met with the demonstration of Rydberg blockade, and its use for a two-qubit entangling quantum logic gate. I will review the physics of the Rydberg blockade effect, and show how it can be used to coherently control the interaction strength of two atoms with a contrast of 12 orders of magnitude.

Experiments that use Rydberg blockade to implement an entangling quantum gate between neutral atom qubits will be presented, as will progress towards a multi-qubit scalable architecture.

Nanophotonics and plasmonics I
Squeezing light into the nanometer scale: quantum plasmonics
M Hawkeye, F M Huang, S Vignolini, R Taylor, M Millyard and J Baumberg
University of Cambridge, UK

While we are commonly taught that light cannot be focussed smaller than a half-wavelength spot, the new field of plasmonics uses nanostructured metals to routinely concentrate light into volumes well-below the diffraction limit. By coupling to resonant electron oscillations (plasmons), light can be confined into ultra-small volumes determined by the characteristic dimension of the metal nanostructures. This greatly enhances light-matter interactions on the nanoscale and introduces a host of new scientific and technological possibilities.

Central to the plasmonic manipulation of light is the construction of intricate metallic geometries. As the feature sizes are pushed towards a single nanometre to maximize plasmonic light concentration, fabrication becomes exceedingly difficult and conventional approaches, which are expensive and slow, become ill-suited. Consequently, we explore a wide range of self-assembly methods for realizing complex and dynamic plasmonic nanostructures. Using these approaches we are able to create high-precision, nanoscale plasmonic structures with intense light-matter interactions as well as push these systems into the quantum mechanical limit of plasmonic nanofocussing.

Optical tweezing and micromanipulation

Light driven toy models to study hydrodynamic synchronization at the micron scale

R Di Leonardo
National Research Council of Italy, Italy

Hydrodynamic synchronization is a fundamental physical phenomenon by which independently driven oscillators communicate through perturbations in the surrounding fluid and converge to a stable synchronized state. This is an important factor for the emergence of regular and coordinated patterns in cilia and flagella motions. When dealing with biological systems however it is always hard to disentangle internal signalling mechanisms from external purely physical couplings. We have used the combination of two photon polymerization and holographic optical trapping to build a number of micron scale models of interacting propellers driven by light. The versatility of holographic traps gives a high degree of control over all the relevant physical parameters in the problem. We demonstrate that rotors can be synchronized by hydrodynamic interactions alone and provide new insights into the physical mechanism that drives the effect.

Optical diagnostics in engineering

Infra-red imaging in experimental mechanics

J Barton
University of Southampton, UK

Infra-red imaging is usually associated with fairly the crude temperature measurements made to assess the condition of structures and for thermal based non-destructive evaluations. Highly sensitive infra-red detectors are now available that allow high spatial resolutions along with temperature resolutions of about 20 mK. If lock-in processing is used the temperature resolution can be improved to 2 mK. A technique that takes advantage of the high spatial and temperature resolution of modern IR detectors is TSA (thermoelastic stress analysis). Here the infra-red (IR) detector is used to ‘measure’ the small reversible temperature change associated with the thermoelastic effect from a component subjected to cyclic load. The detector output signal is related to the changes in the sum of the principal stresses on the surface of the material. Therefore the ‘thermal image’ provides full-field data that is a function of the surfaces stresses. For orthotropic materials, such as laminated composite structures, the small temperature change is related to the changes in the stresses in the principal material directions on the surface of the material. The data is recorded and processed in a matter of seconds enabling practically real-time studies and hence providing clear benefit in damage evaluations. In the presentation the background theory underpinning the application of TSA is provided. The focus of the presentation is application of infra-red imaging to polymer composites, sandwich structures and foam core materials. Examples of applications as well as some more fundamental physical issues will be presented.
Quantum optics I

Cavity optomechanics: exploring the coupling of light and micro- and nanomechanical oscillators

T Kippenberg

EPF Lausanne, Switzerland

The mutual coupling of optical and mechanical degrees of freedom via radiation pressure has been a subject of interest in the context of quantum limited displacements measurements for Gravity Wave Detection for many decades. Recent advances in nano- and micro-mechanical oscillators have for the first time allowed the observation of radiation pressure phenomena in an experimental setting and constitute the emerging research field of cavity optomechanics(1).

Using on-chip micro-cavities that combine both optical and mechanical degrees of freedom in one and the same device(2), radiation pressure back-action of photons is shown to lead to effective cooling(3-6) of the mechanical oscillator mode using dynamical back-action, which has been predicted by Braginsky as early as 1969(4). With this novel technique the quantum mechanical ground state of a micromechanical oscillator has been prepared with high probability using both microwave and optical fields. In our research this is reached using cryogenic precouling to ca. 700 mK in conjunction with laser cooling, allowing cooling of micro-mechanical oscillator to only 1.7 quanta. - implying the oscillator resides more than 1/3 of its time in the quantum ground state. Moreover it is possible in this regime to observe quantum coherent coupling in which the mechanical and optical mode hybridize and the coupling rate exceeds the mechanical and optical decoherence rate (7). This accomplishment enables a range of quantum optical experiments, including state transfer from light to mechanics using the phenomenon of optomechanically induced transparency(8) and quantum phenomena of macroscopically engineered structures.

[3] V. B. Braginsky, S. P. Vyatchanin, Low quantum noise tranquilizer for Fabry-Perot interferometer. Physics Letters A 293, 228 (Feb 4, 2002).

Silicon and carbon photonics

Integrating plasmonics with silicon photonics

A Chelnokov

CEA-Leti, France

Silicon photonics technology is quickly becoming mature, with first commercial products being successfully deployed at high volume markets. Its current uses are mostly the extra-chip datacoms. To be used for the intra-chip links, the Si photonics still have to:
Bridge the size gap between a large Si waveguide and a small modern (nano-) transistor. Reduce the energy spent per bit transmitted.

Can a merge of Si photonics with plasmonics be the solution? Can metal-oxide-silicon photonics enable other applications?

Latest results from all over the world and from the CEA Leti hint that such a combination of Si photonics with guided plasmonics does have an interesting potential, and allows building an efficient optical interface with nanoscopic devices.

We will discuss the issues of integration, the configurations of guided passive devices and the ways towards active plasmonic devices integrated with Si photonics.

**High performance optical modulators in silicon**


1 University of Southampton, UK, 2 University of St Andrews, UK, 3 University of Leeds, UK, 4 University of Warwick, UK, 5 University of Surrey, UK, 6 Universitat Politecnica de València, Spain, 7 III-V Lab, a joint lab of ‘Alcatel-Lucent Bell Labs France’, ‘Thales Research and Technology’ and ‘CEA Leti’, 8 CEA, LETI, France, 9 Ghent University, Belgium

In this work we present results from high performance silicon optical modulators under development within the two large European silicon photonics projects; UK Silicon Photonics (UKSP) and HELIOS. Two designs of phase modulator based upon carrier depletion in a silicon rib waveguide are first presented. The first made in the UKSP project is a device based in 400nm overlayer silicon on insulator (SOI) which targets polarization independent performance. Modulation has been demonstrated with a 7.3dB extinction ratio at 10Gbit/s and 6.5dB at 40Gbit/s for both TE and TM polarisations. The second design produced within the HELIOS project is based in 220nm overlayer SOI and demonstrates 40Gbits/s modulation with a 10dB extinction ratio as well modulation at 50Gbit/s for the first time. In both cases the phase modulators are incorporated into Mach-Zehnder Interferometers. Further to this the 220nm design is put in both ring resonator and slow wave structures. For the ring resonator based optical modulator, 40Gbit/s, 32fJ/bit operation is shown from a device with a 6um radius. The slow light version of the device uses a corrugated waveguide to modify the group index. The corrugated waveguide device shows a modulation efficiency down to 0.45V.cm compared to 2.2V.cm in the fast light case. 40Gbit/s modulation is also demonstrated from this device. Conventional photonic crystal structures are also investigated and have shown an enhancement factor of 8 over the fast light case. Ge/SiGe Stark effect devices operating at 1300nm and produced within the UKSP project are described. Finally an integrated transmitter featuring a III-V source and MZI modulator operating at 10Gbit/s is presented.
Trapping in fluids

Controlled deformation of emulsion droplets with ultralow interfacial tensions using optical tweezers

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¹Rutherford Appleton Laboratory, UK, ²University of Durham, UK, ³University of Exeter, UK

Droplets of oil in water can be readily trapped by a tightly focussed laser beam when the emulsion droplets are in the micron size range. Under normal conditions, the forces exerted by optical traps (10⁻⁵ Nm⁻¹) are orders of magnitude weaker than those due to surface tension (10⁻² Nm⁻¹), which keeps the droplets spherical. However, surfactants can be used to lower the oil–water surface tension to approach a microemulsion phase transition (10⁻⁶ Nm⁻¹). At this point optical forces can compete with surface tension. We have shown that emulsion droplets with ultralow interfacial tensions can be deformed by optical tweezers into ellipses, triangles or squares as the number of traps is increased from two to three to four¹.

With higher laser powers a droplet can be stretched into a dumbbell shape which then divides into two smaller droplets. These droplets remain connected by a thin oil thread barely discernable under microscopic imaging. Nanofluidic networks have be been fabricated using this phenomenon and we demonstrate that oil can be transported from one drop to another using these threads by variation of laser power². We also present the latest developments from the EPSRC Funded Critical Mass Grant “Optical Control of Emulsion Drops for Nanofluidics and Microfabrication”.

Fringe Analysis Special Interest Group (FASIG): Techniques

Fringe analysis – fit for purpose?

D Burton
Liverpool John Moores University, UK

Modern Fringe Analysis is the result of much effort over a 40 year period by a wide cross section of scientists. From humble beginnings in hand-digitisation of photographic images the technique has progressed through many stages to its modern form in which images are captured by high speed, high resolution, CCD cameras and analysed in computers using a wide variety of methods at, or near, real-time. The complexity of the method has grown exponentially as has the complexity of applications and patterns that can be analysed.

So is modern Fringe Analysis at the end of its journey – is this a problem we have solved? Are modern fringe analysis systems capable of delivering results in more or less any application area? Or are there issues still as yet to be faced?

In this paper we will briefly review the development of the subject and examine the question “where do we stand today with Fringe Analysis?” Is Fringe Analysis fully ready for commercial exploitation? What, if any, are the areas that we still need to address and what is the future likely to hold for the subject?

Quantum optics II

Single artificial atom optical dispersive bistability

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The field of circuit quantum electrodynamics describes the physics of artificial solid state based qubits strongly coupled to electromagnetic modes in superconducting resonators. These systems are fabricated on a chip and designed to perform basic quantum information processing. These devices behave as a few-body interacting systems out of equilibrium whose transient dynamics needs to be accurately controlled on short time scales compared to the relaxation and decoherence times. In addition, subtle quantum optical effects and interactions have been demonstrated in these systems such as number splitting and synthesis of arbitrary photonic Fock states.

The high power transient response of superconducting qubit-cavity systems has recently become a method to perform high fidelity readout of transmon qubits. We show that in the steady state, the system exhibits a bi-stable behavior that can be observed on the single shot level, with the cavity state switching stochastically between dim and bright states. The switching times are shown to be long compared to the cavity and qubit lifetimes. Some features of the bi-stability can be explained by mean field theory, while its switching dynamics is studied with large scale simulations. Besides being an interesting regime to study quantum activation, understanding its dynamics will be crucial for studying the transient response, an essential aspect of the qubit readout.
Nanophotonics and plasmonics II

Optics with electron beams in plasmonic metamaterials

T Coenen
FOM Institute AMOLF, The Netherlands

We introduce Angle-Resolved Cathodoluminescence Imaging Spectroscopy (ARCIS), that enables, for the first time, measurements of both the local optical density of states (LDOS) and the band structure of nanophotonic structures at deep subwavelength resolution. ARCIS employs a 30 keV electron beam in an SEM to excite plasmonic resonant modes with 10-nm spatial resolution. The radiation from these modes is collected in the SEM and analyzed using both a spectrometer and a 2D imaging CCD detector.

We use this new technique to demonstrate to resolve the radiation mechanism of elementary plasmonic nanowire antennas using ARCIS, directly probing the spatially resolved antenna radiation profile. Furthermore, using the angular detection capabilities of ARCIS, we carry out deep-subwavelength momentum spectroscopy, enabling reconstruction of the full band diagram and LDOS of two-dimensional photonic crystals over the entire visible to near-infrared spectral range. Finally we measure the spectral and spatial features of Mie resonances in subwavelength silicon disks and study the resonant behavior for various diameters.

Trapping tools and techniques

Trends in optical micromanipulation: Tailored light fields meet nanocontainers & absorbing particles

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University of Münster, Germany

After a brief review of established advanced optical micromanipulation techniques such as holographic optical tweezers, this talk will provide an insight into the highly topical field of complex beam shaping for applications in optical micromanipulation and nanomanipulation. Especially elliptical Ince-Gaussian beams are a highly promising beam class for future applications as they offer a variety of optical potential landscapes that can be employed for the versatile manipulation of (multiple) particles of different shapes. In our presentation, we will demonstrate the flexible holographic generation of tailored light fields and discuss their potential for the manipulation and assembly of various particles, such as non-spherical nanocontainers and absorbing particles, which is not easily accessible with conventional optical tweezers.

Nanocontainers can incorporate, transport and deliver various kinds of medical agents, or other functional molecules such as dyes. Zeolite L crystals will be introduced as one example of nanocontainers which allows new physical or optical functionalities if assembled by optical micromanipulation. We show the construction of complex functional Zeolite L structures which exhibit different photonic functionalities, including a microscopic polarization sensor.

As most of today’s techniques in optical micromanipulation are restricted to the manipulation of dielectric materials, there is a high demand for the manipulation and assembly of absorbing materials. Using sophisticated holographic techniques, hollow intensity distributions (“bottle beams”) can be created, which allow for the three-dimensional manipulation of absorbing particles. By this it becomes possible to simultaneously manipulate multiple absorbing particles in air using photophoretic forces and rearrange them in time and space.
Fringe Analysis Special Interest Group (FASIG): Techniques and application

Calibration of optical surface topography measuring instruments using the transfer function

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¹National Physical Laboratory, UK, ²Loughborough University, UK, ³Imperial College London, UK

There are a range of optical instruments now available that measure surface topography, for example coherence scanning (white-light) interferometry, confocal microscopy and focus variation microscopy. The manufacturers of such instruments often quote accuracies of the order of nanometres, sometime less, and claim that the instruments can reliably measure a range of surfaces. However, for many years there has been debate about the interpretation of the data from optical surface topography measuring instruments. Optical artefacts in the output data and a lack of a calibration infrastructure mean that it can be difficult to get optical instruments to agree with contact stylus instruments. In this paper, the current situation with areal surface topography measurements is discussed along with the ISO specification standards that are in draft form. An infrastructure is discussed whereby the ISO-defined metrological characteristics of optical instruments can be determined, but these characteristics do not allow the instrument to measure complex surfaces. Current research into methods for determining the transfer function of optical instruments is reviewed, which will allow the calibration of optical instruments to measure complex surfaces, at least in the case of weak scattering. The cases of coherent and incoherent illumination are discussed and experimental results presented for each case.

Nanophotonics and plasmonics III

Efficient coupling of ultrathin tapered fibers with nanoemitters and microsphere resonators

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Hokkaido University and Osaka University, Japan

Tapered fibers can be used for light coupling with micro-optical resonators or with nanoemitters. The use of tapered fibers at \( \lambda \sim 600 \) nm is particularly important because stable nanoemitters such as CdSe/ZnS nanocrystals (QDs) or diamond nitrogen vacancy (NV) centers have their optical transitions at around this wavelength. The taper diameter of \( \sim 300 \) nm is necessary for light coupling with nanoemitters or with microresonators at \( \lambda \sim 600 \) nm. Here we report on our two recent results: (1) the efficient coupling of ultrathin 300-nm-diam tapered fibers with QDs and (2) critical coupling of such ultrathin tapered fibers with microsphere resonators at 7 K.

We have demonstrated highly efficient fluorescence coupling from single QDs into single-mode optical fibers by using 300-nm-diam tapered fibers. 7.4% of the total emitted photons from single CdSe/ZnS QDs were coupled into the tapered fibers. This is one of the brightest fiber-based single photon sources ever reported [1].

We have demonstrated cooling of ultrathin tapered fibers down to 7K and its controllable coupling to high-Q microsphere resonators at \( \lambda = 637 \) nm. The stable nano-positioning of the 310-nm-diam tapered fibers to the microsphere have been realized, enabling the observation of the waveguide-cavity critical coupling. This cryogenic coupling at this wavelength is crucial for the coherent optical excitation of diamond NV centers [2].

We acknowledge the financial support from MIC-SCOPE, JST-CREST, Q-Cybermetrics, KAKENHI, FIRST, MEXT-PDIS, G-COE, and OST.

Thursday 6 September

**Optical vortices, polarization, coherence and non-Gaussian beams I**

Atomic size OAM electron beams as tools for characterization and manipulation of nanoparticles

J Verbeeck

University of Antwerp, Belgium

Electron vortices were recently created inside a transmission electron microscope. They form the counterpart of the better known optical vortex beams which carry orbital angular momentum caused by their phase signature. The optical wavelength is replaced by the De Broglie matter wavelength which is of the order of picometers in a typical electron microscope. This much smaller wavelength allows us to make vortex probes with diameters of the order of Angstroms. Such small electron vortex probes have much in common with electrons in atomic orbitals except for the fact that the probe electrons are free and propagate in space along the optical axis. The fact that electrons are charged particles leads to more difference with photon vortices in that the spiraling nature of the probability current leads to a magnetic field surrounding the vortex. The result of these differences is a much increased interaction with matter as can be exploited in electron energy loss spectroscopy. Indeed, the spectroscopic signal contains information about the magnetization of a material due to a breaking of symmetry caused by the incoming vortex beam. As such, electron vortex beams hold great promise for magnetic mapping of materials at atomic spatial resolution.

**Fibre optics and wave guidelines I**

Si slow light photonic crystals: four wave mixing and on-chip quantum interference

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¹University of St Andrews, UK, ²CUDOS, UK

The process of four-wave mixing (FWM) is a key effect in all-optical signal processing, enabling the realisation of all-optical amplifiers, wavelength converters, tunable delay lines, signal regenerators and sources for quantum computing. Dispersion engineering in slow light photonic crystal waveguides has proven to be a powerful tool to enhance the effective nonlinearities of silicon; our recent work [OE19:4458(2011)] has shown that with careful attention to realistic propagation loss and mode shape variations with group index, silicon slow light waveguides can indeed achieve FWM conversion efficiencies comparable to those of nanowires, but over much shorter lengths, therefore allowing for tighter integration.

To further demonstrate the potential of slow-light enhanced FWM, we investigate the application of dispersion engineered photonic crystal waveguides in the experimental realisation of a correlated photon pair source [OL36:3413(2011), JSTQE(in press)]. Such a device represents a key step towards the realisation of a miniaturised single photon source [arXiv:1201.2659v1], with a view for the full on-chip integration of quantum sources and quantum interference components.
Quantum dots I: colloidal quantum dots

Electron-hole wavefunction engineering as a tool to control the exchange interaction in CdSe/CdS nanocrystals: towards novel quantum light sources

G Rainò¹, I Moreels¹, T Stöferle¹, R Gomes², Z Hens² and R F Mahrt¹
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Colloidal semiconductor quantum nanostructures allow controlling the confinement of charge carriers through material composition and geometry. Besides being a unique platform to study the corresponding opto-electronic properties, these materials also attract considerable interest due to their potential in photonics and quantum communication applications.

Hetero-nanostructures like CdSe/CdS offer new prospects to tailor their optical properties as the small conduction band offset (~0.3 eV) allows tuning of the electron delocalization from type-I toward quasi type-II. Indeed, the energy of the quantized levels and their radiative rates can be controlled by adjusting the core size and the shell thickness.¹

In the present work, we use precisely engineered colloidal CdSe/CdS dot-in-rod hetero-nanostructures to experimentally demonstrate the tunability of the exciton fine-structure splitting by electron-hole wavefunction manipulation. Our results demonstrate that samples with small core and/or thick-rod diameters exhibit a strongly reduced fine-structure splitting resulting from a reduced electron-hole exchange interaction. Therefore, well-engineered nano-junctions provides a new degree of freedom to tune the electron–hole exchange interaction, well beyond what can be obtained by quantum confinement alone.³

The exciting tuning capabilities and the control of the fine-structure splitting has important implications in the field of optical quantum communication and could, in particular, pave the way toward a new source of non-classical light.


Optical and quantum metrology I

Frontiers in photon-counting

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Heriot-Watt University, UK

Single-photon detectors are a key enabling technology for a host of applications at the frontiers of science, from atmospheric sensing to quantum information processing.

These advanced photon counting applications place exacting demands on detector performance, spurring the development of new detector technologies. I will give an overview the state-of-the-art in solid-state photon counting technologies for time-correlated single-photon counting at infrared wavelengths.

I will then focus on emerging superconducting single-photon detector technologies. These new devices offer wide spectral sensitivity (from visible to mid-infrared wavelengths) combined with low dark counts, short recovery times and exquisite timing resolution. These low temperature detectors can now be integrated into practical cryogen-free refrigerator systems.
I will discuss the impact of these high performance detectors in applications ranging from quantum cryptography to time-of-flight depth imaging.

**Optical vortices, polarization, coherence and non-Gaussian beams II**

**Measuring the orbital angular moment with custom refractive optical elements**

M Lavery¹, David Robertson², J Courtial¹, G Love² and M Padgett¹

¹University of Glasgow, UK, ²Durham University, UK

The desire to increase the amount of information that can be encoded onto a single photon has driven research into many areas of optics. One such area is optical orbital angular momentum (OAM). These beams have helical phasefronts and carry an orbital angular momentum of $m\hbar$ per photon, where the integer $m$ is unbounded, giving a large state space in which to encode information.

We recently developed two bespoke refractive optical elements to transform OAM states into transverse momentum states. This is achieved through the use of mapping the azimuthal position of the input plane to the lateral position in the output. A mapping of this type transforms a set of concentric rings at the input plane into a set of parallel lines in the output plane. A lens can then separate the resulting transverse momentum states into specified lateral positions, allowing for the efficient measurement of multiple states simultaneously.

We will present our latest design increasing the bandwidth of measurable states to over 50 OAM modes.

**Quantum dots II: self-assembled quantum dots**

**Optical control of spins in semiconductor quantum dots**

A Greilich

Technische Universität Dortmund, Germany

Currently, the most attractive quantum bit (qubit) candidate in semiconductors is an electron or hole spin in a quantum dot (QD). Due to confinement the spin is largely protected from relaxation mechanisms, leading to decoherence times in the $\mu$s-range. This time has to be contrasted with the time to perform coherent manipulations on the qubit, which should be orders of magnitude shorter for useful implementations. A tool which has the potential to reach this goal is pulsed optical excitation, which has been shown to generate/initialize a fast and efficient spin polarization using ps-laser pulses.

First, we demonstrate the ultrafast optical rotations of single spins about arbitrary axes of the Bloch sphere on a picosecond timescale using laser pulses as control fields.

In the next step, we demonstrate ultrafast optical control of two interacting electron and hole spins in two separate QDs using optical initialization, single-qubit gates with short pulses, and two-qubit gates with longer pulses or through precession in the exchange field. Local entanglement between the two spins is inferred from the coherent evolution of superposition states as measured in Ramsey fringes.

The two-qubit gate speeds achieved here are over an order of magnitude faster than in other systems. These results demonstrate the viability and advantages of optically controlled quantum dot spins for multi-qubit systems.
Quantum dot resonance fluorescence: progress and outlook
M Atature

University of Cambridge, UK

Self-assembled semiconductor quantum dots are interesting and rich physical systems. Their inherently mesoscopic nature leads to a multitude of interaction mechanisms of confined spins with the solid state environment of spins, charges and phonons. Nevertheless, the relatively clean spin-dependent optical transitions make quantum dots strong candidates for stationary and flying qubits within the context of spin-based quantum information science. The recently observed quantum dot resonance fluorescence has become a key enabler in this quest. I will discuss how resonance fluorescence allows coherent generation of tailored single photons suitable for linear-optics quantum computation and for establishing a high efficiency spin-photon quantum interface within a distributed quantum network.

Optical and quantum metrology II

Metrology for quantum optical technologies
C Chunnilall, J Cheung and A Sinclair

National Physical Laboratory, UK

Industrial technologies and applications based on the production, manipulation, and detection of single and entangled photons are emerging [1, 2]. In order to support the development of this quantum industry, the National Physical Laboratory (NPL) is using traditional as well as quantum approaches to provide traceable performance measures for devices used in these technologies.

Quantum key distribution (QKD) and quantum random number generator (QRNG) systems are two technologies already available in the marketplace, and the focus of current work at NPL is on characterising these types of systems.

We will report on the development of our measurement infrastructure for quantum optical technologies, covering various aspects of single and entangled photons, photon counting detectors, and optical fibre links. This ranges from ‘traditional’ measures such as photon number, and detection efficiency [3], to others such as indistinguishability that determine device utility for quantum applications. We will review our progress in evaluating the viability of quantum cloning [4] to establish optical power measurements at photon counting levels in optical fibre at telecom wavelengths.

Finally, we will discuss the application of the various measurements to the characterisation of the performance of components of QKD and QRNG systems.

Oral presentation abstracts

Monday 3 September

Active and adaptive optics

Adaptive optics for light sheet microscopy

C Bourgenot, C Saunter, J Taylor, J Girkin and G Love
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We report on the incorporation of adaptive optics (AO) into the imaging arm of a selective plane illumination microscope (SPIM). SPIM provides a method of recording high speed optically sectioned images from within in vivo selected samples with reduced photo-damage. The sectioning is obtained by the use of light sheet illumination that selectively excites a “slice” of the intact sample at the focal plane of a microscope objective placed perpendicular to the illumination sheet, thus enabling an entire optical section to be recorded in a single shot. SPIM provides a very interesting system for the incorporation of AO as the illumination and imaging paths are decoupled and AO may be useful in both paths. In this paper, we will report the first use of AO applied to SPIM, demonstrating significant improvement in image quality of a 3D z-stack of a zebrafish embryo using a wavefront modal sensorless AO system on the imaging path.

These experimental results will be linked to a computational model showing that significant aberrations are produced by the tube holding the sample in addition to the aberration from the sample itself. Finally, we show that AO on the imaging path can be used to correct for some aberrations on the illumination path.

Wavefront sensing and adaptive optics in high resolution microscopy

M Shaw¹ and C Paterson²
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Focussing light inside complex, non-uniform specimens, such as biological organisms and tissues, results in wavefront aberrations. In biological imaging such aberrations reduce resolution and signal-to-noise and prevent the formation of images deep inside specimens. Adaptive optic (AO) techniques offer the potential to restore diffraction limited imaging, ideally at high speed and with minimum light exposure. A number of schemes have been proposed for achieving this, many of which rely on image optimisation. Our research has focussed on the use of direct wavefront sensing and we have developed an experimental microscope system incorporating a Shack-Hartmann wavefront sensor to measure the wavefront in the pupil of the microscope objective lens and a deformable mirror to correct it. This system has been used to study the application of closed-loop AO correction for imaging a variety of different samples including standard artefacts. We present experimental results showing wavefront sensing and correction using artificial fluorescent ‘guide stars’ to provide a source of reference wavefronts. We also show results from theoretical simulations describing the propagation of aberrated wavefronts through various parts of the microscope system, including the objective lens and the confocal pinhole, and their effect on the images obtained. Finally we discuss some of the challenges associated with wavefront sensing in biological microscopes and high numerical aperture imaging systems more generally.
Femtosecond laser direct write waveguides using adaptive optics: beam shaping and aberration correction
P Salter and M Booth
University of Oxford, UK

Femtosecond micro-fabrication enables the structural modification of micron-scale regions within transparent media, avoiding damage to surrounding areas or the surface. In certain glasses it is possible to create a smooth local increase in the refractive index enabling the manufacture of waveguide structures. Experimentally we demonstrate waveguide fabrication in fused silica using a liquid crystal spatial light modulator (SLM) for shaping the beam from a regeneratively amplified Ti:Sapphire laser with a 1kHz repetition rate. It is shown how the SLM may be used effectively as an adaptive slit to tailor the waveguide cross-section during fabrication, while also offering fine power control. In addition it is shown that the SLM can be simultaneously used to cancel depth dependent spherical aberration, which is generated due to the mismatch in refractive index between the sample and immersion medium of the objective.

Additionally, it is demonstrated that a hologram displayed on the SLM can generate a multisport focal intensity distribution appropriate for the creation of waveguides of desired cross-section, in a manner similar to the “multiscan” method typically used for waveguide writing with a higher repetition rate femtosecond laser. The high degree of uniformity required in the spot intensities necessitates a direct feedback from the experiment when calculating the hologram. The supercontinuum emission from the plasma generated at focus during fabrication is employed for such feedback.

Interferometric metrology using reprogrammable binary holograms
M Cashmore¹, G Love¹, S Hall² and M Neil³
¹Durham University, UK, ²National Physical Laboratory, UK, ³Imperial College London, UK

Lithographically created computer generated holograms (CGHs) have been used extensively in interferometric metrology for many years, and are vital in the testing of highly aberrated or aspheric surfaces where nulling optics are required. One example of this is the segmented primary mirrors of the next generation of large telescopes, comprised of off axis aspheric surfaces and thus necessitate that the surface measurement technique used be fast, accurate and also preferably of low cost.

Standard production of CGHs involve writing the hologram onto a plate using methods such as electron beam lithography and thermochemical writing. Naturally the resulting optic is static and only suitable for use in testing the specific optical component used in the design process. Here an alternative method of CGH production is presented where the hologram is displayed on a binary ferroelectric liquid crystal on silicon spatial light modulator (FLCOS SLM). These devices allow for arbitrarily reconfigurable wavefronts to be produced much faster than the more traditional lithographic writing processes, allowing cheaper and more versatile nulling optics for use in interferometric metrology. Both simulated and experimental results are given of measurements of produced phase aberrations on a 1280 x 1024 FLCOS SLM showing production of Z5 astigmatism and Z9 Trefoil and show a variation between repeat measurements of 0.001 waves RMS between repeat measurements. The system will be further evaluated for accuracy by comparison against aberration artefacts traceably calibrated at NPL.
Quantum information I

Microfabricated ion trap chips for quantum technologies

A Sinclair, G Wilpers, P See, J Thom and P Gill
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Precise control of trapped ion strings has resulted in significant experimental advances in quantum information processing and quantum metrology [1]. Ion trap arrays are a suitable architecture [2] for progressing towards larger systems of qubits. Although 2D electrode arrays [3] are popular due to their ease of fabrication, 3D trap geometries are the optimal configuration for creating a superior trapping potential.

We describe the operation of a novel ion microtrap linear array [4] etched from a silica-on-silicon wafer. The device uniquely combines the advantages of a 3D electrode geometry with the scalability of microfabrication techniques, to create a trap array in a monolithic chip. We observed confinement of $^{88}$Sr$^+$ ions over a wide range of the trap stability parameter, and radial motional frequencies of a few MHz. The 3D geometry yields a deep and efficient trapping potential. The measured ion heating rate is low and ion storage times are long. Spectroscopy of the 5s $^3S_{1/2}$ – 4d $^2D_{5/2}$ optical qubit transition in a single ion shows confinement in the Lamb-Dicke limit.

Operating characteristics indicate that the microtrap is suited to the creation and control of entangled states. These will be realised through coherent spectroscopy of the optical qubit transition in $^{88}$Sr$^+$. The system can then be used to study the transport of entangled states, and will be applied to precision quantum metrology. Current progress and future directions will be described.


Computational quantum walks

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Quantum versions of random walks have diverse applications that motivate experimental implementations and theoretical studies. The main impetus behind recent interest is their use in quantum algorithms, which have always employed the quantum walk in the form of a program running on a quantum computer. Recent results showing that quantum walks are “universal for quantum computation” relate entirely to algorithms, and do not imply that a physical quantum walk could provide a new architecture for quantum computers. Nonetheless, quantum walks used to model transport phenomena in spin chains and biomolecules broaden their scope beyond algorithms, reopening the question of whether a physical implementation might provide useful computational outputs. Quantum walks with multiple walkers extend the paradigm beyond the standard algorithmic application. Interacting quantum walkers are quantum cellular automata, known to be universal for quantum computation. Indistinguishable but non-interacting bosonic walkers can have intermediate computational power [Aaronson/Arkhipov arxiv:1011.3245]; this discussion is thus especially relevant for photonic quantum walk implementations. Even where the quantum experiment will clearly win for larger numbers of walkers, it is important to estimate where the crossover occurs. Many instances of quantum walks are tractable on classical computers up to sizes way beyond current experimental capabilities. Like the problem of factoring large numbers, the crossover point is high. I will explain the conditions under which a physical quantum walk experiment could provide useful results beyond the reach of classical computation, and assess whether this is likely before universal qubit quantum computers can outperform them.
Bosonic and fermionic quantum walk dynamics in waveguide arrays

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Quantum walks are the quantum-mechanical analogue of classical random walks, the stochastic motion of a particle in a discrete space. Integrated quantum optics is an excellent platform for realising photonic quantum walks, where evanescent coupling between single mode waveguides is well described by a nearest-neighbour coupling Hamiltonian used to model the dynamics of continuous time quantum walks. This system maps to spin chains and models for example energy transport in molecules.

While single particle quantum walks can be described using classical wave mechanics, multi-photon quantum walks show quantum mechanical correlations which depend on the quantum statistics of the used particles and cannot be mimicked with classical physics efficiently.

Here we present the coherent evolution of quantum walks of two indistinguishable photons using arrays of 21 evanescently coupled waveguides fabricated in silicon oxynitride technology. We measure the bosonic output statistics of three different lengths of array corresponding to different time evolutions. We observe quantum interference features that violate classical predictions in each time step. The longest array includes reflecting boundary conditions. We use entangled input states to emulate fermionic and bosonic quantum interference including Pauli exclusion and bosonic bunching [1].


Quantum-enhanced metrology with entangled coherent states using linear and non-linear phase operations

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Quantum-enhanced metrology enables measurement of physical quantities beyond the sensitivity of the standard quantum limit, through use of non-classical states.

We present a quantum-enhanced phase estimation scheme employing entangled coherent states (ECS). We demonstrate that these states give the smallest variance in the phase parameter (for measurement of an unknown linear phase), in comparison to NOON and BAT states with the same average particle number. We employ the standard Fisher information to quantify the phase variance. Our results hold under perfect conditions and also for the more realistic scenario including particle loss [1].

In addition, we investigate the phase variance achieved with ECS states for a generalised non-linear phase operation, finding a similar advantage over other non-classical states for both the lossless and low loss scenarios. As these advantages of ECS emerge for very modest particle numbers (or expectation values), the optical version of quantum-enhanced metrology with entangled coherent states is potentially achievable with current technology.

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Metamaterials and cloaking

Perfect plasmonic absorption and transparency: the anti-lasing spaser
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Time reversal inverts the direction of light propagation and converts gain into loss. Under time reversal, a laser emitting coherent light becomes a ‘coherent perfect absorber’, as recently demonstrated in a bulk optical cavity device that can absorb all radiation incident upon it [Science 331, 889 (2011)]. Here we show that when the concept of time reversal is applied in plasmonics, regimes of perfect transparency and perfect absorption can be achieved in a system of sub-wavelength thickness - a single layer of nanostructured metal less than one tenth of a wavelength thick. We demonstrate the phenomenon experimentally in a ‘lasing spaser’ configuration, using a planar metamaterial array of plasmonic resonators. We show that by controlling the interference between counter-propagating beams on a thin, lossy plasmonic film one can either eliminate or double the plasmonic Joule loss of energy (or indeed achieve any intermediate level). The highly sensitive system of beams interacting on a metamaterial film in precise resonant balance may serve applications in sensing, coherent detection, high-bandwidth variable attenuation and unique light coherence control devices.

The scattering properties of spherical particles coated with epsilon near zero (ENZ) materials
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The materials with epsilon near zero (ENZ) like low loss noble metals Ag and Au at infrared and optical frequencies or some semiconductors near their plasma frequencies are under significant attention of researchers [1]. As shown in the article [2] the peculiarities of epsilon near zero materials revealed new features and the singularity in Mie scattering theory, where the dielectric properties of the scattering uniform spherical particles and surrounding medium are considered in the epsilon near zero limits. The scattering theory for coated spheres is generalized when particles shell, cores and surrounded medium are considered in the epsilon near zero limits. The simultaneous zeros of dipole electric and dipole magnetic polarization coefficients and consequently the condition of near invisibility for coated particles are investigated. The possibility to achieving the magnetic dipole resonances and significant effective permeability for aggregate of particles coated with ENZ materials is demonstrated.


Transformation mechanics and transformation media
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We show how it is possible to cast several distinct wave theories (including electromagnetism) into a single prescription. This greatly simplifies the process of learning how to use transformation theories to make transformation devices (``T-devices''), because now you only need to learn one procedure - that for the unified wave theory. Nevertheless, however elegantly they might be expressed, the possible wave theories contained within the formulation are not all equivalent. Thus although the prescription is general, we find that there is a test for whether or not a given T-device is allowed in a particular case. That test is based on the form-invariance of the wave
model - if the transformed theory is not the same, perhaps because it demands impossible material properties - then the hoped for T-device is likewise impossible.

Specifically, we will demonstrate how to combine electromagnetism, scalar acoustics, and even some important types of pentamode acoustic waves into a form consisting of a pair of first order differential equations for the behaviour of two rank-2 tensors, linked by a rank-four constitutive tensor. For the less mathematically inclined, we will also show that a careful rewriting enables us to present the same description much more simply, and entirely in terms of matrices. As examples we will discuss some new spacetime T-devices analogous to the ground-plane spatial devices that already exist: we show how (and if) we can construct spacetime carpet cloaks, peepholes, and tardises in both electromagnetism and acoustics.

Ultrafast and attosecond optics I

First and third-order quasi-phase-matching of high harmonic generation using ultrafast pulse trains

K O’Keeffe and S Hooker
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High harmonic generation (HHG) offers a straightforward way for generating coherent soft x-ray radiation in the XUV region. However, a significant drawback of HHG is that it is inefficient due to the difference in the phase velocities of the driving and generated radiation. One way to overcome this problem, and thereby greatly increase the efficiency of HHG, is to employ quasi-phase-matching (QPM). In this approach, HHG is suppressed in regions where the locally generated radiation is out of phase with the harmonic beam. Radiation from the remaining regions can then combine constructively, resulting in the monotonic growth of the harmonic intensity. QPM can be achieved using a train of counter-propagating laser pulses; suppression occurring in regions where the driving laser pulse overlaps with a counter-propagating pulse. Here we investigate QPM by trains of up to 8 uniformly-spaced laser pulses colliding with a driving laser pulse within a hollow capillary waveguide, and demonstrate up to 40-fold enhancement of the harmonic flux at 42eV. Variations of coherence length within the waveguide are considered and shown to place a limit on the total number of pulses which can be used with this technique. The variation of QPM with pressure within the target is also studied. It is found that additional peaks in the harmonic intensity are consistent with higher-order QPM processes.

Characterisation of the transverse properties of high harmonic radiation using a variable-separation pinhole pair

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High harmonic generation (HHG) offers a straightforward way for generating coherent radiation at XUV photon energies, and has many potential applications, including table-top coherent diffractive imaging. In order to fully optimize the application of HHG to such imaging techniques it is necessary to characterize the transverse spatial properties of the harmonic beam. To date, no technique has been demonstrated which measures the spatial coherence as well as the intensity and phase profiles of a beam in a single scan.

In this paper we present a technique for the spatial characterisation of a light source, which retrieves the radial phase and intensity profiles, as well as the spatial coherence of the beam. Determination of these properties is crucial to the optimisation of imaging systems. The combination of a pair of non-parallel slits placed in front of a single slit forms a pair of pinholes, the separation of which may be varied by translating the slit pair. A single scan of this type allows the spatial coherence and transverse intensity and phase profiles of the beam to be retrieved. The technique described is applicable to a wide range of light sources and is not limited by the spectral width of the incident field.
We present the results of experiments to apply this method to measurement of the transverse spatial properties of high flux, quasi-phase-matched HHG radiation, drawing comparison with HHG generated from a gas cell.

Towards optical attosecond pulses: broadband phrase coherence between an ultrafast laser and OPO using lock-to-zero CEO stabilization

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The carrier-envelope-offset frequencies of the pump, signal, idler and related sum-frequency mixing pulses have been locked to 0 Hz in a 20-fs-Ti: sapphire-pumped optical parametric oscillator, satisfying a critical prerequisite for optical attosecond pulse synthesis.

Nonlinear second-order media provide frequency conversion bandwidths of 1 - 2 PHz, sufficient to support sub-500-as optical fields, offering a radically different route to this temporal regime than attosecond pulses produced by high-harmonic generation. Sum-frequency mixing (SFM) and second harmonic generation (SHG) within a femtosecond optical parametric oscillator (OPO) provide a practical means of creating the short parent pulses needed to coherently synthesize sub-femtosecond pulses over a wide visible bandwidth. A major obstacle is that the parent pulses produced by these processes are normally mutually incoherent because their carrier-envelope-offset (CEO) frequencies are all different combinations of those of the pump (p), signal (s) and idler (i) pulses.

Here we describe how broadband phase coherence between a pump laser and multiple outputs from an OPO spanning > 0.6 PHz in bandwidth, was achieved experimentally by locking the CEO frequencies of both the pump and the OPO to 0 Hz. Phase coherence was confirmed by time-domain interferometry. This broadband output can be used to synthesize sub-cycle optical waveforms through direct interference of their electric fields.

New trends in laser ablation-induced high-order harmonic generation

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The basic ideas of high-order harmonic generation (HHG) in laser-produced plasmas have been outlined in few recent reviews. It seems timely to return back to the practice of showing the broad pattern of various developments in this field. It is also obvious that the comprehensive overview of recent findings can help in defining the next steps of the development in this relatively new and attractive area of nonlinear optical studies. We will highlight some new work in this field as well as offer a detailed overview of related studies. These include new approaches in application of two-colour pumps, generation of extremely broadened harmonics, further developments in HHG in clusters (fullerenes, carbon nanotubes), destructive interference of harmonics from different emitters, new approaches in resonance-induced enhancement of harmonics, applications of high pulse repetition rate lasers for the enhancement of average power of generating harmonics and observation of quantum path signatures, single harmonic generation, etc. We show that this method of frequency conversion of laser radiation towards the extreme ultraviolet range became mature during multiple sets of studies carried out in many laboratories worldwide and demonstrated new approaches in the generation of strong coherent short-wavelength radiation for various applications. In addition, we give an outline of expectations of the future evolution of HHG in laser-produced plasma plumes.
**Imaging and displays technology**

**Integral imaging system for capture and display of 3D content**

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Creating 3D content has been the goal of many researchers in the academia and industry as well as artists for many years (e.g. in Cinema, TV and performing arts). There has been a trend in cinema in producing films with 3D enriched content such the latest adventure film “Avatar”. Currently stereo imaging is the technology being used to capture 3D-film. This requires complex multiple camera configurations for clever image registration and focusing to obtain multiple perspective views of the scene. However, it is known that stereo imaging cause eye-strain and headaches in some people.

The above facts have motivated researchers to seek alternative means for capturing true 3D content. Two of the most recognised being holography and Integral Imaging. Due to the interfering of coherent light fields required to record holograms, their use is still limited and mostly confined to research laboratories. Integral Imaging in its simplest form consists of a lens array mated to a photographic film or digital sensor with each lens capturing perspective views of the scene. The light field in this case does not need to be coherent and ‘holoscopic’ colour images can be obtained with full parallax. A project funded by the EU-FP7 ICT-4-1.5 – Networked Media and 3D Internet, entitled “3D Live Immerse Video-Audio Interactive Multimedia” (3D VIVANT) offers a number of advances in the integral imaging technology for capture, representation, processing and display of 3D content. In this paper, recent advances made by the authors with respect to the Integral imaging technology from the point of view of optical systems for capture and display of 3D content are presented.

**An assessment of the temporal integrity of a high speed rotating mirror camera**

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A mainstay modality for the purpose of capturing full frame image sequences of dynamic events that occur over microsecond timescales, rotating-mirror framing cameras were first conceptualised in the late 1930’s. Based on the ‘Miller principle’, after CD Miller who initially developed the optical design concept, the first practical incarnations were realised during the Manhattan Project, where their focus was to study the detonation of the secondary explosives in the first nuclear device. The core concept of the Miller principle provides an instrument capable of generating a succession of static images relayed by a rotating mirror, so that, provided the target scene is framed at a sufficiently high rate, the short time taken to expose the imaging frame in effect captures the scene without temporal blurring. Some of our recent work has however discovered that even when imaging [apparently] within the Miller principle’s optical regime, a subtle temporal aberration can be present that may lead to significant misinterpretation of data. Here we will highlight several examples illustrating such distortion, and follow on to describe how the anomaly can be detected and characterised in a straightforward manner. Furthermore, we present proposals to take advantage of this effect for assessing system performance and more interestingly for operating in an enhanced imaging mode suitable for observing events requiring framing rates in the elevated MHz range.
Modelling of high resolution liquid crystal on silicon devices

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Liquid crystal on Silicon (LCOS) devices are being fabricated to high resolution and have application in diffractive displays, laser tweezing and beam steering. As the pixels become smaller the inter-pixel gap becomes more significant, not only because the fields between adjacent pixels become greater than the field across the liquid crystal layer, but also because surface effects become more significant. Modelling of the liquid crystal director structure using software developed at UCL (QLC3D) \[1\] has been carried out to simulate the formation of defects in and around the gaps. The results show that both surface pre-tilt of the liquid crystal director and fringing fields can form structures which affect the device performance. Investigations will be presented into the effect on the optical properties of the eventual director structure, both in terms of the accuracy of the optical patterns that arise compared to the electrode pattern, and the phase modulation and polarisation modulation that result from the switching around the edges of the LCOS pixels. Surface relief patterns on the substrate in the inter-pixel gap can also be simulated and results will also be presented.


Planar InAs photodiodes fabricated using ion implantation

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The infrared spectral region between 1.5 and 3.5 µm is of great interest for a number of applications including military imaging, gas sensing and free space communications. Recently InAs has been demonstrated to operate as an excellent avalanche photodiode (APD) over this spectral range. While at room temperature the bulk current is dominant in these APDs with diameters above 50 mm, further improvement in the fabrication is desirable to suppress the surface leakage current in small area APDs, such as 25 mm x 25 mm or smaller to pave the way for the development of InAs APD arrays. In addition the surface leakage becomes increasingly dominant as the bulk current reduces at low temperature hindering the low temperature performance of InAs APDs. A potential method to reduce the surface leakage current and hence increase the device reliability is to fabricate planar photodiodes, as commonly employed in the fabrication of HgCdTe photodiodes. Ion implantation can be used for fabrication of planar photodiodes and has been used in wider bandgap semiconductors such as GaAs and InP to form planar devices.

In this work we evaluate the use of different ions (Silicon or Beryllium) and implant conditions to produce localised highly doped regions in InAs as well as investigating using Helium implantation to electrically isolate neighbouring devices to investigate the possibility of fabricating planar InAs photodiodes. We have show that it is possible to produce planar photodiodes with comparable dark currents and quantum efficiencies to chemically etched reference mesa InAs photodiodes.
Computational physics

Simulation of digital holographic microscope imaging using hybrid of FDTD method and Fresnel diffraction for the micro phase object

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Digital holographic microscope (DHM) is a powerful tool for fast, nondestructive, high resolution quantitative phase imaging for biological samples, for example, blood cells, cancer cells and so on. It has two important functions that are 3D-imaging using optical path length and the in-focus measurement without the mechanical scanning. The in-focus measurement is carried out using Fresnel diffraction and then optimal reconstruction distance must be determined. To assess the reconstruction algorithm and the effect of reconstruction distance on amplitude and quantitative phase imaging, we make the model of DHM imaging simulation using hybrid of finite difference time domain (FDTD) method and Fresnel approximation. This hybrid method allows us to calculate the output images through the lens system. To demonstrate the proposed model of DHM, we make a comparison between the simulation and the experiment results for the micro phase object, for example, a micro-bead. As a result, both results are similar qualitatively. However this model has some assumptions that are far-field approximation and Fresnel approximation. The effect of these assumptions is investigated.

Numerical investigations of the effective parameters for two center holographic recording in photorefractive lithium niobate and strontium barium niobate crystals

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Non-volatile holographic storage based on two-center holographic recording (TCHR) is one of the most powerful methods compared with thermal fixing, electrical fixing, two photon recording and frequency-difference holograms.

The dependence of the diffraction efficiency of LiNbO$_3$ for TCHR on various parameter values is calculated by an implemented computer program and is compared with those obtained from the experimental results. The applicability of this method to other photorefractive crystals is important for practical purposes of view.

The holographic recording parameters of the usable photorefractive crystals and of the recording conditions such as electron mobility, level concentrations, electron recombination coefficients, bulk photovoltaic coefficient, spatial period of modulation, dielectric constant, and modulation depth are studied numerically, for LiNbO$_3$ and SBN crystals.

It's coming out that the deep level electron recombination coefficient is the main parameter. Also, the electron mobility and the doping concentration of the deep levels play an important role in TCHR. A detailed analysis of the variation of parameters will be presented.

A meshless RBF-FD method for 2D bandgap calculations

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In this paper, we report on the development of a radial basis function (RBF) based finite difference method (RBF-FD) for solving the Maxwell equations as applicable to two-dimensional photonic crystals. We apply the method to produce bandgap diagrams for simple crystal structures, which are found to be in good agreement with those
produced by a leading plane-wave expansion method code. Our method returns an average error below 1% for several sets of parameters, and these results show that this meshfree method is a promising scheme for predicting band gaps of photonic crystals.

**Modelling of long period gratings with metallic (Pd) jacket**

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Metal coated long period grating based sensors and tuneable filters have attracted considerable interest in recent years. The replacement of guidance of cladding modes by total internal reflection with reflection by a metallic layer has complicated the system with no simple formal model to describe the transmission spectra of these forms of LPG being available. We report the extension of standard long period grating (LPG) modelling techniques to incorporate an infinite thickness (optically opaque) metallic jacket layer. The effect of the inclusion of a metal layer on the available radially symmetric cladding modes is discussed both for low order and higher order, double coupling cladding modes. Particular care is taken to consider the effect on the coupling coefficients between core and cladding modes which result in a significant reduction in the effective strength of the grating in the presence of a complex, absorbing refractive index layer.

**Structured optical materials**

**Smaller is better: sub-wavelength front-side periodic patterning for thin and thick crystalline silicon solar cells**

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Crystalline silicon (c-Si) is the dominating photovoltaic material because it absorbs a large range of the solar radiation, is very abundant and can be post-processed using well known techniques. However, it represents 30% of a module cost, the use of ultrathin c-Si layers could help reducing them but at the expense of the efficiency due to a reduced absorption. In order to keep the efficiency high, we propose to enhance the absorption by patterning the front side at a sub-wavelength scale. We focus on the theoretical case of a stand-alone layer, whose top surface is patterned with a periodic square array of holes. We consider both thick and ultrathin (wavelength scale) layers. We aim at finding ideal nanopattern shapes and dimensions maximizing the solar light absorption, hence the photocurrent. The period, diameter, depth and shape of holes are the optimization parameters. Rigorous Coupled Wave Analysis is used to solve Maxwell’s equations and to calculate the absorption spectrum. Results are compared with those obtained for planar homogeneous reference layers of identical thicknesses covered by an antireflective coating. For both thick and ultrathin layers, the removal of material on the top surface leads to a significant increase of the absorption with respect to the reference. Even without any antireflective coating, the patterned c-Si layer is more absorbing than the reference (coated) layer. We show that this absorption enhancement is due to the wave nature of light and could not be reached with traditional texturing, limited to random scattering effects.
The butterfly's photonic nose: how nature can substitute for our sense of smell

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Structurally coloured natural photonic structures found in living organisms, such as butterflies or beetles, are complex optical materials often made of ordered porous chitin structures and giving rise to astonishing visual effects. A signature of structurally produced coloration is the iridescence, i.e. the colour changes with the viewing angle.

The photonic nanostructure located on the dorsal side of the fore and hind wings of the male Purple Emperor, Apatura iris (Linnaeus, 1758), a butterfly of the Nymphalidae family, is studied in detail. This species is found near tree leaves in woodlands throughout Asia, Europe and North Africa. It displays ultraviolet iridescent colours, which turn to violet at grazing incidence. The underlying pattern is brown with white spots. Optical microscopy reveals the presence of overlapping tiny scales on its wings: like roof tiles.

A Christmas-tree-like nano-architecture, i.e. aMorpho-type structure, observed on the scales and characterised by Scanning Electron Microscope (SEM) and Transmission Electron Microscope (TEM), is at the source of the iridescence. We demonstrate, through numerical simulations based on rigorous coupled wave analysis, that the observed nanostructure is responsible for the measured optical reflectance spectra.

This open architecture makes Apatura iris an interesting candidate for the study of colour changes induced by relative gas/vapour concentration variations in the surrounding atmosphere. At the Conference, we will present preliminary experiments on the modifications of the reflectance spectrum induced by gas/vapour concentration changes and we will discuss related gas/vapour sensing applications.

2-D structuring of silver-glass nanocomposite

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Dielectrics containing metallic nanoparticles constitute a promising class of materials for various photonics applications due to their unique linear and nonlinear optical properties, which result mainly from the strong surface plasmon resonances (SPR) of the metallic inclusions. Since these resonances can be varied within a wide spectral range throughout the visible and near infrared by choice of the metal and dielectric matrix as well as by manipulation of size, shape, and spatial distribution of the metal clusters, such materials allow flexible engineering of their optical properties. In particular, metallodielectric photonic crystals have recently been proposed as possible candidates for achieving a photonic bandgap in the visible-wavelength range. However, production of optical micro- and nanostructures in metallodielectrics requires gaining control over the above-mentioned parameters of the metallic inclusions. Established elaborate techniques such as electron-beam lithography or those that involve lasers, while proven to be powerful and flexible tools for this purpose, are often costly and/or time-consuming.

Here, we demonstrate a comparatively simple technique to prepare large-area, regular photonic micro- and nanostructures in silver-doped nanocomposite glass by modifying the spatial distribution of the nanoparticles with a direct current (DC) electric field. The technique exploits the effect of "electric-field-assisted dissolution" (EFAD) of metallic nanoparticles: silver nanoparticles embedded in a glass matrix can be destroyed and dissolved in the glass in the form of Ag⁺ ions by a combination of an intense DC electric field and moderately elevated temperatures.
Highly organised microstructuring of copper

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Copper, its alloys and metals with similar metallurgical behavior (e.g., gold) are important materials for many technical applications due to their unrivalled thermal and electrical conductivity. The latest social and environmental developments lead to a much higher electrification of our everyday lives. Therefore, laser processing (structuring, welding etc.) of metals like copper and gold are key technologies for this trend. However, the high thermal conductivity (~ 16 times higher than that of stainless steel) together with low absorptivity of these materials at the fundamental wavelength of typical solid-state bulk, fiber and diode lasers makes their processing a challenge.

Here, we explore experimental conditions required for the formation of highly organised, periodic microstructures on a copper (Cu) target upon multi-pulsed laser irradiation at 532 nm in air. The microstructures exhibited an average separation between tips ranging from 40 to 80 μm, depending on the hatching overlap between consecutive scans. The tips of the generated structures are at the level of the original substrate. We will also demonstrate that the suggested approach is scalable for highly organised structuring of other metals (e.g., titanium and stainless steel).

Ultrafast and attosecond optics II

Mode filtering of a carrier envelope offset frequency stabilized optical parametric oscillator

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A femtosecond Ti:sapphire ring laser was used to synchronously pump a magnesium doped periodically poled lithium niobate (MgO:PPLN) crystal in an optical parametric oscillator (OPO) at a repetition rate of 280 MHz. Part of the laser output was also used to pump a photonic crystal fibre for supercontinuum generation. The OPO produced signal pulses at 1500 nm which were stabilized by beating the pump + signal from sum frequency mixing in the OPO with the pump supercontinuum to give the CEO frequency of the signal pulses. The difference between this and a frequency reference was measured and provided feedback to a piezoelectric stack in the OPO. A 1.4 GHz Fabry-Pérot cavity was used to filter the OPO output and excellent suppression of the 280 MHz input was observed. The repetition rate of the laser will be locked to produce a frequency comb and we aim to shorten the Fabry-Pérot cavity and stabilize it to increase the mode separation to 9 GHz to enable resolving of the modes on a conventional spectrometer and to provide a near-IR comb source for spectroscopy.

Quasi-phase-matching of high harmonic generation using polarization beating in optical waveguides

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High harmonic generation (HHG) is a nonlinear process in which odd multiples of a fundamental driving field are produced when an intense laser pulse is focused into a low density gas. HHG is an attractive source of coherent, tuneable light with wavelengths in the XUV and soft X-ray range and has found a broad range of applications in ultrafast physics and imaging. However, due to the phase mismatch between the driving and generated fields, the intensity of the generated harmonics oscillates as a function of propagation distance, z, between 0 and some maximum value. One way of overcoming the problem of phase-mismatching is quasi-phase matching (QPM), in which harmonic generation is suppressed in those regions in which the locally-generated harmonics are out of phase with the harmonic beam. Here we propose a new QPM technique – polarization beating QPM (PBQPM) – which utilizes polarization beating in a birefringent waveguide to modulate the generation of harmonics. The key
advantage of PBQPM is its simplicity compared to other QPM techniques. The only requirement is a birefringent waveguide with a suitable value of the birefringence. It is well known that the single-atom efficiency of HHG depends sensitively on the polarization of the driving laser field which arises from the fact that the ionized electron must return to the parent ion in order to emit a harmonic photon. In PBQPM, a birefringent waveguide is used to generate beating of the polarization state of a driving linearly-polarized driving laser pulse, where the polarization beats from linear to elliptical to linear and so forth, thereby modulating the harmonic generation process. QPM will occur if the period of polarization beating is suitably matched to the coherence length of the harmonics. The performance of this scheme as a function of experimental parameters is investigated.

**Imaging systems**

**Interrogating 3D structure of optically deformed suspensions**

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Given favourable conditions (moderate to large refractive index mismatch, maintained ultra-low surface tension regime), optical forces can be sufficient to manipulate the 3D shape of soft matter suspensions.

There are a number of techniques which may be used to generate spatially complex optical landscapes and thereby to control the shape of such deformable suspensions; in all cases it is necessary to determine the agreement between the intended and the resultant shape.

We present comparative experimental results for a number of through-objective 3D interrogation techniques that have been applied to the visualisation of optically deformed ultra-low surface tension oil-in-water emulsion droplets. We discuss the possible application of these techniques to a wider range of microscopic 3D visualisation applications, including biological imaging, and the fundamental ambiguities and other limitations with regard to e.g. reconstruction of sparse vs dense fields of suspensions.

**Analysis of aberrations in STED microscopy**

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Stimulated emission depletion (STED) microscopy is a fluorescence technique that achieves resolution beyond the diffraction limit by using a high intensity shaped focal spot to deplete the excited fluorescence around the focal region, resulting in a sub-diffraction point spread function (PSF). The imaging properties and PSF of a STED microscope depend most critically upon the intensity profile of the depletion pattern. The intensity profile of the ring-shaped depletion beam is dependent upon the phase aberrations present in the microscope. Aberrations also affect the excitation and detection paths, although these have only a secondary effect on image quality. We present a theoretical and numerical analysis of the effect of phase aberrations in STED microscopy. Using Zemike polynomials to model the phase in the pupil plane of our imaging system, we rigorously derive the effects that single and multiple combinations of Zemike modes have on the shape and intensity of the STED depletion pattern and consequently the imaging properties of the microscope. We investigate the effects these aberrations have when using different methods of generating the STED depletion pattern, i.e. a helicoidal phase screen for xy confinement of the PSF or top hat phase screen for xyz confinement.
Image processing for spinning-disk, wide-field optical sectioning microscopy

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Spinning Disk microscopy is a structured illumination microscopy technique capable of producing wide-field optically sectioned images in real-time. A disk etched with a pattern is placed in critical illumination and return light is imaged to 2 separate cameras: one containing wide-field plus confocal information, and the other containing wide-field minus confocal. A confocal image can then be recovered by subtracting the camera frames from each other. However, sub-pixel registration is needed for this operation and a simple global affine transformation is insufficient, with distortions in the optical systems often requiring true elastic registration.

Here we describe a method for high-speed registration of images using the graphics processing unit (GPU) in OpenGL. This technique relies on the ability of the GPU to innately perform affine transforms and interpolations quickly, and uses a custom pixel shader to enable image subtraction during the drawing process. In addition, a technique is employed for flatfield correction which rectifies differences in brightness between both images and also vignetting or other brightness artefacts. Overall raw frame processing rates of over 200 fps are easily achievable for 1.3MPixel images on even modest hardware (Geforce 320M is used here), though in practice this is limited by the bandwidth of the camera bus.

Optical eigenmode imaging

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Structured illumination or higher order beams have found many applications in microscopy, plasmonics, metamaterials and more generally optical interactions. Most generally, it consists in the creation of optical fields that have special properties with respect to a specific interaction. Higher order beam, such as the Airy beams, Bessel beams and Laguerre-Gaussian beams show particular usefulness in specific circumstances. However, the general question arises of the existence of a beam profile or structured illumination for each device or interaction considered. Here, we build on the optical eigenmode method to show that it is possible to define specific beams that optimally probe the optical properties of a sample reconstructing its 2D image from the photocurrent of a single detector. We further study the resolution limit of this approach, its aberration correction capabilities, imaging through diffuse media and its applicability to achieve optimal structured illumination for 3D imaging.

Normalised ghost imaging

B Sun, S Welsh, M Edgar and M Padgett
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Classical ghost imaging (GI) is an imaging technique using correlation measurements of classical pseudo-thermal light. A series of random light patterns are used to illuminate an unknown object, for which the reflected or transmitted light is measured using a single element detector. The measured light intensity for each speckle pattern can be utilized within iterative GI algorithms to reconstruct an estimate of the unknown object. These algorithms are a useful resource for imaging where alternative techniques are required in the future.

We have performed an experimental comparison between different iterative GI algorithms. Generally in GI, the speckle patterns are separated into two arms, the object arm where the object and single element detector are located, and the reference arm where a CCD camera is used to capture the speckle patterns. We use a computer-controlled spatial light modulator (SLM) to generate random, but known, speckle patterns, removing the
requirement for a CCD camera in the reference arm and reducing the number of components necessary for GI experiments. A single element detector is used in the reference arm to monitor the incident light intensity and normalize the object intensity. We show by using this normalised object intensity in the traditional GI algorithm (TGI), the signal-to-noise ratio (SNR) is dramatically increased, especially for transmissive objects. We call this algorithm Normalised Ghost Imaging (NGI). Finally we adopt this NGI method in compressive ghost imaging also showing an increase in SNR in the reconstruction.

Diffractive optics

Characterisation of a liquid crystal spatial light modulator and its application in diffractive optics
T Lu, B W Wang, B Robertson and N Collings
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Liquid crystal on silicon (LCOS) devices are becoming a basic enabling technology for real-time phase-only holography for manipulation of laser beams by diffraction. We describe two techniques to measure the phase retardation and birefringence of liquid crystals (LCs) and hence investigate the phase response of the liquid crystal spatial light modulators (LCSLMs). One of the commercial interests of these devices in recent years has focused on reconfigurable add-drop multiplexers (ROADMs). The ROADM network contains an optical switch which can selectively add or remove a given wavelength to the wavelength multiplexed data stream. This paper proposes a compact design of the switch with diffractive gratings on the LCSLMs to access and manipulate 4 different channels with each channel modulating a different telecom wavelength.

Multiple NUV femtosecond laser beam direct writing of volume Bragg gratings
D Liu, Z Kuang, W Perrie, G Dearden, S Edwardson and K Watkins
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Presently, no Spatial Light Modulator (SLM) based on nematic liquid crystals operates in the UV near 355 nm due to photodegradation of the liquid crystal or the polymer alignment layer with such high photon energy. Thus, exposure at wavelengths shorter than 400 nm combined with high peak intensity risks irreparable damage and possible device failure. By placing a thin BBO crystal immediately after an SLM, the first order diffracted NIR components at 775 nm can be converted to parallel NUV beams at 387 nm, avoiding this potential problem while simultaneously reducing the order of non-linear absorption for Δn structuring.

Parallel Δn structuring with 18 NUV beams inside poly(methyl methacrylate) is demonstrated. This procedure requires careful attention to phase matching of multiple beams and opens up dynamic parallel processing at UV wavelengths. By overlapping filamentary modifications, an efficient, stable volume grating with dimensions $5 \times 5 \times 2.0$ mm$^3$ was fabricated in 18 minutes and reached 70% first order diffraction efficiency at the Bragg angle.

Design and fabrication of nanostructured micro and diffractive optics
A Waddie, R Buczynski, J Nowosielski and M Taghizadeh
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The stack-and-draw method, used in the fabrication of photonic crystal fibres, is ideally suited to the development of high NA micro-optical devices. These components, which exploit first and second-order effective medium theories and vectorial domain EM simulation methods, rely on the creation of all-glass nanostructures with features significantly below the wavelength of the incident light. These nanostructures, which are typically in the 25-100nm
range, produce a component with a refractive index variation determined by the local (on the order of the wavelength of incident light) relative distribution of the two constituent glasses. In order to ensure a high degree of fidelity between the initial macroscopic pre-form and the final drawn-down micro-optic, the constituent glasses must be well matched both mechanically and thermally. To date two main families of glasses which satisfy these conditions have been used in the fabrication of a range of different micro-optical components – NC21A/F2 and SF6/LLF1. The customised NC21A and LLF1 glasses were developed by R. Bucynski within the Glass Laboratory of the Institute of Electronic Materials (ITME) in Warsaw, Poland.

In this paper, we will present the design and fabrication details of a number of different nanostructured micro- and diffractive optical elements using both of the glass families. These components - high NA lenses, fan-out diffractive elements and artificially birefringent material – give a comprehensive demonstration of the flexibility of the nanostructuring technology and point to further potential applications for this micro-optics platform technology.

**Cascade conical diffraction**

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Propagation of light along an optic axis of a crystal depends on the symmetry properties of the crystal. The beam does not change if the crystal is optically uniaxial, since it will travel along the unique optic axis. However, upon propagation in a biaxial crystal (cut in a particular way) its intensity and polarisation distribution undergo a unique transformation. The beam will evolve as a hollow slanted cone, and at the exit surface it will refract as a hollow tube, with each set of two diagonally opposite points being orthogonally polarised. This phenomenon is known as "conical diffraction/refraction" [e.g., Proc R Soc A 462, 1629 (2006)].

Recently, M. V. Berry calculated the transmitted field for a cascade of N biaxial crystals, with their optic axes parallel but with arbitrary orientation about this axis, and arbitrary strengths [J. Opt. 12, 075704 (2010)]. He predicted that the focused pattern should consist of the superposition of \(2^{N-1}\) single-crystal concentric conical diffraction patterns, whose radii are combinations of those from the individual crystals in the cascade.

I will present experimental results on the cascade conical diffraction phenomenon from up to four crystals. The experimental observations are in full agreement with Berry's theoretical predictions.

**Quantum information II**

Raman effects on correlated photon-pair generation from a chalcogenide waveguide  
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University of Sydney, Australia

Correlated photon-pair generation at telecommunication wavelengths is attractive for quantum communication, requiring sources that are both bright and low noise. Although sources based on spontaneous parametric down conversion in periodically poled lithium niobate (PPLN) waveguides, and spontaneous four-wave mixing (SFWM) in silicon platforms have been widely studied, PPLN requires bulky temperature control for phase matching and silicon suffers from two-photon absorption. Recently we demonstrated an As\(_2\)S\(_3\) chalcogenide glass waveguide as an attractive alternative platform for correlated photon-pair generation but was limited in performance by significant spontaneous Raman scattering (SpRS) noise photons within the SFWM bandwidth.

Here we investigate the impact of cooling on SpRS in an As\(_2\)S\(_3\) fiber photon-pair source by measuring the photon statistics of correlated pair generation, showing a 7-fold increase in the coincidence-to-accidentals ratio at 77K
compared to room temperature. We employ a new technique to directly measure SpRS at large detuning from the pump. The results show cooling the chalcogenide can reduce the SpRS and improve the photon statistics for frequencies close to the pump. We finally demonstrate that careful post-tuning of the waveguide length allows efficient pair generation in a low Raman gain window, far detuned from the pump, with no need for cooling.

Experimental realisation of Shor’s quantum factoring algorithm using qubit recycling

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Quantum algorithms are computational routines that exploit quantum mechanics to solve problems exponentially faster than the best classical algorithms. Shor’s quantum algorithm for fast factoring of composite numbers is a key example and the prime motivator in the international effort to realise a quantum computer. However, due to the large number of resources required, to date, there have been only four small scale demonstrations. Here we address this resource demand and demonstrate a scalable version of Shor’s algorithm in which the n qubit control register is replaced by a single qubit that is recycled n times: the total number of qubits is one third of that required in the standard protocol. Encoding the work register in higher-dimensional states, we implement a two-photon compiled algorithm to factor N = 21. Significantly, the algorithmic output exhibits structure that is distinguishable from noise, in contrast to previous demonstrations. These results point to larger-scale implementations of Shor’s algorithm by harnessing substantial but scalable resource reductions applicable to all physical architectures.

Cluster state generation using fibre sources

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In one-way quantum computation, a multipartite entangled state, the cluster state, is used as a resource for running a quantum algorithm represented by a sequence of single-qubit measurements [1]. In this experiment we generate a four photon star-cluster state, and use it to perform universal quantum logic.

We have previously demonstrated a pair-photon source based on four-wave-mixing in photonic crystal fibre, which utilizes an intrinsically pure-state phase-matching scheme to avoid spectral correlations, generating a signal at 625nm and an idler at 860nm not requiring narrow filtering with associated loss [2]. Using a Sagnac loop configuration we detected pairs of polarization-entangled photons. We have also characterised a fusion operation which uses a parity measurement to project two photons from separate sources onto an entangled state, allowing the generation of larger entangled states from multiple pairs of photons [3].

Using two entangled sources and performing the fusion operation on the signal photon from each source, we produce four photons entangled in a GHZ state, locally equivalent to a star-cluster. We will present a full characterisation of the state using polarization tomography, and process tomography for universal quantum computing.

Photonic orbital angular momentum for quantum information processing

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The photonic orbital angular momentum (OAM) has a great potential in the quantum information field, as it provides a natural choice for implementing single-photon qudits, the units of quantum information in a higher dimensional space. Moreover, the combined use of different degrees of freedom of a photon, such as OAM and spin, enables the implementation of entirely new quantum tasks. Recently we introduced and tested experimentally a series of optical schemes for the coherent transfer of quantum information from the polarization to the OAM of single photons and vice versa (Nagali et al., Phys.Rev.Lett. 103, 013601 (2009)). All our schemes exploit a new optical device, the q-plate, which enables the manipulation of the photon OAM driven by the polarization degree of freedom. We have combined the polarization and OAM in order to experimentally implement single-photon ququart states, i.e. quantum states in dimension \(d = 4\). Such ququart can be exploited for quantum cryptographic purposes, as well as to carry out fundamental tests of quantum mechanics. In particular we report the experimental observation of an impossible-to-beat quantum advantage on a four dimensional quantum system, compatible with the maximum advantage allowed using post-quantum resources (Nagali et al., Phys.Rev.Lett. 108, 090501 (2012)). Finally we demonstrate how the adoption of the polarization and the OAM allow to implement rotational-invariant qubits, which play a key role in misalignment free communication protocols. Such qubits are robust against atmospheric turbulence and noise related to the transmission channel, thus providing a good candidate for long distance communication.

Advances in laser science

Spectral dependence of Raman gain in diamond

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The recent substantial improvement in the optical quality of synthetic diamond means that it is now a credible material for solid-state laser engineering. The excellent thermo-mechanical properties of diamond are best exploited if diamond is used as a laser gain material in its own right. This can be achieved by building a Raman laser, taking advantage of the material’s high Raman gain. In this report, the magnitude of the Raman gain coefficient in high-optical quality synthetic single-crystal diamond is measured using a pump probe technique and the dependence of the gain on orientation and, in particular, wavelength will be discussed. A Raman gain coefficient of 43±5cm/GW is measured at a pump wavelength of 532nm for light propagation along the \(<110>\) direction with the pump and probe polarization along the \(<111>\) direction in diamond: pump-probe data confirms that this orientation accesses the highest gain. This compares to a value of 21±3cm/GW previously measured at a pump wavelength of 1064nm. Measurements of the Raman gain at other wavelengths will also be reported and the future prospects for high power diamond Raman lasers discussed.

Active Q-switched Nd:YAG laser using MEMS micromirrors

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University of Strathclyde, UK

In this paper we present the latest investigation on the use of electrostatic resonantly actuated Micro-Electro-Mechanical Systems (MEMS) micromirrors as active Q-switch elements in diode-pumped solid-state lasers. Micromirror-based Q-switches have the potential to become a low-cost and miniature replacement to traditional acousto-optic and electro-optic Q-switches.
The MEMS mirrors were fabricated using a commercial multi-user silicon-on-insulator process with a single 25um thick layer. Using a 200Vp-p signal, the electrostatic comb-drive was actuated to generate a torsional resonant mode of the 0.7mm-diameter silicon micromirror. A maximum full optical scan angle of 39° was measured at a frequency of 8.82 kHz. A 500nm thick gold coating was deposited on the silicon micromirror surface resulting in a measured reflectivity of 87% at 1064nm, therefore enabling intra-cavity laser use.

A laser-diode side-pumped Nd:YAG resonator was built using a 3 mirror configuration, with the MEMS micromirror as a cavity end-mirror, and a 20% output-coupler at the other end. Q-switched operation was achieved with average output powers of 65mW at a pulse repetition rate of 17.64Hz. The pulse durations measured at 105 ns was within 5% of the theoretical minimum pulse width expected in this type of laser configuration. The average output power was limited by thermal damage to the gold coating on the micromirror. The latest results on the power-scaling of these lasers, including results achieved using alternative dielectrically-coated MEMS micromirrors, will be presented and the challenges faced by this technique discussed.

**High power femtosecond pulsed amplifier combining Ytterbium-doped materials in a MOPA configuration.**

C Ramirez, I Thomson, C Leburn, D Hall, D Reid and H Baker

Heriot-Watt University, UK

We report the construction of a diode-pumped YbKYW-Yb:YAG femtosecond master oscillator power amplifier (MOPA) operated in the near infrared region (1030 nm).

The master oscillator was built using a 26-W laser diode pump emitting at 980 nm focussed into a 1.5 at.% Yb:KYW Brewster-cut crystal. Three GTI mirrors were used to compensate for dispersion and a SESAM to generate a stable modelocked pulse train from the laser. An optimization of the output coupler was made to match the oscillator wavelength with the amplifier at 1030 nm. Currently the seed laser is capable of generating over 4.5 W of average power at a wavelength of 1030 nm with slope efficiency greater than 30%. Pulses as short as 460 fs and 3 nm bandwidth have been observed at a pulse repetition frequency of 53 MHz.

This seed laser was coupled into a Yb:YAG planar waveguide power amplifier. A 6-bar diode laser stack capable of generating 400 W was used to single side pump the 2% doped Yb:YAG waveguide of 150 μm thickness, which gives an incident pump intensity of 22 kWcm$^{-2}$.

With the seed laser in modelocked operation it was possible to generate 50 W when the seed light was folded through the amplifier 5 times at a repetition frequency of 53 MHz. The pulses after the amplifier have been measured at ~700 fs.

**Highly-efficient 1-GHz repetition-frequency femtosecond Yb:KYW laser for supercontinuum generation**

T Schratwieser, C Leburn and D Reid

Heriot-Watt University, UK

We report on a 1.024 GHz repetition-rate femtosecond Yb:KYW laser utilising a semiconductor saturable absorber mirror for self-starting mode-locking. Pumping was accomplished using two commercially-available polarisation-maintaining fibre-pigtailed laser diodes operating at 980 nm, stabilised with fibre-Bragg gratings, and focussed to a spot radius of 17 μm (1/e$^2$ intensity) in the gain crystal with an overall power of 1274 mW. Using a 10-at.%-doped Brewster-angled Yb:KYW crystal, an output coupler of 5% transmittance, and a double-passed GTI mirror with a total GDD of ~2600 fs$^2$ in a z-fold, asymmetric astigmatically-compensated configuration, 770 mW was achieved with exceptionally high optical-to-optical efficiencies of 61%, and slope efficiencies of 69%. The sech$^2$ pulses had a spectral bandwidth of 3.8 nm. Interferometric autocorrelation yielded pulse durations of 278 fs.
We performed relative intensity noise (RIN) measurements of the system and one of the laser-diode pumps. Below frequencies of 1 kHz the Yb:KYW noise exceeded the pump noise due in part to external acoustic noise coupling into the system, whilst at above 1 kHz the inverse was true because the upper-state lifetime of Yb:KYW (0.3 ms), damping any modulations of faster timescales. We investigated spectral broadening by launching 360 mW of the light into a 3-metre photonic crystal fibre and measured a broadened spectrum of >400 nm. Pre-compression of the pulses is expected to further improve the bandwidth.

**Broadly tunable ultrashort pulse quantum-dot based laser with different diffraction grating orders**

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The broad gain spectrum from quantum dot (QD) materials is very attractive feature for the development of broadly tunable lasers, broadband amplifiers and ultrashort pulse generation. It has been demonstrated, quantum-dot external-cavity passively mode-locked lasers (QD-ECMLLs) are excellent candidates for versatile ultrashort pulse generation. Due to the flexibility that external-cavity mode-locking configurations can offer a broad tunability for both the repetition rate and the wavelength could be achieved. Likewise, quantum-dot semiconductor optical amplifiers (QD-SOAs) are suitable for the broadband pulse power amplification.

In this paper, a tunable master-oscillator power-amplifier (MOPA) picosecond optical pulse source using all chirped QD structures was investigated. The MOPA system consisted of a QD-ECMLL and a tilted tapered QD-SOA. A comparison between 1<sup>st</sup>-order grating diffraction and 2<sup>nd</sup>-order grating diffraction for this tunable QD-MOPA were further investigated. The maximum fundamental mode-locking (FML) wavelength tuning range of nearly 100 nm (from 1187 nm to 1283 nm) has been achieved under a 900 mA current applied on the gain chip with a 2<sup>nd</sup>-order grating diffraction.

In this paper we also demonstrated that the peak power spectral density achieved with the 2<sup>nd</sup>-order diffraction (Max.: 31.4 dBm/nm) is much higher (~2-4 dB) than that from the 1<sup>st</sup>-order diffraction under the similar conditions. The narrowest optical spectrum width has been achieved from the 2<sup>nd</sup>-order diffraction, and the narrowest pulse of ~13 ps was found for the setup with the 1<sup>st</sup>-order grating diffraction. The wavelength tuning range from both orders can be increased by increasing injection current of the gain chip without deteriorating the stability of FML.
Tuesday 4 September

Optical biosensing and bioimaging

Organic distributed feedback biosenser

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Organic, or ‘plastic’, lasers have a number of attractive attributes for biosensing, which include:

- interfacing compatibility with biological molecules
- mechanical-flexibility enabling integration with standard assays
- high-throughput and miniaturisation potential.

While these attributes are recognised, little work has been done thus far in the biosensing domain apart from one demonstration using a dye-doped laser structure\(^1\).

In this paper, a refractive index optical sensor based on a vertically-emitting distributed-feedback organic laser is demonstrated. The device structure consists of an epoxy base, imprinted with a one-dimensional diffraction grating, and a blue-emitting organic gain medium (oligofluorene truxene\(^2\)). The laser wavelength depends on the refractive index of the material in contact with the light-emitting surface and can therefore be used to monitor changes occurring at this surface.

The sensing capabilities are demonstrated by immersing the device in glycerol-water solutions of different volume ratios, hence different refractive indices. The organic laser emission wavelength is found to redshift >5 nm for increasing glycerol solution refractive index, corresponding to a refractive index detection sensitivity of 21 nm/refractive index unit. The results are compared to, and shown to agree with, a theoretical model. Adsorption effects and detection of large molecules will also be presented.


Random-access spectral imaging

R Kelleher and A Harvey

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Imaging spectrometry is a powerful analytical tool used in many applications from remote sensing to microscopy and which encompasses a broad range of technologies. The most common approaches rely on building up a hyperspectral datacube piecewise by time-domain scanning in either the spatial or spectral dimensions. However due to their time-sequential nature these techniques are ill-suited for effectively monitoring of dynamic events, such as scenes with a lot of natural background motion or fast moving objects. Time-resolved spectral imaging devices generally trade-off resolution to enable this snapshot data capture capability. Described here is a prototype spectral imager that uses a random-access approach to spectral imaging to overcome the limitations of traditional instruments. This is achieved by using a spatial light modulator (SLM) to enable the construction of a two channel system that has an observation arm used to select interesting pixels from across the field of view; these are then switched to the spectroscopy arm where a dispersive spectrograph is used to determine their spectra. In most practical scenes there are relatively few points of interest, by filtering the uninteresting points from the spectral arm with the SLM, the size and complexity of the data set and any subsequent processing is therefore reduced. Multiple
arbitrary points across the field of view can be chosen and measured simultaneously. Demonstrated here are the capabilities of the system, including results obtained via an endoscope.

High-speed light sheet microscopy for imaging 3D behaviour during Dictyostelium Discoideum development
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Coordinated Cell motility is one of the core mechanisms of tissue dynamics underlying development and disease. It study requires novel imaging methods that allow observation of labelled cells in tissues for long periods of time. Existing imaging methods such as wide-field, confocal, multi-photon and deconvolution microscopy often result in excessive photo-damage. Light-sheet microscopy provides a novel imaging method that allows long term high resolution imaging of cell behaviours during development of many different types of embryos ranging from Drosophila to mouse. We have built such an instrument to study tissue dynamics during gastrulation in the chick embryo and during multicellular development of the social amoebae Dictyostelium. In our approach we have combined laser scanning (DSLM) with high-sensitivity high-speed scientific CMOS camera that allows for acquisition speeds exceeding 20 frames per second. High axial resolution is achieved by use of um thin light-sheet and high NA water immersion imaging objective. In this talk we will present results of our study of 3D behaviour of Dictyostelium cells during aggregation and mound formation stage.

Verstatile volumetric imaging by oblique plane microscopy
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Oblique Plane Microscopy (OPM)\(^1\) is a light sheet microscopy technique that uses a single high numerical aperture microscope objective to both illuminate a tilted plane within the specimen and to collect fluorescence from the illuminated plane via the insertion of correction optics between the primary microscope objective and the CCD camera. OPM can be used to image conventionally mounted specimens on coverslips, tissue culture dishes or multwell plates and has the low out-of-plane photobleaching and phototoxicity of selective plane illumination techniques. Since an optically sectioned image is obtained without the need for moving parts, the system is able to run at high speeds limited only by the frame rate of the camera.

The Ca\(^{2+}\) dynamics of individual cardiac myocytes loaded with Fluo-4 are imaged using OPM at 29 volumes per second\(^2\), allowing the Ca\(^{2+}\) concentration throughout the cell volume to be monitored in real-time. The imaging of GFP-labelled zebrafish embryos is achieved by a stage scanning acquisition modality, allowing entire embryos to be imaged in tens of seconds. The technique has been applied to the tracking of tumour growth in early stage embryos.

Preliminary results reporting the use of scientific CMOS cameras to allow simultaneous 2 channel imaging and to further increase the imaging rate and number of image voxels will also be presented.

Quantum dot nano-thermometry for optofluidic devices

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Temperature is a key physical factor affecting intra-cellular dynamics. Investigating a live cell’s response to local changes in temperature can offer new insights towards the development of temperature-based therapeutic and diagnostic applications. Optofluidic micro-environments can be tailored to mimic in vivo conditions and offer a non-invasive method to achieve such measurements in vitro. The small dimensions of optofluidic channels introduce complications in the accurate determination of their internal temperature making traditional "contact" methods of temperature measurement futile. We demonstrate the use of single – walled carbon nanotubes as nano-heaters and semiconductor quantum dots as probes for temperature sensing within an ultrafast laser inscribed optofluidic device with a monolithically integrated near-infrared waveguide. The spectral dependence of laser-induced thermal increments inside the locally illuminated optofluidic device is evaluated to illustrate its significance in on-chip cell manipulation. High-resolution spatio-thermal imaging is performed using confocal scanning microscopy to reveal the magnitude and spatial distribution of the thermally effected region inside the device, achieving a lateral spatial resolution of 0.6 µm and thermal sensitivity of 0.1 °C. This study presents a rapid, non-intrusive optofluidic temperature sensor platform and elucidates how light-induced thermal loading can be adapted for applications such as targeted cell hyperthermia.

Advances in THz technology I

Measurements of THz pulse delay in sooty flames

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We report on pulse delay measurements, by THz Time-Domain Spectroscopy, of ultrashort broadband THz pulses through flames in the presence of soot. The laminar diffusion flame is contained in a specially designed high-pressure burner with THz-capable windows. The time-domain waveform of the THz electrical field is recorded, followed by a standard fast Fourier transformation to yield the spectral amplitude and phase. The parameter envelope of the methane-air co-flow, for a fixed 0.2 l/min methane flow rate, varies from 0 to 15 l/min air flow rate. Within the parameter envelope, cold (without ignition) and hot (flame) co-flows were investigated. A number of absorption lines are observed in the range 0.5-3THz, due to water vapour. By applying a previously introduced procedure for calculating delay variations caused by refractive-index change (IEEE Sensors J vol 11, issue 10, p.2507, 2011), we demonstrate that the THz pulse delay increases linearly with the air flow rate until 10 l/min and saturates for higher flow rates. This is accompanied by a decrease in the integrated peak height with the air flow. These observations are interpreted in terms of the probe beam behaviour at the cold/hot gas boundary, while the width of the hot gas area decreases with the flow rate.

Possible options to utilise the spectral amplitude and phase of the transmitted THz radiation are briefly discussed.
**THz nanodevices based on layered superconductors**

S Savel’ev  
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Electromagnetic waves in layered superconductors (Josephson plasma waves (JPWs)) propagates if their frequency is above the Josephson plasma frequency, which being in the terahertz (THz) range.

We show [1] that a moving Josephson vortex (JV) in spatially modulated layered superconductors generates out-of-plane THz radiation. This radiation can be emitted to the vacuum without the impedance mismatch.

We show [2] that JV lattices can produce a photonic band gap structure (THz photonic crystal) with tuneable forbidden-frequency-zones controlled by the in-plane magnetic field. These proposals are potentially useful for controllable THz filters.

We predict [3] surface JPWs propagating along sample surfaces below the plasma frequency. These predicted surface Josephson plasma waves can be excited by incident THz waves, which could be used for THz detectors.

We predict [3] the propagation of nonlinear JPWs with frequencies below the plasma frequency. In analogy to nonlinear optics, these waves exhibit numerous remarkable features, including the slowing down of light, self-focusing, and wave mixing.

We derive [4] a quantum field theory of THz Josephson plasma waves (JPWs) in layered superconductors. This theory suggests a new class of one photon THz emitters and detectors.


**Tunable monolithically integrated photonic THz heterodyne system**

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In this work, we present the tuning performance of a high-purity, heterodyne photonic THz source for coherent systems, demonstrating 4 GHz continuous tuning range at a given THz frequency and the possibility of a 300 MHz linear sweep. The monolithically integrated source consists of two OPLLs integrated on the same chip. The two distributed Bragg reflector (DBR) slave lasers are phase locked to lines of an external optical frequency comb generator to create frequencies from 25 GHz (comb spacing) to 1.6 THz (comb span). The phase lock is realised by detecting the heterodyne between the master and the slave on the integrated photodetector and comparing it with an external RF source in the phase detector to generate an error signal. The advantage of the offset phase lock loop system is that it enables continuous tuning of the source between the comb lines. We demonstrate, for the first time, the capabilities of the monolithic source for a continuous linear frequency sweeps of 300 MHz and tuneability between comb lines from 2 GHz to 6 GHz offset. The limitation of the tuning range was due to variations in the DC level of the control signal from the integrated OPLL, which affected operation of the digital electronics exclusive-or phase detector on the external circuit board. The phase noise was < -90 dBc/Hz for offsets larger than 10 kHz.
Deeper insight into material optical properties extraction procedure from THz TDS in a transmission mode

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THz Time Domain Spectrometry probes the complex polarization-response of materials. The improvement of analysis and processing of the data from THz TDS are ongoing as there is no generally excepted standard of optical constants determination. Extraction procedure has commonly been done before now by iteratively varying material parameters in order to achieve a match between experiment and a theoretical transfer function (TF). The poly-root behaviour of a TF is emphasized for measurements with reflections in time domain. It results in critical dependence of the final parameters on the initial guesses required for the iterative fitting procedure. This study provides a comprehensive analysis of the influence of the initial guesses on extracted material parameters, which has not been done yet. The instances when the usual algorithms fail to predict correct values of parameters are discussed and the way to overcome this drawback is proposed. In addition various ways of representation of multiple reflections inside the sample (Fabry-Perot effect) are analyzed. The uncertainty of final parameters resulting from misinterpretation of Fabry-Perot term in TF is pointed out and quantified for the first time. Finally, a clear distinction is made between the simplistic extraction procedure and the enhanced one, in terms of associated uncertainties of material parameters.

THz torch technologies for 21st century applications

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Terahertz systems are notoriously very expensive, from complete systems down to individual active devices and passive components. For this reason, there are few ubiquitous applications in the far-infrared (0.3 to 30 THz) and mid-infrared (30 to 120 THz) parts of the electromagnetic spectrum.

An ultra-low cost intruder alarm was demonstrated in 1965 [1]. Here, a thermal noise source was made from a domestic torch with exposed photographic film filter and the front-end receiver employed a bipolar transistor with 5 cm diameter lens; breaking the incoherent infrared beam triggers the alarm.

Very recently, using modern ‘THz Torch’ technologies, short-range wireless links for single-channel data transfer [2] and frequency-division multiplexed spread-spectrum [3] applications were demonstrated.

The “THz gap” represents the upper frequency limit of conventional electronics and the onset of photonics; portrayed as the part of the electromagnetic spectrum between 0.1 and 10 THz [4]. However, the ultra-low cost ‘THz Torch’ technology combines electronics and photonics, through the use of thermodynamics between ca. 10 and 100 THz.

With the large amounts of freely available spectrum and high atmospheric attenuation, there is an extremely low probability of intercept and code grabbing, making this technology ideal for security applications. Those that do not require high data rates but must be ultra low cost (e.g. secure RFID, smart key fobs and absorption spectroscopy) can be manufactured in large volumes, potentially opening-up the THz spectrum.

This presentation will explore the many facets of re-inventing the 19th century flashlight for 21st century applications.
Quantum information

Observation of Hong Ou Mandel interference as a function of Berry's phase

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Emerging models of quantum computation driven by multi-photon Hong Ou Mandel interference, while not universal, may offer an exponential advantage over classical computers for certain problems. Implementing these circuits via geometric phase gates could mitigate requirements for error-correction to achieve fault tolerance while retaining their relative physical simplicity. We report an experiment in which a geometric phase is embedded in an optical network with no closed-loops, enabling Hong Ou Mandel interference between two photons as a function of the phase.

Analysis of detector performance in a GigaHertz clock rate quantum key distribution system

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Quantum key distribution (QKD) is currently the only means by which two parties can distribute a cryptographic key with verifiable security. Since the first demonstration of QKD, experimentation has mainly focussed on increasing the transmission distance, clock-rate and/or the key exchange rate. Much research has taken place on optical fibre based systems operating at wavelengths in the regions around 1310 nm and 1550 nm where the attenuation of standard telecommunications fibre is low. This reduced attenuation can lead to increased transmission length when compared to systems at shorter wavelengths. The semiconductor detectors used at longer wavelengths typically suffer from high dark rates and after-pulsing probability which can limit the maximum achievable clock-rate. At shorter wavelengths there is a wider availability of different single-photon detector types.

We will present a detailed analysis of a gigahertz clock rate environmentally robust phase-encoded QKD system utilising several different detectors, including a prototype single-photon avalanche diode. The system operates at a wavelength of 850 nm to permit the comparison of several different detectors. A general-purpose theoretical model has been developed and predictions are made for realistic detector developments. The theoretical model will predict how detector parameters can be optimised to maximise key exchange rates.

High efficiency near field microwave quantum key distribution

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Microwave communications have an almost ubiquitous presence in modern communications systems and are an essential element of computer networking. It is therefore highly desirable to create encryption schemes using microwaves as the central element. Quantum cryptography using single photon exchange is one of the few systems that are capable of creating and distributing genuinely secure cipher keys[1, 2]. Microwave photons are however extremely difficult to create and detect[3,4] making them unsuitable for this form of quantum key distribution. However, over the last decade, an alternative scheme for quantum key distribution using continuous variables has emerged[5], which is readily applicable to microwaves. Here we demonstrate secure near field microwave key distribution using off the shelf components at 2.4GHz (WiFi band) using a quantum channel and trusted classical communication to create a secret key. Eve, can also detect the signal and has a variety of attacks that she can apply on the quantum channel. However, because she cannot accurately clone the quantum state, each attack can...
be efficiently thwarted by the two way communication protocol which is designed to look for irregularities that come from signal interception and tampering.


An experimental demonstration of quantum digital signatures
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The distribution and authentication of digital signatures is becoming increasingly relevant in the modern information age. Digital signatures allow secure signing of documents so that others can be sure of their origin and authenticity, with security that most often relies on unproven assumptions regarding the computational difficulty of reversing certain "one-way" mathematical functions. Standard digital signatures require two keys - the public key (transmitted to all parties) and the private key (retained by the sender), which form a key pair. The key generation algorithm is designed in such a way that anyone having a public key can certify that a message originates from the sender and has not been tampered with. Signing a message can only be done using the private key, and is thus an action available to the sender alone.

Given sufficient computational resources, or through future advances in computational or mathematical sciences, present standard classical digital signature systems can be broken. On the other hand, schemes for quantum digital signatures, where the public keys are quantum states, can be made secure based on information-theoretical limits and quantum mechanics.

We have constructed an experimental system to permit the sharing of quantum digital signatures and carried out a comprehensive series of experiments using it with a series of different operating parameters - the first experiments of this type (to the best of our knowledge). We will present experimental results from this system under a variety of different conditions and verify the security.

Entanglement detection in hybrid optomechanical systems
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We study a device formed by a Bose-Einstein condensate (BEC) coupled to the field of a cavity with a moving end mirror and find a working point such that the mirror-light entanglement is reproduced by the BEC-light quantum correlations. This provides an experimentally viable tool for inferring mirror-light entanglement with only a limited set of assumptions. We prove the existence of tripartite entanglement in the hybrid device, persisting up to temperatures of a few milli-Kelvin, and discuss a scheme to detect it.

Quantum probes for complex systems: applications to quantum simulations

S Maniscalco
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I will describe two examples in which the dynamics of a quantum probe interacting with a complex environment allows to characterize nontrivial properties of the environment such as the occurrence of a quantum phase transition.

I will focus on a quantum dot immersed in an ultracold atomic gases [1] and on a central spin in an Ising model in transverse field [2]. In both cases I will study the information flow between the quantum probe (open quantum system) and the environment. In the first case I will show that from the dynamics of the probe we can identify in a nondestructive way a transition from a 3D to a quasi 2D and 1D Bose-Einstein condensates. In the second case, I will single out a quantity, associated to the probe dynamics only, able to pinpoint the critical value of the renormalized transverse field in correspondence of which a quantum phase transition in the spin environment occurs.

Both examples prove that, under suitable conditions, the dynamics of a quantum probe can be useful to characterize global properties of the complex environment the probe is interacting with, and therefore to probe quantum simulators.


Nonlinear photonics

Nonparaxial refraction laws for spatial solitons at cubic-quintic material interfaces

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The behaviour of light at the interface between different materials essentially underpins the entire field of Optics. In nonlinear photonics, a building-block geometry comprises a spatial soliton incident on the planar boundary between two dissimilar Kerr-type media. Seminal analyses by Aceves and co-workers [Phys. Rev. A 39, 1809 (1989)] were ground-breaking and highly instructive, but they were limited by the assumption of the paraxial approximation. Interface geometries are, in general, intrinsically nonparaxial: angles of incidence, reflection, and refraction (measured relative to the interface in the laboratory frame) may be of arbitrary magnitude.

Sánchez-Curto et al. have proposed a Snell law governing arbitrary-angle refraction of spatial solitons at the interface between different Kerr materials [Opt. Lett. 35, 1347 (2010); 32, 1127 (2007)]. Analyses were facilitated by solution of an underlying nonlinear Helmholtz equation, and they completely lifted the angular limitation that is inherent to paraxial theory.

In addition to angular (off-axis) nonparaxial effects, material considerations are also central to studies of refraction. Here, we extend our early Kerr-based analyses to non-Kerr regimes involving optical media with the classic cubic-quintic nonlinearity [Opt. Quantum Electron. 11, 471 (1979)]. A key result is the derivation of a generalized Snell law, which was obtained through the deployment of exact analytical bistable Helmholtz solitons [Phys. Rev. A 76, 033833 (2007)]. Excellent agreement has been uncovered, across wide parameter ranges,
between theoretical predictions and numerical calculations. Simulations have also identified qualitatively new phenomena, strongly dependent on the beam incidence angle, that were not captured by analysis.

**Continuous-wave intra-cavity Optical Parametric Oscillator**

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We present a continuous-wave intracavity optical parametric oscillator (CW-ICOPO) based upon MgO-PPLN and pumped internal to a diode-pumped Nd:YVO₄ laser capable of producing >100mW of narrow-linewidth radiation over the spectroscopically important 3-4μm band. In order to circumvent the quasi-chaotic relaxation oscillation-like instabilities commonly encountered with this class of device, we include an additional, frequency-doubling nonlinear optical material within the pump-only section of the cavity. The nonlinear loss which this presents to the circulating pump field effects a virtual elimination of the self-induced relaxation oscillation instabilities with very little penalty paid in down-conversion efficiency. We present a thorough characterisation of this effect, the linewidth and tuning performance of the device, and its viability in the context of some preliminary high-resolution spectroscopic measurements.

**Locking of laser cavity solitons**

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Laser cavity solitons (LCS) are transverse, nonlinear, self-localized and dissipative states that possess both translational and phase invariance. Since spatial LCS in broad-area semiconductor lasers have the potential for massive parallelism and the formation of complex arrays, it is important to investigate their interaction and synchronisation properties. Phase-locked bound states with solitons have been predicted in mode-locked lasers for the temporal case and in lasers with saturable absorbers for the spatial case. Corresponding phase-quadrature states have been observed experimentally in fibre lasers.

Here we present an entirely different kind of soliton locking. We demonstrate experimentally and theoretically Adler-type locking and synchronization of spatial LCS in a vertical-cavity surface-emitting laser with an external Bragg grating that provides frequency-selective feedback. In particular we explain the role played by defects resulting from fluctuations during the epitaxial growth process. Besides fixing the position, these defects induce a shift in the LCS natural frequency. The interaction of pinned LCS with different intrinsic frequencies is well described by the Adler locking mechanism that is typical of the synchronisation between two coupled oscillators. We show that strong enough couplings can overcome the natural disorder of the system leading to a synchronous regime characterized by an emission at a common frequency. In the locking regime the phase difference of the two LCS displays an archetypical dependence on the soliton frequency difference with good agreement between theory, simulation and experiment.
Biophotonics

Higher-order aberrations in the human eye cause task-specific degradations to visual performance: A comparison between letter recognition and reading

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The human eye is an imperfect optical system and its refractive elements can distort an incident wavefront. Low-order aberrations (defocus and astigmatism) are routinely corrected, however higher-order aberrations remain that can impair vision. It is important to understand how these aberrations impact vision and what benefit can be attained by correcting them. Here we show that effects of these aberrations are task-specific.

We imposed defocus, coma and secondary astigmatism at five amplitudes in the range 0.5-0.9 μm rms in the rendering of letter stimuli. We measured subjects’ contrast threshold for identification and compared the results to a prediction of the confusability of letters. Single letter recognition shows a relationship with the confusability that is the same for all three types of aberration. Previously we tested the effects of these aberrations on reading performance and showed that defocus and secondary astigmatism gave the same relationship but that coma produced a greater performance loss at a lower confusability value. This impairment is specific to reading multiple letters, but we additionally show that word recognition is not impaired. Instead, coma could cause disruptions to the planning of eye movements, which occurs during the preceding fixation, or crowding effects, which occur when adjacent letters are in close proximity to each other causing a decrease in signal-to-noise ratio and interference in the signal integration processes.

Even for related tasks, such as letter recognition and reading, there are differences between these aberrations. A single measure of acuity is insufficient to fully characterise their effects on vision.

Tracking ophthalmic drugs in the eye using a confocal fluorescence instrument

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We have built a non-invasive instrument based on confocal scanning microscopy for tracking inherently fluorescent drugs in the anterior chamber of the living eye. We have measured the diffusion of Sodium Fluorescein and an active ophthalmic pharmaceutical compound for treating open angle glaucoma, with high temporal resolution of under 25 ms in a cuvette, in vitro porcine eyes and in vivo primate eyes. We have also monitored the naturally occurring fluorescence in living human eyes over the course of a week. In this paper, we demonstrate the capability of the instrument to accurately measure the concentration and location of the fluorescent compound within the anterior chamber of the eye with a precision of 5 μm and an axial resolution of 200 μm. We show that the instrument has high sensitivity and can measure concentrations of < 1 μM / L of compounds with a quantum yield as low as 0.01 with high specificity for the compound of interest. The role of this instrument to measure the efficiency of any inherently fluorescent ophthalmic drug as well as other medication that might create fluorescent compounds in the eye will be discussed. We furthermore will evaluate the possibilities of applying this measurement technique to other areas of research such as skin monitoring.
Correlative fluorescence and label-free optical microscopy of model lipid membranes

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Transient formation of laterally organised nanoscale domains (rafts) within the lipid bilayer is a key aspect of cell membrane biochemistry. To date experimental studies of membrane rafts remain indirect and controversial. Herein we present studies on macroscopic lipid raft analogues in a model system; Giant Unilamellar vesicles (GUVs).

We have produced GUVs up to 100um diameter via the gentle hydration method from dried lipid films. A conventional way in the literature to confirm unilamellarity and macroscopic raft formation is via epi-fluorescence microscopy with labelled-lipids. However fluorescence labelling raises the question if the observed membrane behaviour is real or artefactual, and is subject to photo-bleaching. Here, we present a label-free novel way to characterise GUV unilamellarity via quantitative differential interference contrast microscopy (QDIC). In QDIC, the optical path length difference is measured between two adjacent regions of the specimen. Two images of opposite incident polarizations are combined to produce a normalised image proportional to the partial derivative of the object phase along the shear axis. Numerical integration techniques in Fourier domain are then utilised to recover the optical phase and hence the thickness of the GUV membrane in a quantitative manner. We have also utilised epi-fluorescence with labelled-GUV to demonstrate unilamellarity and directly compared these results with QDIC on the same GUV. Measurements were conducted using a 20x0.75NA dry objective and 1.4NA oil condenser with phase shift introduced by a De-Senarmont compensator. We will present these results alongside fluorescence and Coherent anti-Stokes Raman microscopy measurements characterising the formation of macroscopic rafts.

Heart-stopping moments with zebrafish: real-time optical synchronization for precision imaging and intervention in the beating heart

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We describe a non-invasive technique for real-time synchronized image acquisition within the living, beating zebrafish heart. An important application for this is three-dimensional fluorescence imaging of the heart in vivo, something once considered prohibitively difficult due to the challenges presented by the rapid motion of the beating heart. We present results acquired using our selective plane illumination microscope (SPIM) with heartbeat synchronization. This has biological applications in developmental and functional studies, both for the heart itself and also for high-resolution imaging of surrounding tissue, which also moves in response to the heartbeat. Our system offers high resolution images while minimizing phototoxic damage in fluorescence imaging.

We will also show a unique application of our synchronization system, for precision laser targeting of moving tissue for cell labelling, intervention or damage recovery studies. Such experiments would not previously have been possible in the freely beating heart.

Specific biological interest in these technologies includes the identification of functional genetic mutants in pathways that affect cardiac repair following injury.
Advances in THz technology II

Frequency agile THz source based on Parametric generation

M Dunn, C Thomson and D Walsh
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Optical parametric generation is a valuable method for producing widely-tuneable terahertz radiation. We have demonstrated a variant of this technique in which the nonlinear medium responsible for the parametric down-conversion is located within the optical cavity of the laser used to generate the pump-wave; referred to as the intersecting cavity technique. Since the nonlinear crystal is now subject to the intra-cavity radiation field of the pump laser, which is typically an order of magnitude greater than the field that can be coupled out of the pump laser for external use, the power required from the pump laser in order to reach oscillation threshold for parametric generation is similarly reduced, and an efficient and compact device results. Recent developments with regard to this terahertz source and its incorporation into a terahertz spectrometer will be described. Typically, pulses of THz radiation of duration <10ns and pulse energy ~20nJ (peak powers > 2W) at repetition rates up to several hundred hertz are generated. The device can be continuously tuned over the spectral range 0.5-5THz, and spectral line-widths can be selected between 50GHz and 100MHz depending on the optical configuration employed. The terahertz beam can be focussed to sub-millimetre dimensions, implying M² values of 1.5-2. Interfacing to detectors (bolometer, Golay, pyroelectric) thereby leading to a computer controlled spectrometer which also features wavemeter-based calibration and data-processing will be described and illustrated by spectrographic studies. Recent observation of cascading nonlinear processes, in particular difference frequency generation, will be described.

Periodically-poled materials for the parametric generation of THz radiation

C Thomson, D Walsh and M Dunn
University of St Andrews, UK

Optical parametric generation is an established method for producing widely-tuneable terahertz radiation. The most common nonlinear material employed for this purpose is bulk lithium-niobate. We have recently undertaken a study of periodically-poled lithium niobate (PPLN) as an alternative nonlinear material. In the case of the bulk material a non-collinear phase matching geometry is employed in order to ensure that the generated THz radiation rapidly exits the crystal (through a side face) in which it is otherwise heavily absorbed. This necessitates the pump and idler waves also being non-collinear. The use of PPLN offers the advantage of a collinear geometry for the pump and idler waves, while still maintaining the rapid exit of the THz radiation (signal wave) through the presence of the grating vector associated with the poled material. We report the development of such a device which is also based on the intra-cavity geometry that we have pioneered. However, since the grating vector is a bipolar vector, there are now two possible phase-matching solutions associated with a given geometry. It now becomes crucial to design the crystal, in particular through choice of the grating period and orientation, such that the solution with the lower oscillation threshold is also the solution where the generated THz radiation impinges on a side face of the crystal at less than the critical angle, and so can be extracted. Comprehensive poled crystal design criteria will be presented. Performance of the devices based on both bulk and poled nonlinear material will be compared and contrasted.
Intracavity terahertz parametric oscillator for stand-off spectroscopy applications

N Hempler, K Ruzton, G Robertson, M Chateauneuf, F Theberge, G Maker and G Macolm

1M Squared Lasers Ltd, UK, 2Defence Research and Development Canada, Canada

M Squared has recently introduced Firefly THz, the first commercially available high peak power terahertz OPO. It combines hands-free operation with a ruggedized design, suitable for many demanding applications.

The system is designed on the basis of an intracavity pumping arrangement using a Q-switched Nd-based solid-state laser operating at 1064 nm. The nonlinear element is MgO-doped lithium niobate configured in an intersecting cavity geometry. This configuration allows easy and continuous tuning of the THz output between <0.8THz and >2.5THz. The intracavity approach enables a compact design while delivering high average power (500nW) and very high peak power (>1W) combined with a narrow linewidth of ~50GHz. These properties make the Firefly THz an ideal terahertz source for proximity and especially stand-off spectroscopy and imaging applications.

The suitability for stand-off spectroscopy was investigated by Defence Research and Development Canada who have developed a new terahertz spectrometer to identify hidden, energetic materials at stand-off distances. The system utilised a cooled (4K) bolometer in conjunction with a telescope and beam steering mirrors for delivery of the radiation onto the target. In this configuration, the system was able to successfully detect tartaric acid, a simulant for explosives, hidden under layers of polyester at stand-off distances of 8 m.

Full detail of the source as well as the detection system will be given in this presentation alongside a discussion about the problems and opportunities associated with THz spectroscopy.

Quantum coherent control I

Atom-light interactions at high densities and high magnetic fields

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Strong atom-light interactions are a key feature of many proposed implementations of quantum information and technology. The interaction can be enhanced by using a high-density medium. However at increasingly high densities inter-particle interaction become important. The application of magnetic fields gives rise to additional physics such as the Faraday effect [1].

In our group we have developed a model for the absolute susceptibility of a vapour of alkali-metal atoms [2-4], and used it to predict Doppler-broadened spectra; analyze EIT spectra and for designing optical filters.

Here we present experimental results describing the measurement of the absolute absorption spectra of hot Rubidium vapour, including the effects of self broadening and a strong magnetic field up to 0.8 kG; we also present a full Stokes characterization of the polarization of the probe beam as a function of detuning. There is excellent agreement between theory and experiment.

An integrated photonic atom chip

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We have constructed an atom chip using 12 integrated, microfabricated optical waveguides [1], cut by a trench, where light can pass through laser-cooled atoms. The chip is integrated into a chip for magnetic trapping. Launching cold atoms into the trench, we have used resonant absorption and fluorescence to detect, on average, less than 1 atom crossing a light mode. We have used atoms to probe the intensity and polarisation of guided light. With a focussed external fluorescence beam, we have imaged an excited-state cloud using the waveguide array.

We have developed a two-frequency interferometer to measure atomic density in a magnetic trap nondestructively [2]. We achieve statistically limited phase noise with 700 photons/microsecond. We combine atomic loss rates with the phase response to form a figure of merit: more sensitive measurements need more photons, but cause greater loss. With this figure, we show smaller beams make for better detectors. We intend to use the technique to make real-time observations of BECs in the trench of the waveguide chip.

It is plausible to use this hybrid chip for QIP, using hyperfine states of small atomic ensembles to encode qubits, with one qubit per optical waveguide, and the Rydberg blockade mechanism for 2-qubit operations. Fidelities up to 99% may be possible [3].


Atomic motion in the evanescent field of tapered optical fibers

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Optical nano-fibers have many useful properties: their sub-wavelength diameter leads to most of the light being confined in the evanescent field and the confinement of the guided fiber modes means that the fiber mode can maintain its profile over a much greater distance than the Rayleigh range of the equivalent free space mode. It was recently shown that atoms can be trapped in the vicinity of the nanofiber in a cylindrically symmetric potential due to the evanescent field surrounding the fiber [1,2,3]. The trap is created using a combination of blue detuned repulsive plus red detuned attractive fundamental (HE11) mode evanescent fields. Here we investigate the possibility of transferring orbital angular momentum to atoms confined in such a trap. This is done by subjecting the trapped atoms to the field of the HE21 mode which can, along with the TE and TM modes, be excited by coupling a beam in the LG10 mode (doughnut beam) to the fiber. The trajectory of an atom due to the radiation pressure of a Laguerre Gaussian in free space has previously been shown to spiral about the beam's axis [4]. We investigate the trajectories of atoms subject to the evanescent field of the equivalent fiber mode for a range of fiber parameters.

Control of the Goos-Hanchen and Imbert-Fedorov shift via pump and driven fields

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We present a cavity configuration containing a three-level atom medium where we realize a control of both Goos-Hanchen and Imbert-Fedorov shifts for a light beam via a pump field and a coherent control field. As the susceptibility of atom gas has opposite behaviors for turn on and off pump field, for a fixed driven field, we can change the sign of these shifts by simply switching on and off the pump field. Therefore, our proposal can control the intensity and direction of GH and IF shifts in a compact structure.

Nonlinear photonics II

Characterisation of cross-phase modulation in a hydrogenated silicon optical fibre

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Optical fibres with novel functionality are promising candidates for a variety of potential applications, such as all optical signal processors, and transmission in windows beyond that of conventional fibres. In particular, hydrogenated amorphous silicon-core (a-Si:H) optical fibres have demonstrated strong optical nonlinearity in short centimetre fibre lengths. A number of nonlinear mechanisms have been observed and characterised in these fibres such as two-photon absorption (TPA), free-carrier absorption (FCA), self-phase modulation (SPM) and cross-absorption modulation (XAM). In order to observe cross-phase modulation (XPM) effects from a high power source on a separate weak signal, we employ a pump-probe technique to establish the extent of nonlinear frequency modulation and shifting caused by XPM.

Experimental and numerical investigations are performed to demonstrate the strength of spectral modulation due to XPM providing the maximum wavelength shift. The overlap of a femtosecond pump pulse at 1540nm and probe pulse at 1600nm is controlled by an optical delay line. The pump and probe are focussed into a 1cm long 6μm core a-Si:H fibre and finally terminated in an optical spectrum analyser. Results of XPM on the probe indicate strong spectral modulation while showing excellent agreement with numerical simulations. Numerical analysis may be extended to quantify the shift in the central probe wavelength as a function of delay providing insight for wavelength switching applications. Emphasis on improving the peak wavelength shift for Kerr-induced switching and modulation with maximum probe extinction will be presented.

Four-wave mixing and cascaded nonlinearity yielding low-noise high-brightness tunable ultrashort pulses

P Mosley, S Bateman and W Wadsworth
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High-brightness sources of tunable light in the visible and near-infrared are required for many applications in nonlinear microscopy and imaging. Thanks to developments in photonic crystal fibre (PCF) technology, it has become possible in recent years to generate ultrabroad supercontinuum light that is extremely versatile. However, supercontinuum can suffer from very high pulse-to-pulse noise and limited spectral brightness.

We present recent developments in light sources based on four-wave mixing (FWM) in birefringent PCF. By co-propagating a low-power narrow-band seed with high-power 1064nm picosecond pump pulses we can generate FWM sidebands around 950nm and 1220nm. These can be tuned widely by sweeping the seed laser across the
broad phasematching bandwidth of our PCF, yet the bandwidth of the outputs remains narrow (and the spectral brightness high) due to the presence of the seed. Additionally, due to the high quality of the output pulses, further nonlinear operations can be performed, for example sum-frequency generation to the visible (approximately 570nm) using a nonlinear crystal.

Unlike picosecond supercontinuum, the output pulses from these sources have very favourable noise characteristics. With careful seeding their pulse-to-pulse amplitude fluctuations can be lower than those of the pump laser. We present new measurements of the noise performance of our sources along with numerical modelling. We are currently working on extending this technique to other wavelength regimes, with a particular emphasis on providing a cost-effective alternative to Ti:Sapphire laser systems around 800nm.

**Dispersion of nonlinearity and modulation instability in subwavelength semiconductor waveguides**

A Gorbach, X Zhao and D Skryabin

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Tight confinement of light in subwavelength waveguides induces substantial dispersion of their nonlinear response. We demonstrate that this dispersion of nonlinearity can lead to the modulational instability in the regime of normal group velocity dispersion through the mechanism independent from higher order dispersions of linear waves. Our analysis is based on the coupled mode equations for interacting harmonics, which are derived by using perturbation expansion of small-amplitude solutions of Maxwell equations with the nonlinear (Kerr-type) polarization term. Also, we demonstrate that, under certain approximations, the coupled mode equations can be reduced to a simple generalized Schrödinger equation with the intensity dependent group velocity dispersion. The latter model was used for numerical studies of the novel regimes of modulational instability in subwavelength semiconductor waveguides pumped with picosecond pulses.

**Negative frequency resonant radiation**

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Resonant radiation (RR), often also referred to as dispersive-wave or Cherenkov radiation is a nonlinear optical process by which a soliton propagating in an optical fibre sheds light through a resonant-like process to a blue-shifted frequency. A very similar process occurs also in bulk media where the stationary 1D fibre soliton is now replaced by the stationary 3-dimensional X-wave.

In this work we show how alongside the usual RR spectral peak observed in many experiments, a second, further blue-shifted peak is also predicted. This new peak may be explained as the result of the excitation of radiation that lies on the negative frequency branch of the dispersion relation. We thus call this “negative resonant radiation” (NRR).

Measurements confirm our predictions. The energy transfer is favoured in the presence of steep shock fronts or more generally, by a non-adiabatic variation within the pump pulse. Experiments were therefore performed in both bulk media and waveguides with optimised dispersion landscapes so as to allow the process to occur with a relatively high efficiency.

The importance of this effect lies in the fact that positive-to-negative mode coupling, such as that observed here between RR and NRR, enables parametric amplification, opening new perspectives for photon creation.
Negative temperature states in arrays of optical waveguides

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We consider a large array of identical, weakly coupled waveguides. In such an array, when high intensity light is injected into a few neighbouring waveguides, it modifies the refractive index through the Kerr effect and decouples the injected waveguides from the rest of the array. This phenomenon corresponds to light localisation and leads to the formation of discrete spatial solitons also known as breathers.

Light propagating in arrays of waveguides is well described by the Discrete Non-Linear Shrödinger Equation (DNLSE). Here we explore the statistical behaviour of the DNLSE and find a parameter region where optical propagation in the array evolves towards a state with a finite density of breathers and a negative temperature. Negative temperature states are above the infinite temperature line and have been used to describe uncommon thermodynamics such as those of nuclear spins, lasers and systems with two conserved quantities. Negative temperature states in the DNLSE are metastable but they last over astronomical time scales. During the metastable phase, the system relaxes to a regime with a finite density of breathers that are continuously created and annihilated. In these states, the micro-canonical temperature converges to negative values.

We present two simple mechanisms to generate negative temperature states from an initial condition at positive temperature: localised dissipations with removal of light intensity at the boundaries of the array and free expansions in arrays of larger size. We generalize these mechanisms to models with continuous variables and discuss possible experimental realisations in semiconductor and silicon-on-insulator waveguide arrays.

Advanced optical microscopy techniques

Structured illumination design and polarisation effects in super resolution microscopy

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Structured illumination microscopy is a technique used to generate super resolution images by recovering spatial frequencies normally outside the passband of a microscope. This is achieved by exploiting moiré patterns generated by exciting a fluorescent sample with a pattern of known spatial frequency. This is usually performed by both phase stepping and rotating a sinusoidal intensity pattern which is imaged onto a sample. Reconstruction of a super resolution image requires good contrast of the imaged pattern.

A common way to generate this sinusoidal excitation pattern is to interfere two beams that lie diametrically opposite each other, centred around the optic axis of the objective lens. The polarisation states of these beams becomes important when using a high NA objective lens; using non s-polarised light results in contrast reduction.

In order to maintain high contrast, the polarisation states of the interfering beams are usually rotated with the pattern. Although this creates a high contrast sinusoidal excitation pattern, it restricts the excitation beams to lie on a particular axis. Removing this restriction allows for the design of more intricate interference patterns. Such patterns can result in a simplified apparatus with a more favourable geometry for the image reconstruction algorithm.

Here we explore the effects of polarisation state on the contrast of sinusoidal illumination patterns. Using these effects we construct two-dimensional illumination patterns that allow recovery of super resolution images without pattern or polarisation rotation. Both theoretical and experimental results will be presented.
**Single source multi-modal D-CARS/TPF/SHG microscopy of lipids in living mammalian cells**

I Pope, P Watson, W Langbein and P Borri
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Understanding the fundamental principles behind the trafficking and storage of lipids in mammalian cells has far reaching implications in both the understanding of disease states, and the development of therapeutic strategies. CARS microscopy is ideally suited to this application as a chemically sensitive, label free imaging technique which does not influence the biological processes being studied. We have recently developed differential-CARS (D-CARS) with improved contrast and chemical specificity using a single broadband sub-10fs laser and simple passive optical elements, tuneable over the spectral range 800-2200cm⁻¹ [1]. Here we demonstrate our next generation system with a 5fs Ti:Sa source featuring a 350nm bandwidth (650 to 1000nm) hence capable of exciting the full vibrational range from 1000-3500cm⁻¹. The excitation/detection is integrated with an inverted Nikon Ti-U microscope (equipped with an environmental chamber for the study of live cells) offering conventional epi-fluorescence, dark field and differential interference contrast (DIC) imaging. A novelty of the system is that a portion of the infrared laser spectrum (910nm-960nm) separate from Pump and Stokes beams is used for two-photon fluorescence (TPF) and/or second-harmonic generation (SHG) simultaneously with CARS. In this way, the spectral and temporal pulse requirements of these modalities are optimised independently. Combining the ease of use of epi-fluorescence and DIC imaging capabilities with correlative D-CARS, TPF and SHG imaging provides a truly versatile multimodal microscope. Applications of these imaging modalities to understand lipid droplet formation in living cells will be presented.


**Quantitive CARS and D-CARS study of model and lipid droplets**

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Coherent anti-Stokes Raman Scattering (CARS) micro-spectroscopy has recently risen up the ranks in molecular biology because of its capability to offer label free molecular discrimination, 3D sectioning and increased signal levels compared to conventional Raman. We have explored the potential of differential CARS (D-CARS) recently invented in our group [1] as a further improved technique capable to eliminate the non-resonant CARS background and improve chemical specificity. To this end, model systems consisting of micron sized lipid droplets (LDs) were generated in an agarose-water solution with lipids of diverse physical structures, e.g. different carbon chain lengths, number of carbon-carbon double bonds and double bond position. Each of these systems was then investigated in the CH-stretch region (2,600-3,100cm⁻¹) with an in-house developed microscope that was set to acquire CARS/D-CARS spectra and 3D images. Detailed quantitative analyses on such data and comparisons with Raman spectra on the same model systems have confirmed the D-CARS capability to better distinguish lipid compositions for differently sized droplets. This represents the first step towards a more quantitative study of lipid metabolism in living cells. D-CARS micro-spectroscopic experiments are in progress on living HeLa and adipocyte cells fed with oleic/linoleic/linolenic acids, in order to characterise the relationship between lipid composition and LD formation with chemical specificity in a non-invasive label-free way.

Non-linear ultrasound modulated optical tomography with laser speckle detection

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Ultrasound modulated optical tomography can provide ultrasonic imaging resolution for optically imaging in heavily light scattering thick tissue. Focussed ultrasound can be used to modulate light as it passes through the region defined by the ultrasound focal zone. Methods such as pulsing the ultrasound and time gating the detection enables pulses to be time resolved along the ultrasound axis and hence improve axial resolution. Non-linear approaches utilising harmonics of the ultrasound wave can improve lateral resolution due to the tighter beam waist of harmonics compared to the fundamental. Here, we demonstrate non-linear pulsed ultrasound modulation tomography using an optical speckle based detection method. In this method, a pair of ultrasound pulses which are inverted in phase sequentially modulates the light within the tissue resulting in second harmonic ultrasound modulated laser speckle pattern. Another pair of ultrasound pulses shifted by π/2 (second harmonic shifted by π) modulates the second laser speckle pattern. By taking the difference of these speckle patterns allows the non-linear optical modulated signal to be obtained. Analogous to pulse inversion ultrasonic imaging, the second harmonic frequency detection can improve the lateral resolution of the ultrasound modulated optical tomography. Images of optically absorbing edge embedded in a 16mm thick gel of scattering coefficient 2.3mm⁻¹ demonstrate that the full width half maximum of the linewidths is improved from 9.6mm (DC light) and 4mm (light modulated at fundamental frequency) to 2.4mm for light modulated at the second harmonic ultrasound frequency.

Fibre optics sensors

Analysis of array waveguide grating based interrogation of fibre Bragg gratings for dynamic strain measurement

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Fibre Bragg gratings (FBGs) are commonly deployed as strain sensors, however high-speed interrogation (>10’s kHz) presents challenges for many readout systems. An arrayed waveguide grating (AWG) can be utilised as a FBG interrogation system by aligning the FBG sensor spectrum between two AWG channels. The ratio of the power in these channels gives a measure of the grating wavelength, while offering some immunity to common mode intensity noise.

In this work the design considerations for such a system have been investigated through a combination of modelling and experimentation. A model was created to predict the effect of factors such as the FBG and AWG spectral widths on the system performance. Of interest are the measurement range, sensitivity and noise. In addition, modelling was carried out using the transfer matrix method to investigate the effect of spatially varying strain on FBG sensitivity and its dependence on the physical grating length in comparison with the strain field wavelength.

Calibration experiments were carried out using a range of FBG sensors and two different AWGs. System range, linearity and sensitivity were measured. System performance was further characterised by measurement of the signal-to-noise ratio for different configurations, including an analysis of possible system improvement resulting from inclusion of a semiconductor optical amplifier to increase the optical signals. Our experimental and modelled analysis of this system offers greater understanding of how to optimise such an interrogation system, leading to intelligent system design for any given application.
Range-resolved optical fibre interferometry for quasi-distributed dynamic strain sensing

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A novel signal processing scheme that combines range modulation with quadrature phase measurements is proposed, using only a single electro-optic modulator to achieve both functions. The scheme is based on single-sideband pseudo-heterodyne signal processing, which operates at a single carrier frequency only. As a non-integrating scheme, absolute phase changes can be measured and immunity to intensity and visibility changes is strong. Range resolution is accomplished by encoding a pseudo-random code using time shifted versions of the carrier waveform as code symbols. Contrary to most schemes, this allows code orthogonality, important to achieve out-of-range signal suppression, to be achieved using temporal shifts of the carrier waveform alone instead of requiring additional precise interferometric phase steps.

The potential of the technique for dynamic strain sensing is explored by applying the scheme to a quasi-distributed fibre strain sensor. This sensor is made up of equidistant fibre segments each separated by splices. The weak back reflecting signal from every splice is interferometrically measured and electronically subtracted from the neighbouring signal resulting in a difference measurement of the interferometric phase for each segment. The minimum gauge length of the sensors is approx. 4 m and the strain resolution is well below 1 microstrain at a signal bandwidth of 100 kHz, allowing strain changes of up to 30 millistrain/s to be tracked. Possible applications include precise and cost-effective strain sensors for dynamic load characterisation and fault detection in large engineering structures such as wind turbine blades, aircraft wings, bridges and railway tracks.

Ultra high resolution single-mode fibre-optic distributed Raman thermometer using superconducting nanowire single-photon detectors

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Distributed fibre-optic sensors are an attractive alternative to multiplexed point sensors, because a single fibre-optic cable can potentially replace thousands of individual sensors, dramatically simplifying sensor installation and readout. We demonstrate a distributed fibre Raman sensor based on optical time-domain reflectometry (OTDR) for absolute temperature measurement with spatial resolution on the order of 1 cm at 1550 nm wavelength in single-mode fibre using superconducting nanowire single-photon detectors (SNSPDs). Using inexpensive single-mode fibre at standard telecommunications wavelengths enables extremely low-loss experiments and compatibility with existing fibre networks.

Rapid measurements are shown, with less than 60 s integration period, allowing the demonstration of temperature evolution in an optical fibre recorded at over 100 resolvable, 1.2 cm spaced positions along the fibre simultaneously with ~ Kelvin uncertainty. High spatial resolution mapping of a 2D area is demonstrated with 3m of sensing fibre.

Measurement uncertainty is discussed, decreasing with longer integration periods or reduced spatial resolution and ultimately limited by the calibration uncertainty. Future improvements and the feasibility of scaling to ~ km range sensing while maintain ~ cm spatial resolution and ~ Kelvin uncertainty are described.


POF based moisture and pH sensor in soils for e-agriculture applications
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Sensitised Polymer Optical Fibre (POF) sensors have been developed to measure moisture and pH in a variety of environments. This study aims to provide a capability for the monitoring of spatial differences around the root systems of developing plants. Mapping localised variations and temporal changes in moisture and pH provides a method for imaging soil behaviour and the effect of micro-organisms within.

Tests are performed using water, foam, sand, and agricultural soil with moisture levels between 10 and 40% W/W, and pH range from 5 to 8 pH units using a length of polymer optical fibre (POF) with a decladded or sensitised region along its length. Continuous wave (CW) optical sources (either laser or LED based) are used to interrogate the fibres and each fibre type is characterised to demonstrate its response to moisture and pH.

By alternating various procedures which expose and then remove the decladded or sensitised fibres from the experimental measurement setup, high repeatability and measurement accuracy are demonstrated. This provides an accurate means for deploying either single sensors as an array or puts forward an adequate technique for producing distributed sensors using optical time domain reflectometry (OTDR).

Quantum coherent control II
Overcoming decoherence in the collapse and revival of spin Schrödinger-cat states
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In addition to being a very interesting quantum phenomenon, Schrödinger-cat-state swapping has the potential for application in the preparation of quantum states that could be used in metrology and other quantum processing. We study in detail the effects of field decoherence on a Schrödinger-cat-state-swapping system comprising a set of identical qubits, or spins, all coupled to a field mode. We demonstrate that increasing the number of spins actually mitigates the effects of field decoherence on the collapse and revival of a spin Schrödinger-cat state, which could be of significant utility in quantum metrology and other quantum processing.

Adiabatic state preparation of interacting two-level systems
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We consider performing adiabatic rapid passage (ARP) using frequency-swept driving pulses to excite a collection of interacting two-level systems. Such a model arises in a wide range of many body quantum systems, such as cavity QED or quantum dots, where a nonlinear component couples to light. We analyze the one-dimensional case using the Jordan--Wigner transformation, as well as the mean field limit where the system is described by a Lipkin--Meshkov--Glick Hamiltonian. These limits provide complementary insights into the behavior of interacting systems under ARP, suggesting our results are generally applicable. We demonstrate that ARP can be used for state preparation in the presence of interactions, and identify the dependence of the required pulse shapes on the
interaction strength. In general interactions increase the pulse bandwidth required for successful state transfer, introducing new restrictions on the pulse forms required.

**THz coherent control in Rydberg states in silicon**

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Impurities from group V of the periodic table implanted into silicon are of enormous technological importance. These impurities are closely analogous to free hydrogen atoms but with the level energies scaled by the dielectric constant and effective mass. For typical donors in Si, the lowest energy Lyman series line is in the THz regime. In order to explore the coherent and incoherent dynamics in silicon impurities we used a free-electron laser. We have already performed incoherent pump-probe experiments for the population lifetime (200 ps) of phosphorus impurities in silicon, for the first time in the time-domain. We have also demonstrated coherent control of quantum superpositions, by observing the optical analogue of the spin echo and a complete Rabi oscillation. The photon echo experiment shows that the coherence decay time in commercial material is 160 ps. This means that the lattice introduces almost no extra homogeneous decoherence other than the phonon emission responsible for the population decay, in spite of the fact that the electron interacts with a million other electrons in the host crystal. Very recently we have been exploring coherent control using more sophisticated pulse sequences.

**Nanophotonics and plasmonics I**

**Tunable optical cavities with femtoliter mode volumes**

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Control of the light matter interaction using optical microcavities is important for a wide range of applications, from quantum information processing to advanced sensor systems. Here we report progress in developing open-access microcavities with Q factors > 10,000 and mode volumes < 1 μm³, that are fully tuneable and provide efficient coupling of cavity photons into external optics.

An attractive capability of these cavities, and a consequence of their small size, is the modification via the Purcell effect of emission with a natural homogeneous width that is significantly broader than the cavity line width. In this regime, emission resonant with a confined cavity mode experiences an elevated optical density of states and so occurs faster, at the expense of emission off-resonance for which the density of states is reduced. By measuring the photoluminescence from colloidal quantum dots at room temperature within our microcavities, we observe efficient emission into the resonant cavity modes, and a modest change in the lifetime indicating that resonant enhancement dominates off-resonant suppression of the emission process. We furthermore demonstrate single mode emission, and cavity-coupled fluorescence from single dots, with a significant increase in the photon count rate compared to standard microscopic techniques.

Modelling of the microcavities suggests that mode volumes as small as λ³ and Q factors as large as 10⁶ may ultimately be possible, providing fields per photon > 1 kV cm⁻¹ and leakage rates < 1 GHz, allowing experiments in the strong coupling regime for a range of emitters.
Coupling of silicon nanocrystals and plasmonic nanostructures

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The interaction of plasmonic nanoantennas with quantum dot emitters provides a method of enhancing their photoluminescent (PL) emission. Plasmonic nanoantennas sustain localized surface plasmon resonances which change the emission properties of an emitter they interact with. The strength, localization and frequency peak of this enhancement depend specifically on details of the size and shape of the antennas. Here, we present results related to the coupling of Au gap nano-antennas to silicon nanocrystals (Si-necs). Au nano-antennas were fabricated through electron beam lithography on the surface of Si-implanted glass cover slips, which have been annealed to induce the formation of Si-necs. Photoluminescence and lifetime enhancement in the vicinity of individual nano-antennas was then studied through the use of a confocal fluorescence microscopy based system as a function of both antenna gap size and bar length, which were varied to have resonances on or near the Si-nc emission peak. The resonance of the antennas themselves has been verified through the use of dark field microscopy to analyse their scattering spectra. Enhancement of the emission by an order of magnitude has been observed. The obtained results are compared to and discussed alongside FDTD simulations of the antenna structures.

Novel cavity and waveguide architectures in hyperuniform disordered photonic materials

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We introduce a new class of cavity and waveguide architectures built around hyperuniform point patterns, which allow to confine the light in a statistically isotropic way and to guide it through arbitrarily oriented pathways.

Generally, photonic band gaps and the associated cavity localization mechanisms are thought to be an exclusive property of long range ordered (periodic or quasiperiodic) systems. We show that there exists a far wider class of cavity and waveguide architectures that are built around a newly introduced class of disordered materials with large complete band gaps, namely, hyperuniform disordered structures. Hyperuniform disordered dielectric structures are statistically isotropic and possess a constrained randomness such that density fluctuations on large scales behave more like those of ordered solids, like crystals or quasicrystals, than like those of conventional amorphous materials. The PBG formation in disordered photonic materials results from a combination of global hyperuniformity, uniform local topology, and short-range geometric order, and recent experiments performed on microwave hyperuniform structures have demonstrated the existence of PBGs in these materials.

We demonstrate that point-like defects can support localized modes with a variety of symmetries and multiple frequencies. By employing advantages unique to hyperuniform disordered structures, we have also introduced new designs of arbitrarily shaped waveguides, along which the light can be guided through the excitation of localized resonances similar to the ones found in the point-like defects. These cavity and waveguide architectures are promising candidates for achieving highly flexible and robust platforms for integrated optical micro-circuitry.
Controlling tamm plasmon polariton states in organic microcavities

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In recent years a new type of electromagnetic surface state – the Tamm plasmon-polariton has been theoretically and experimentally investigated [1-3]. Tamm plasmon-polaritons can be excited at the interface of a Bragg reflector and a metal layer. In this work a silver film has been incorporated into a planar dielectric microcavity consisting of a half-wavelength cavity of the organic compound Alq3 doped with DCM and sandwiched between two TiO2/SiO2 Bragg reflectors (DBRs). The thickness of the silver layer is graded at 0.4 nm per micron and with a maximum thickness of 40 nm. Photoluminescence experiments show the emergence of two coupled Tamm states, localized at opposite sides of the metal layer. These Tamm states demonstrate anticrossing behaviour and a large TE-TM splitting of up to 30 meV. The origin of this splitting is the different penetration depths into the DBRs of the TE- and TM-polarized modes, detuning of the cavity mode with respect to the centre of the DBR stop band, and the polarization-dependent phase shifts occurring at the metal-dielectric interfaces. The experimental results are described by a theoretical analysis which predicts the dispersion relations of the eigenmodes of the system. The large polarization splitting of the cavity Tamm states at room temperature suggests that such structures have potential applications in optoelectronics, and particularly in controlling photon spin in nanostructures.

Wednesday 5 September

Optical tweezing and micromanipulation

Overcoming polarisation issues in circularly polarised conical refraction optical tweezers

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Conical refraction is the phenomenon whereby an optically biaxial crystal refracts an incoming Gaussian beam into a cone of light with a unique polarization distribution. This effect was first predicted and observed by Hamilton and Lloyd respectively in the 1830s and has remained of little practical interest since then, once famously being described as “a curious optical phenomenon, which had no conceivable application”. However, recently it was realised that focusing of the conically refracted beam by use of high numerical aperture objectives affords interesting optical manipulation opportunities.

For the first time, we introduce an optical tweezers system based upon conical refraction of a circularly polarised beam. As such the rings in the Lloyd plane are complete as opposed to the horseshoe distribution observed with the conical refraction of linearly polarised light.

We observe that the conically refracted beam is incredibly sensitive to changes in polarization state and that use of a standard optical tweezers setup results in a distortion of the rings in the Lloyd plane. We present an optimized arrangement for avoiding these distortions enabling the optical manipulation of both positive and negative refractive index particles simultaneously in and out of the ring plane. We demonstrate curious experimental observations including the stacking and manipulation of multiple particles of varying refractive index simultaneously. By removal of a waveplate the system can also be used to study conical refraction of linearly polarized light.

Optical binding in motion: symmetry breaking and periodic motion in optically trapped particle arrays

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Optically bound microparticles in counter-propagating laser traps typically form static arrays constrained to the beam axis. We will present both experimental and theoretical results in a range of different scenarios that show how chains can form some distance from the axis of the trapping beams, in stationary and even stable circulating configurations. We will also see similar effects occurring in evanescent wave traps, and consider how harmonic motion can be sustained in a heavily over-damped system.

Optically trapped nanowires as sensitive force probes

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Optically-trapped nanowires are ideal candidates as super-sensitive force probes for studying the surface topography and mechanical properties of biological cells [1,2]. In this paper we present a theoretical and computational study of such vertically trapped nanowires. The theoretical model predicts that the trap stiffness parallel to the beam axis will scale inversely with the cube of the nanowire length. This is confirmed by rigorous electromagnetic calculations using the discrete dipole approximation.
A typical silica nanowire has a length of 10µm and aspect ratio of 100. Trap stiffnesses for motion perpendicular to the beam are high, but parallel to the beam axis the trap stiffness is extremely low: \( K_{zz} = 1\text{fN/(mWµm)} \). This combination of good lateral positional control, coupled with good vertical force sensitivity, makes the nanowire ideal for use as an optical atomic force microscope (OAFM) probe. Optimisation of the probe, in terms of the dimensions and refractive index of the cylinder, will be discussed.

When the nanowire radius is sufficiently large, propagating modes arise which will affect the trapping characteristics, leading to so-called resonances in the trapping height and strength. Also, coupling between the translational and rotational motion of the nanowire will lead to nonconservative behaviour [3]. We will discuss these effects and explore their implications for the operation of the OAFM.


**Non-spherical optically trapped probes: design, control and applications**

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Non-spherical optically trapped probe particles have a number of advantages over microspheres: rotational motion may be monitored and controlled, the trapping points may be removed from the probe’s tip, and the tip can be more accurately positioned than a microsphere of equivalent radius.

We demonstrate a range of non-spherical probes, and discuss how they may be tailored to specific applications. We consider how probe geometry affects the region of space the tip explores – the ‘tip thermal volume’, and the relaxation times of this motion. By independently position-clamping translational and rotational modes in different ways, we are able to further control the shape of the tip thermal volume, and dramatically improve the position resolution of the probe, with no reduction in force sensitivity.

Using holographic optical tweezers combined with stereomicroscopy, we can both control and track the motion of our non-spherical probes in all three dimensions. Finally, we demonstrate the use of our probes to image surfaces in 3D, and measure force and torque interactions with biological specimens.

**VALOR: Vertical Acoustic Levitation with increased Optical Routing**

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Optical landscapes provide a very effective mechanism for the sorting of particles without the need for antibody tagging or other labelling. As optical microfluidic sorting is typically done at the base of a flow channel, different sized particles experience different flow velocities due to the strong gradient in the Poiseuille-flow distribution at the edges of the channel. Additionally, particles often stick to the surface of the channel causing particle-particle interactions which lead to sorting errors. To avoid these problems we present a method whereby a vertical acoustic levitator is used to move particles away from all surfaces. This allows an optical line trap to be used to sort between polymer spheres of varying sizes as they flow across a virtual “acoustic surface”. The acoustic levitator used in this case is a half-wavelength resonator, which creates an ultrasonic standing wave inside a fluid chamber, such that all particles are moved towards the centre of the chamber due to the acoustic gradient force. Hence the particles are held within a section of the Poiseuille-flow velocity distribution which is relatively flat such that different sized or
shaped particles all experience the same net flow velocity. This, along with the elimination of sticking, greatly reduces both the complexity of tuning the device into its sorting phase (as distinct from other non-sorting dynamic phases) and the incidence of sorting errors.

**Optical diagnostics in engineering**

**Frequency-division multiplexing in interferometric planer Doppler velocimetry**

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An interferometric planar Doppler velocimetry (PDV) system to measure flow velocity fields is described. The system uses a path-length-imbalanced Mach–Zehnder interferometric (MZI) filter to convert Doppler frequency shifts into intensity variations.

In interferometric PDV the flow is illuminated by a light sheet and the light scattered from particles entrained in the flow is collected and imaged via one input of the MZI. The scattered light is Doppler frequency shifted in proportion to the velocity of the particles which in turn leads to a phase change in the recorded interferometric image. To determine the Doppler shift, the relative phase change between Doppler-shifted and un-shifted light must be measured. Previously, this was done by acquiring a reference image with un-shifted light, either by imaging a flow with zero flow velocity, or simultaneously, using polarisation to split the signal and reference images onto separate cameras.

In this work, frequency-division-multiplexing is used to provide simultaneous capture of signal and reference channels on a single image sensor. A reference wavefront of un-shifted light, scattered from a diffuser, is collected on the second input of the interferometer. The channels are multiplexed by applying intensity modulations at different frequencies, and a time-series of the combined images is recorded using a high-speed CMOS camera positioned on one output of the MZI.

The signal and reference images are de-multiplexed using pixel-by-pixel Fourier-domain processing of the time-series. The relative phase for each is evaluated, and the phase difference, Doppler shift and hence flow velocity can be calculated.

**Development of tunable diode laser spectroscopy sensor systems for line-of-sight measurement of water vapour in aero engine exhaust plumes**

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Measurements of exhaust plume water vapour concentration and temperature are acquired on the Rolls-Royce Environmentally Friendly Engine (EFE) demonstrator. Line-of-sight tunable diode laser spectroscopy (TDLS) measurements yield the absorption spectra of water vapour downstream of the engine exhaust, using direct detection and wavelength modulation spectroscopy (WMS) to recover absorption from both the high temperature plume and the surrounding ambient airflow. The annular array of 24 exhaust nozzles has been identified as a suitable platform for future tests to create tomographic maps of exhaust products.

Initial field trials were performed to evaluate optical system performance in the harsh environments experienced downstream of aero engine exhaust nozzles. Beam steering in the exhaust plume and highly vibrating mounting hardware provide the greatest challenges to achieving adequate signal-to-noise ratios. The optical layout of the test bed installation and the overall experimental system is described. The recovered spectra are used to fit a theoretical
signal, created using an assumed temperature and concentration distribution based on anticipated plume dimensions, showing plume temperatures up to 850 K. The presence of water vapour hot lines is also confirmed using high sensitivity WMS techniques and these are compared to lines predicted by the HITRAN 08 spectral database.

**InGaN LED pumped polymer laser explosive sensor**

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Conjugated polymers are attractive laser materials because of their high gain, broad spectra and simple fabrication. In addition they offer the prospect of adding functionality to inorganic semiconductors to make innovative hybrid optoelectronic devices. Here we report work using a Philips LUXEON LED, driven under nanosecond pulsed operation, to pump a highly-efficient green-light-emitting polymer, BBEHP-PPV, with a conventional distributed feedback (DFB) resonator. We observe a lasing peak at 537 nm for drive currents above 21 A/pulse, while the corresponding optical power density from the LED is 389 W/cm\(^2\).

Explosive sensing is a promising, emerging application for polymer lasers. One exciting potential area of the application is to clear landmines left after military actions. As surface-emitting DFB lasers can be readily fabricated and as they can also be pumped using LEDs, there is the prospect for simple explosive sensors based on these materials. We demonstrate that an InGaN LED-pumped BBEHP-PPV laser sensor can detect 10 parts-per-billion of the model explosive, 1,4-dinitrobenzene. After 90 s exposure to explosive vapour, the polymer lasing threshold increases from 32 A/pulse to 50 A/pulse, with the laser emission drops by 62%. These sensitive and inexpensive hybrid sensors could be used in humanitarian demining, complementing existing technologies such as ground-penetrating radar, to improve the detection of hazardous objects.

**Automated analysis of the thermal distribution of jet engine components from thermal paints using optical techniques and principal component analysis**

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Colour-changing thermal paints are used to identify thermal distribution in jet engine parts such as high pressure turbine blades. Permanent colour changes represent the maximum temperature at a given point. These colour changes are marked out by hand visually to obtain isotherms on engine parts. This reading method of the paints is laborious, time consuming, and can only produce temperature bands rather than a continuous thermal distribution. This project aims to reduce the analysis time and increase the accuracy of the reading.

Using a fibre optic probe, reflection spectroscopy data has been taken. Principal component analysis has been used to reduce the dimensionality of the spectra so they can be projected into a 2D space. Spectra taken from engine parts are compared to those from a training set of known temperature spectra and the engine part temperature extrapolated. Using this technique, surface temperature plots have been produced which give a continuous temperature distribution rather than broad temperature bands.
The effective use of Doppler LiDAR in wind power applications

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Doppler LiDAR is finding an increasingly central role in wind assessments for wind power projects as a result of the availability of units suitable for wind power applications. The requirements of these projects influence the development of new techniques because they place quite different demands on LiDARs compared to other meteorological applications, in terms of the parameters being obtained, the degrees of precision and accuracy required, and the instrument configurations necessary to achieve this. Conversely, the acquisition of datasets which were not available to wind analysts and applied eolicists prior to the advent of LiDAR are influencing the methods with which wind project sites are assessed both during the resource assessment and operational phases. High financial stakes, narrow margins and technical risks associated with wind projects are driving a need for accuracy in LiDAR data and leading to assumptions, approximations and received wisdom regarding wind flow features such as turbulence and shear to be challenged as a result of the datasets becoming available. This presentation reviews the interface between LiDAR techniques and wind power studies and the interactions that have led to on-going significant developments in both fields.

Quantum optics I

Modelling, fabrication and measurement of 3-D photonic crystal defect layer in woodpile structures

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We will present the modelling, fabrication and preliminary characterisation of three-dimensional (3D) woodpile photonic crystals (PC) with various defects. Using plane-wave expansion method (MPB or RSoft software) we are able to map the allowed modes and photonic bandgaps (PBGs). Having determined the photonic bands we modify the material from a centre region of the lattice to form a cubic or spherical defect and then add input-output coupling waveguides and model emission into these defects using 3D finite-difference time-domain (FDTD) method (University of Bristol in-house code) [1]. We will present simulated data showing resonance, transmission, calculated Q-factor and mode volume (V).

The fabrication method using direct laser writing (DLW) [2] in 2-photon sensitive resists (polymer and chalcogenide glasses) provides sub-micron feature sizes. This allows us to create 3D high-refractive-index-contrast nanostructures either directly or by backfilling negative structures. Preliminary fabricated structures have been made and we will present first experimental results showing band gaps in optical transmission spectra. Future routes to develop a high-Q cavity strongly coupled to a two level quantum system will be discussed.

Nano-fabricated solid immersion lenses registered to single emitters in diamond

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We describe a technique for fabricating nano-structures incorporating fluorescent defects in diamond, etching an 8 \(\mu\)m diameter hemisphere positioned with a single nitrogen-vacancy defect lies at its origin showing an eightfold increase of the light collection. The negatively charged Nitrogen Vacancy color center NV\(^-\) is a spin active defect with a long spin lifetime at room temperature. In order to directly improve the coupling efficiency from a planar surface we want to fabricate structures, using Focus Ion Beam (FIB) system, such as solid immersion lenses (SILs), who geometrically avoid any refraction at the diamond-air interface. Registration marks on the diamond surface that can be identified in our confocal fluorescence microscope allowed us to initially locate and then characterize particular NV\(^-\) centers in a repeatable way. These registration marks, also visible in the FIB system, allowed us to etch a SIL with a single NV\(^-\) center located precisely at the origin of the hemisphere. This approach allows us to make a direct comparison of the same NV\(^-\) center before and after the FIB-etching process. In order to etch structures precisely over color centers it is necessary to be able to map between the fluorescence images of the NV\(^-\) centers and the FIB images of the diamond surface. To do this we etched registration marks that are identifiable in fluorescence using the confocal microscope. The position of the implanted region within the overall diamond slab was known with an accuracy of tens of microns, so the initial step in correlating the optical and FIB images of the sample was to use the FIB to etch a “ruler” just outside the implanted region. We were then able to search for and catalogue the position of single NV\(^-\) centers relative to the ruler using the confocal microscope.

Interference of independent, telecom wavelength, heralded single photons from PCF and PPLN based sources

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Heralded single photons with wavelength near 1550nm are expected to be an important resource for future quantum communications applications. Such applications often rely on non-classical Hong-Ou-Mandel interference (HOMI) that is observed between indistinguishable, pure photon states. While high visibility HOMI is routinely achieved for photons from identically prepared sources, here we observe interference between photons from two dissimilar systems.

To generate synchronised indistinguishable photons, two photon sources were pumped with a single 1064nm, picosecond-pulsed fibre laser. In one source the laser pulses generated correlated pairs of photons at 810nm and 1550nm through four-wave mixing in photonic crystal fibre (PCF). In the other, the laser was used to generate second harmonic light at 532nm in a bulk crystal, before being launched into a periodically poled lithium niobate (PPLN) waveguide. This structure was designed to generate signal and idler photons through parametric down-conversion, matched in wavelength to the fibre-based source. Idler photons from both sources were input into a fused-fibre coupler in order to measure the HOMI visibility.

HOMI with a net visibility of 70% was demonstrated between photons from the two sources (after accounting for the background due to emission of multiple photons from a single source). A visibility of 80% is anticipated for the current sources after further improvement in the purity of the generated states. This result is the first step towards realising a quantum relay system, in which transmitted qubits produced by low loss, fibre-based photon sources interact with photons produced locally on a chip.
Two-dimensional quantum walks of correlated photons in 3-dimensional waveguide optics

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Quantum walks are the direct quantum-mechanical analogue of classical random walks. They offer the possibility of exploring processes in physical and biological systems and studying large scale quantum interference.

Single particle continuous-time quantum walks (CTQW) can be described in the context of classical wave theory. Conversely, multi-particle CTQW exhibit truly non-classical behaviour and pave the way to new applications in quantum information science.

Here we report a quantum walk network consisting of nine directly laser written waveguides in a glass substrate, evanescently coupled in a 2-dimensional “plus” arrangement. We inject pairs of correlated photons in the array using different input combinations and measure the correlated detections at the output of the quantum walk network. We demonstrate the first 2-dimensional CTQW of correlated particles showing unique quantum behaviour, that strongly depend on the input state. We observe non-classical behaviour, that violates a classically defined inequality, when the photons are indistinguishable and measure visibility for this non-classical interference of up to 98% and violations of the classical limit up to 115σ, for photons injected in same plane or orthogonal planes, revealing truly quantum behaviour.

The results, showing clear non-classical interference in these structures, hold great promise for realising more complex networks on an inherently stable integrated environment, where nearest-neighbouring coupling between sites can be individually addressed and second order coupling is present, enabling simulation of more complex physical phenomena.

3D photonic quantum interferometry

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Quantum interferometry uses quantum resources to improve phase estimation tasks with respect to classical methods. Here we propose to exploit three-dimensional waveguide devices that can be implemented by the recently developed ultrafast laser writing technique. In particular, multiarm interferometers are composed of “tritter” and “tetrater” basic elements, corresponding to the generalization of a beam splitter to a 3- and 4-port splitter, respectively. By injecting Fock states in the input ports of such interferometers we can obtain fringe patterns characterized by nonclassical visibilities and outperform the quantum Fisher information obtained with classical fields for phase estimation tasks. This approach is expected to open new perspectives to quantum enhanced sensing and metrology performed by integrated photonics devices. Furthermore the experimental realization of the tritter device can represent an important step towards the fundamental study of three photon interference and the generalized bosonic coalescence effect.
Silicon and carbon photonics

Narrow linewidth silicon nano light source at telecommunication wavelengths
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The need for higher data processing speeds and bandwidths has created great interest in using photons instead of electrons as data carriers. As in electronics, silicon is emerging as a main material platform in photonics. Although silicon photonics has shown considerable progress in the development of passive devices, a bottleneck remains in the lack of a silicon light source (due to indirect bandgap of silicon). The key features required for such a light source include small size (nano scale), room temperature operation, sub-bandgap emission (ideally around 1500nm) and preferably tunability with high spectral purity.

Here, we demonstrate a silicon nano-emitter that meets all the requirements mentioned above. It is based on luminescence caused by mid-gap defect states created by hydrogen plasma treatment of silicon, which give rise to broadband sub-bandgap luminescence. By coupling this emission with an L3 PhC nanocavity, we get a narrow emission line (<0.5nm) at 1500nm by utilizing the Purcell effect. Combined with the enhancement of luminescence by hydrogen plasma treatment with this Purcell enhancement, we demonstrate up to four orders of magnitude enhancement of luminescence from silicon at room temperature. Furthermore, the emission line is tunable from 1300 to 1600nm in wavelength. This approach can be extended to electrical pumping by incorporating pin junctions around the cavity. This is a significant step forward towards realizing electrically pumped silicon nanolaser and in addition to optical interconnects, it can also find applications in biological sensing due to its high spectral purity.

Designing optimised lateral tapers for integrated silicon photonics

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Silicon photonic waveguided active and passive components may vary significantly in their vertical dimensions, especially in hybrid III-V lasers, optical fibre couplers and electroabsorption modulators. This, coupled with the large contrast in the refractive index between the core and cladding layers of silicon-on-insulator (SOI) waveguide structures, can result in significant mode mismatch and hence poor optical coupling between different structures. Lateral tapers have been proposed and demonstrated as mode adapters in these systems. It is desirable to achieve compact mode adapters with low loss, yet these two aims typically do not lend themselves to being fulfilled simultaneously, and there is a trade-off between the length and insertion loss.

We calculate the optical modes in laterally tapered structures, and analyse the coupling between the optical modes in these structures and calculate the mode conversion efficiency using an eigenmode expansion method. We identify designs for tapers which optimise the trade-off between the insertion loss and the length by allowing the taper angle to vary along the length of the structure. These tapered structures are used to design compact Ge/SiGe multiple quantum well modulators on SOI waveguides with low coupling loss.
Silicon as a platform for integrated quantum photonics


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Quantum information technologies offer new approaches to encoding, processing and transmitting information. By harnessing the properties of quantum mechanics, such as superposition and entanglement, it has been shown possible to realise fundamentally new modes of computation, simulation and communication. Of the many prospective physical systems in which to encode quantum information, photons are a particularly promising approach due to their properties of low noise, easy of manipulation and low transmission losses. To-date, quantum photonic integrated circuits have been realised in low-index-contrast waveguide material systems. Such technologies offer benefits in terms of low propagation losses, but their associated large bend radii limits the scalability. Here we present a quantum technology platform utilising the silicon-on-insulator material system, where quantum interference and the manipulation of quantum states of light is demonstrated in components two-orders of magnitude smaller than previous implementations. Quantum interference is demonstrated in a multi-mode interference coupler with a raw visibility of 80%, and two-photon state manipulation in a Mach-Zehnder interferometer is presented.

In addition, we demonstrate on chip photon pair generation in ring resonators sources. Four-wave-mixing is used to generate photon pairs in well-defined side bands shaped by the ring response and exhibits coincidences to accidental ratio as high as 460.

These technologies pave the way towards a fully integrated platform for quantum technologies where the photon sources, circuits and detectors can all be integrated onto the same chip to provide applications in quantum communication, simulations and computation.

1300 nm wavelength InAs quantum dot photodetector grown on silicon

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Silicon based photonic devices have attracted considerable attention over recent years due to the potential to have optical components compatible with Si based CMOS circuitry. A number of developments have been made over recent years in the development of Si-based waveguides and modulators. For operation at the important telecommunications wavelength of 1300 nm the best Silicon-based infrared detectors are based on growing bulk Ge on Si. However currently these devices have higher dark currents than InGaAs diodes limiting their usefulness in practical applications. Recently great progress has been made at growing In(Ga)As quantum dots on silicon and Ge substrates, to realize lasing at a wavelength of 1300 nm. However there has been limited work on investigating the use of these quantum dot structures as photodetectors.

In this paper we investigate the use of ~1300 nm wavelength InAs quantum dot structures monolithically grown on Si as photodiodes and avalanche photodiodes (APDs). We have obtained the characteristics of our diodes in terms of responsivity versus wavelength, forward and reverse bias dark current densities versus bias, as well as avalanche gain versus reverse bias. These results are compared to those reported for bulk Ge on Si photodiodes and APDs that also operate at 1300 nm wavelength. We also investigate the possibility of using such structures as optical modulators at wavelengths ~ 1300 nm by exploiting the Quantum Confined Stark Effect.
Trapping in fluids

Aerosol coalescence dynamics in optical traps

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The ability to probe how two airborne particles coalesce is important in a wide range of aerosol interaction processes. These events occur widely in the atmosphere as well as in applications such as spray drying and inhaler based drug delivery systems. Optical tweezers offer a natural tool to look at the dynamics between aerosols in certain size regimes and of certain compositions. It is important to understand the influence of the trap on the dynamics of the particle, so this can be accounted of in developing models of the real-world interactions. In this study we examine the binary coalescence of aqueous aerosol droplets of varying salt concentrations, and with traps at 1064nm and 532nm. The different wavelengths, for example, give rise to different heating effects. We make use of high-speed video microscopy (at around 5000 frames per second) and elastic light scattering to examine the particle trajectories and the re-equilibration time of the droplets after they interact. We show that the particle trajectories are often quite complex and that the re-equilibration timescales are on the order of seconds. We also consider dynamics with more complex interactions such as those of mixed phase droplets and explore the future opportunities for these techniques.

Optical shield: measuring turbid fluids' viscosity with optical tweezers

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Optical tweezers use tightly focussed beams of laser light to trap micron particles. Using a high speed camera to monitor the motion of the particles allows us to measure the viscosity of the surrounding fluid. A common challenge with optical tweezers is that freely diffusing particles can be captured by the optical trap. This is of particular concern for long measurements or measurements taken in turbid fluids. With reference to measuring viscosity, we present a technique to reduce the probability of such an event by creating an Laguerre-Gaussian (L-G) beam that focuses to an annulus of light around the optical trap. This annulus provides an optical shield against freely diffusing particles.

The optical shield is holographically formed by a spatial light modulator (SLM) positioned in the Fourier plane of the optical trap. SLM’s are computer controllable allowing a choice of l-modes for the L-G beam, with larger values giving a larger shield diameter. With l=40, a shield is formed that is around 4 times larger that our test particles’ radius, a = 0.4μm.

We tested the shield in a dense sample of Silica particles of radius 0.4μm. We analyse a movie clip with particle tracking software which shows the shield in action. We also find a marked improvement in the length of time we can measure viscosity using the shield.

Optical pulling of liquid droplets

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It was recently shown that a laser beam may be able to pull microscopic objects against its direction of propagation. We report on a detailed theoretical study of the possibility of utilising optical pulling for manipulation of micron-sized droplets of liquid, e.g. for use in microfluidics or microchemistry applications. While pulling is
possible for any liquid whose optical absorption is small, the hydrodynamic surface oscillations set in motion are much greater than for regular optical pushing at the same power. The set-up would thus seem ideal for experimental investigation of laser-induced droplet deformation. For the purposes of droplet transport by optical pulling, a sequence of intense nanosecond pulses allowing the droplet to settle to spherical shape between each pulse is the obvious solution. For such short pulses, electrostriction may have to be taken into account in order to describe the fluid surface motion since the fluid’s speed of sound can no longer be taken to be infinite. We discuss how electrostrictive effects modify the fluid motion of the droplet.

Extraction of membrane proteins from single cancer cells using holographic optical traps

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In order to better understand the development and spread of cancer, the methods by which cells communicate and disseminate information must be closely examined. As such, membrane proteins are an important target in modern cancer research due to their role in cellular signalling cascades. Disruption of these cascades can lead quickly to abnormal cell growth and the onset of cancer. Therefore, characterising the recruitment and action of such membrane proteins is a key facet of the Single Cell Proteomics (SCP) initiative.

Here, work is presented on a project to use holographic optical traps to extract membrane proteins from single cancer cells. The need for non-invasive removal of membrane proteins has led to the development of “Smart Droplet Microtools” (SDMs) as sampling agents. Comprised of micron-sized lipid-coated droplets with either a solid or oily core, SDMs exchange material with the cellular membrane when brought into contact with a target cell. Through manipulation with optical traps, SDMs can be used to simultaneously remove membrane proteins from multiple sites on the same cell, providing spatial selectivity of the protein of interest. These proteins can then be transported downstream by the SDMs in order to interface with other techniques for further experimentation and analysis.

Fringe Analysis Special Interest Group (FASIG): Techniques

A machine learning approach to fringe-location identification

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Machine learning concepts are attracting renewed interest in various computational fields, including machine vision, both in the theoretical and applied domains. Machine learning takes the approach of creating programs which learn how to solve a given problem, rather than programming the machine with exact steps to be performed in order to solve the problem. Before a machine learning system can be deployed, it typically needs to undergo a training phase, which enables it to acquire the necessary structures and information to solve similar problems. The performance of a machine learning system is commonly assessed by measuring how well the system is able to solve problems, which are generally similar but not identical to those used as examples during the training phase.

We investigate applying machine learning to a key step of fringe analysis, namely the identification of fringe locations. Identifying fringe locations correctly can be an especially challenging task due to the inherently noisy nature of speckle interferograms. Traditionally, automated edge detection operators are employed for this task, often producing inferior results, as compared to those produced manually by an expert human operator. We present a machine learning approach to the fringe location identification problem, and discuss its potential and merits on one hand, while also examining the challenges encountered during the training phase, on the other hand. We
describe novel measures for quantifying the learning attainment levels of the system, and describe how these measures can be used to guide the training phase in a methodical and intuitive manner.

Development of a multi-axis phase-contrast wavelength scanning interferometer

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Phase contrast wavelength scanning interferometry (WSI) is a recently-developed technique for measurement of displacement fields within weakly scattering media. In this work we describe recent developments on a WSI system designed to measure from multiple directions, to provide all 3 displacement components throughout the sample, and with spatial resolution of a few mm. In WSI the accurate measurement of the time-varying laser wavenumber changes is of great importance. Consequently, an optical sensor has been developed that allows the dynamic monitoring of wavenumber changes with high resolution and is immune to the ambiguities caused by large wavenumber jumps (mode-hops). The sensor consists of low-cost optical components and is used to monitor the wavelength changes of a customised commercially available Ti:Sapphire laser source with >100nm scan range. Its performance was validated against a high-end commercial wavelength meter. A root mean square (rms) difference in measured wavenumber shift between the two of $\sim 4 \text{ m}^{-1}$ has been achieved, equivalent to an rms wavelength shift error of $\sim 0.4 \text{ pm}$. Data processing procedures have also been developed to handle the mode hops and other nonlinearities present in the scans, which ultimately prevent successful depth reconstructions. The method involves the measurement of phase changes from the interferograms in the optical sensor and re-sampling the intensity on a uniformly-spaced vector of wavenumbers. With these changes, the depth-resolution is improved by a factor of over 100× compared to Fourier transformation of the raw intensity data, and is found to approach the theoretical limit for scan ranges of up to 37 nm.

Optimization of Tilt Scanning Interferometry in tomographic imaging and profilometry

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Tilt Scanning Interferometry (TSI) has been recently proposed as a tomographic technique to image microstructure and phase information inside the volume of weakly scattering materials. As opposed to optical coherence tomography (OCT) which relies on a broadband light source or a tunable laser, TSI only requires a monochromatic source. This fundamental feature makes it insensitive to dispersion. Depth information is obtained by tilting the illumination beam while recording a sequence of interferograms in which depth information is encoded in the temporal frequency of the signal. In this paper we investigate the performance of Tilt Scanning Interferometry in tomographic imaging and profilometry applications, with an emphasis on the factors that limit the quality of image reconstruction. Depth resolution is mainly degraded by a frequency chirp that appears in the temporal interference signal when a large tilting range is scanned. It is shown through a numerical simulation that the chirp depends on the curvature of the illumination wavefront and also on the position of the pivot axis of the illumination beam. Data processing methods are proposed to overcome these limitations and their effects are illustrated with experimental measurements of opaque surfaces and a weakly scattering phantom with internal features.
**An investigation into the accuracy of optical vortex metrology**

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Optical vortex metrology uses phase singularities, produced in the complex signal generated by a Laguerre-Gauss filter operation applied to an image, for displacement measurement. Each phase singularity can be uniquely identified from its structure, enabling it to be tracked between images. We report a numerical and experimental investigation into the factors which affect the accuracy of the measured displacement and rotation. Accuracies of 0.01 pixel for displacement and 0.1 degree for rotation can be achieved.

**Quantum optics II**

**Cavity-photon controlled coherent coupling of quantum dots**

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In quantum information science, the quantum bus technology aims to provide coupling between distant quantum systems without dissipation. In that context, qubits embedded in a solid state matrix are attractive, as they benefit from the lithographic and materials processing techniques developed in the semiconductor industry. We use here micropillar optical resonators which enabled pioneering demonstrations of the strong and quantum strong coupling regime [1] in a solid. The structures consist of InGaAs quantum dots (QD) - providing exciton states (X) of high oscillator strength, located in the anti-node of the optical cavity mode (C) which stores photons for about 10 ps. In these structures a quantum of optical excitation oscillates between the exciton and cavity photon state. The resulting eigenstates of mixed exciton and photon character form a Jaynes-Cummings ladder.

By micro-photoluminescence we reveal a triplet of Xs coupling strongly with C. Such multi-polaritonic features were previously observed [2], and show the coupling between the individual excitons and the cavity mode. An explicit demonstration and further selective manipulation of the cavity-mediated exciton coherent coupling requires extracting and controlling the coherent response of the cavity. We employed heterodyne spectral interferometry [3], to measure the four-wave mixing (FWM) [1]. We find agreement between the measured dynamics and independently computed FWM. We present two-dimensional FWM in which coherent coupling is observed as off-diagonal signals [3]. The observed coherent coupling demonstrates that the cavity can act as a coupling bus for excitonic qubits.


**Quantum statistics of surface plasmon polaritons in metallic stripe waveguides**

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We report on the experimental characterization of the effects of loss on the quantum statistics of surface plasmon polaritons propagating in metallic stripe waveguides [1]. Single surface plasmon polaritons are excited using photons generated via spontaneous parametric down-conversion. The mean excitation rates, intensity correlations and Fock state populations are studied. We show that while the mean excitation rate behaviour follows the classical
intensity rate as the waveguide length increases, the second-order quantum coherence is markedly different from that expected in the classical regime. The observed dependence of this coherence in our experiment is consistent with a linear uncorrelated Markovian environment in the quantum regime. Our results provide important information about the effects of loss for assessing the potential of plasmonic waveguides for future nanophotonic circuitry in the quantum regime.


Maximising and detecting the dimensionality of bipartite orbital-angular-momentum entanglement

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The process of spontaneous parametric down-conversion (SPDC) is a source of bi-photon states that can be entangled in several degrees of freedom, including orbital angular momentum (OAM). Unlike polarisation, which is only bidimensional, the OAM state space is discrete and theoretically infinite-dimensional. High-dimensional entangled states of orbital angular momentum could serve as robust generalised qubits in quantum information. We observe, analyse and maximise the number of OAM modes produced by the down-conversion crystal and detected by our measurement apparatus. We infer the Schmidt number, indicative of the width of the OAM spectrum of the source, for different phase-matching conditions of the SPDC crystal. We experimentally study high-dimensional OAM states with Schmidt numbers up to 50.

Tailored orbital angular momentum correlations via pump-shaping

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Spontaneous parametric down-conversion (SPDC) has been instrumental in exploring the strangeness and usefulness of quantum mechanics. In SPDC, a pump photon impinges on a nonlinear crystal to create a pair of photons which are entangled in various properties, including orbital angular momentum (OAM). Unlike polarization which can take on only two values, OAM has a discrete and unbounded state space which significantly increases the information content that can be encoded in a single photon. In this work, we tailor OAM correlations by illuminating a nonlinear crystal with a non-Gaussian pump beam. We introduce a cover slip to transform the Gaussian output of a 355-nm laser into a Hermite-Gaussian-like mode that then pumps a nonlinear crystal to create the entangled photon pairs. The correlations in OAM and its conjugate variable, angular position are measured holographically using two separate spatial light modulators in the signal and idler arms. We show the transfer of the OAM spectrum of the pump to the entangled photons, which manifests as a redistribution in both the OAM and angular position correlations.
Nanophotonics and plasmonics II

Strong field enhancement of periodically-arrayed gap-mode nanoantennas
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Strong electromagnetic field enhancement in gap-mode nanoantennas was intensively studied due to a range of interesting phenomena: surface-enhanced Raman scattering [1], optical trapping through Plasmon resonance [2], and a series of nonlinear processes [3-4]. This strong field enhancement arises from the “antenna effect”, which confines the incident light on a nanoantenna to a tiny gap region. In most of the studies, nanoantennas are densely packed on a substrate in order to compensate the size mismatch between nanoantenna and incident beam.

In this report, we propose and study two-dimensional periodically-arrayed nanoantennas that exploit “resonant coupling effect” [5], which can efficiently collect the incident light and thus can further enhance the gap field. We theoretically investigated the electromagnetic field for infinite arrays with square-lattice geometry. A pair of gold nano blocks with Plasmon resonance at 800nm was used as a nanoantenna unit. The intensity spectra showed narrow resonance peak (FWHM ≈ 20nm), which moved towards longer wavelength as the array period increased. When this resonance peak coincided with the Plasmon resonance of the nanoantenna unit, strong field enhancement by a factor of more than 10 was observed. Further discussion will be given at the conference.


Interference of strong and weakly radiating modes of nanostructures
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We find the intrinsic internal and scattering field modes of smooth nanostructures, allowing us to understand the optical response to excitation for these systems in both the near and far field. We show that these modes always occur as coupled pairs of internal and external modes, and for each such pair we find the corresponding optimal surface excitations that maximises their amplitudes. We also identify strong and weakly radiating modes and study how multimode interference can lead to enhanced or suppressed interaction of nanostructures with light. This theory is then applied to consider optimising the interaction of nanostructures with point-like radiating sources such as atoms and molecules.

Spaser spectroscopy
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The advances of nanotechnology open an opportunity of development of existent spectroscopy methods. We suggest a novel method that combines the ideas of tip-enhanced optical spectroscopy and of laser spectroscopy. The latter, offering no spatial resolution, provides an extremely high sensitivity and reveals even prohibited (non-dipolar) transitions. The combination is enabled by invention of plasmonic laser (spaser) [1], which generates plasmons due to nonradiative energy transfer from the gain medium (quantum dot) to SPP, localized at a
nanoparticle. Recently we have suggested a spaser radiating 1D plasmons [2]. The device suggested here is based
on 1D spaser generating plasmons on a needle with narrow tip. We show that the sensitivity allows detection of
some dozens of atoms with high (sub-wavelength) spatial resolution.

[1] D.J. Bergman, M.I. Stockman // Surface plasmon amplification by stimulated emission of radiation:
Quantum generation of coherent surface plasmons in nanosystems // Phys. Rev. Lett. 90, 027402
(2003).

spaser: Coherent excitation of one-dimensional plasmons from quantum dots located along a linear

A novel technique for measuring absorption and scatter in metallic nanoparticle colloids

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The optical properties of metallic nanoparticles are dependent on their size and shape. For more than 30 years
researchers have exploited this feature by designing and fabricating specific nanoparticle systems that utilize their
enhanced scatter for biomedical imaging; or use the enhanced absorption of the particles for thermally destroying
unwanted biological materials or enhancing Raman signals for detection purposes. In these applications and many
others, it is essential to know how much incident light the medium removes through scattering processes and how
much through absorption. Extinction data uncovered by conventional spectroscopy is unable to give such
information and other scatter measuring techniques such as Dynamic Light Scattering have limitations.

Here we demonstrate a novel cw laser based comparative technique for determining the absorption and scattering
coefficients of gold nanoparticles ranging in diameter from 25 – 146 nm dispersed in water at four incident light
wavelengths from visible to near-infrared. The results presented for the gold nanoparticles and those for similarly
sized silver nanoparticles agree well with the values theoretically predicted by Mie theory. We will show that the
simplicity and the speed of the measurement process allows for real-time monitoring of changes in the absorption
and scattering properties, which makes the technique well suited for studying aggregation of nanoparticle systems.

Trapping tools and techniques

A compact holographic optical tweezers system

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Holographic optical tweezers have found many applications including, the construction of complex micron-scale 3D
structures and control of probes for position, force and viscosity measurement. They can be configured as
dedicated workstations for bio applications such as the patterning of cells where the system is optimised for use by
the non tweezers specialist. We have developed a compact holographic tweezers system which can be easily
transported and interfaced to a wide range of microscopy systems, making it a valuable tool for collaborative
research. Its orientation can be easily changed whilst in operation, e.g. tilting the system on its side. This makes it
well suited to applications such as measuring the force of gravity acting on trapped micro beads.

Our compact holographic tweezers measures approximately 30 x 30 x 35cms and is based on a 5W fibre coupled
laser @1070nm, a spatial light modulator and a custom inverted microscope. Trapping can be achieved using a
tightly focussed single laser beam as well as dual beams, created using a mirror behind the sample. Using a lower
magnification, longer working distance, objective widens the range of potential applications using different types of
sample cell. In compact optical systems that use short focal length lenses, particular care must be taken to correct for resulting aberrations. We can easily compensate for aberrations by making a correction to the spatial light modulator, achievable through our easy to use LabView software. We demonstrate that our system can measure particle position to accuracy better than 0.5nm, for a 1 second measurement.

Optical tweezers at high pressures
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The properties of materials can change significantly in extreme environments, such as high pressure. We report on progress towards optical trapping and tracking of microscopic particles in a diamond anvil cell (DAC), which is capable of reaching pressures of tens of GigaPascals. Recently, the optical trapping group at Innsbruck have used holographic optical tweezers to create dual-beam optical traps which can hold and move particles through a low magnification, long working distance microscope. We have implemented this approach, using our compact holographic tweezers system. These optical traps hold a particle between the foci of two beams propagating in opposite directions, one of which is created by projecting a laser spot behind the mirror, such that it is reflected back into the sample.

Using a diamond anvil cell optimised for light microscopy, we have easy optical access to the sample, which allows us to trap and track colloidal particles. By tracking the resulting dynamics of the trapped particles moving under residual Brownian motion this will enable the measurement of material properties such as viscosity and elasticity as a function of pressure.

Miniaturised optoelectronic tweezers driven by CMOS-controlled micro-LEDs for trapping and manipulation of T-cells
A Jeorrett\(^1\), M Dawson\(^1\), A Wright\(^1\), E Gu\(^1\), N McAlinden\(^1\), D Massoubre\(^1\), J McKendry\(^1\), R Henderson\(^2\) and S Neale\(^3\)
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An optoelectronic tweezers (OET) system driven by a gallium nitride micro-LED array has been designed and built for the manipulation and fluorescence analysis of T-lymphocytes [1]. The system comprises an OET device in which a photoconductive layer of hydrogenated amorphous silicon is coated onto one of two parallel transparent electrodes. Complementary metal-oxide semiconductor (CMOS) technology drives the micro-LEDs, providing computer-controllable light-patterning of the photoconductive electrode. Micron-sized particles are manipulated within the OET device by light-induced dielectrophoresis (LIDEP). A ‘chequerboard’ micro-LED device (a 16 x 16 array of independent 99 x 99 µm 450 nm-emitting pixels, 100 µm pitch) used here introduced a new level of pattern-programmability under direct CMOS control, offering simplification and miniaturisation over other approaches. Using this OET set-up, and one providing image demagnification of 4x, dynamic control of 10 µm and 3 µm polymer beads in low conductivity medium has been achieved where, respectively, negative and positive LIDEP is observed. Manipulation of live T-lymphocytes in sugar solution has also been achieved; live cells are separated from dead cells due to their differing internal conductivities. Fluorescence imaging in combination with tweezing is possible using the micro-LED light transmitted through the photoconductive electrode to excite dye-labelled beads and, in future, dye-labelled cells. We will discuss our progress in such demonstrations and towards integrating fluorescence-lifetime measurements using pulsed micro-LEDs and CMOS single-photon avalanche diode arrays [2].

Optical immobilisation techniques applied to Raman analysis of individuals cancer cells
S Casabella, P Scully, P Gardner and P Fielden
The University of Manchester, UK

Due to the high level of molecular information which can be obtained using vibrational spectroscopic techniques, both IR absorption and Raman Scattering (RS) have great potential in the analysis of biological tissue and cells, for example in distinguishing between cancerous and non-cancerous samples. In the case of live cells, Raman spectroscopy is perhaps the more suitable technique due to superior spatial resolution and the low RS cross-section of water, however in such cases it is often necessary to isolate individual cells from a surrounding substrate which may also be Raman active.

This presentation discusses two methods of isolating and immobilising individual cells for Raman analysis: single beam trapping (Optical Tweezers) and the use of two counter-propagating beams via an optical fibre arrangement. The advantages of each approach will be discussed, including the potential for integration into a ‘Lab on a Chip’ setting, for example as a means of capturing and discriminating specific cells of interest, or allowing a single cell to be continuously monitored while environmental conditions are changed.

Fringe Analysis Special Interest Group (FASIG): Techniques and application
Metrology of thin films using interferogram analysis techniques
D Towers, C Towers and C Dipresa
University of Leeds, UK

Thin films have widespread applications from generation of coatings for displays to solar cell manufacture and for surface property modification. In many cases the thin film is generated by creation of a liquid film which subsequently dries. A popular approach is to use spin coating which creates a flow over the surface to form the film. In a number of cases the surface to be coated includes topographic features, required for the functionality of the device, that perturb the formation of the film and create long lasting ripples over the surface.

In this paper we present a technique for metrology of thin liquid films, to give both the profile of the exterior surface and information on the thickness of the film. The method relies on calculation of an interference phase term and the modulation depth of the fringes created. Example data will be included from some fluid films of known geometry in order to validate the method.

Measurement of the hygroscopic expansion coefficient of Ethylene Vinyl Acetate using wavelength scanning interferometry
S Rashtchi, P Ruiz, R Wildman, I Ashcroft and A Elmahdy
Loughborough University, UK

EVA, a copolymer of ethylene and vinyl acetate, is a common encapsulant material used in silicon-based PV modules. It contributes to the structural integrity of the modules, provides electrical insulation and also acts as an environmental barrier. However, water can diffuse through EVA into the modules, leading to swelling and chemical degradation, which can impact interfacial bonds, leading to delamination and allowing more ingress to occur that can eventually end up in accelerated corrosion and device failure. Finite element predictive models of photovoltaic module behaviour require a number of mechanical constitutive parameters, including the hygroscopic expansion coefficient (HEC) of the encapsulant, which couples water absorption and mechanical stress. In this paper, we propose a method based on Wavelength Scanning Interferometry (WSI) to determine HEC. The system uses a
tunable near-infrared laser to illuminate a layer of EVA laminated onto a mirror. The interference signal between light reflected at different interfaces (air-EVA, EVA-mirror and air-mirror) and a reference wavefront is modulated with temporal frequencies proportional to the optical path difference between them. Fourier transformation of the interference signal leads to peaks that locate the position of the interfaces. The refractive index and thickness of the EVA layer can be determined by comparing the distances between pairs of peaks in the Fourier spectrum. By evaluating the phase at those peaks as the sample is subjected to controlled relative humidity levels in an environmental chamber, the change in thickness is measured and the HEC is established.

**Thickness measurement using THz interferometry**

T D Nguyen, J Valera and A Moore

Heriot-Watt University, UK

We report measurements of the variation in thickness for a test object that is opaque at visible wavelengths. The system used a Mach-Zehnder interferometer comprising a THz laser and a Golay cell detector. The change in phase between different sections of the object enabled thickness variations to be measured with an uncertainty of 10 µm. The laser frequency was tuned to provide an unambiguous measurement range in excess of 4 mm. Internal defects in the test object were also identified.

**A widefield, two laser, interferometer**

M Clark, R Patel, S Achamfuo-Yeboah and R Light

The University of Nottingham, UK

An interferometer has been developed that captures the full field fringe pattern generated from interfering two independent light sources rather than from a single split source. Two (separately) stabilised He-Ne lasers produce outputs with narrow linewidth and reasonably stable output frequencies. Interfering these two sources produces a heterodyne interference pattern with an unknown beat frequency. The beat frequency is continuously variable because of the variation in output frequency of each laser, but can be crudely tuned (by varying the stabilisation points of the lasers) to lie within the MHz region (although still randomly variable by ~5MHz).

A custom modulated light camera (MLC), capable of demodulating light within this beat frequency region, is used to capture the interferogram and phase. This system, based on a previously reported ultrastable interferometer [Opt. Express (20), 17722 (2012)], uses an electronic feedback system to cancel out the effects of time varying phase changes common to all pixels. In this arrangement the MLC derives the reference signal from a single pixel in the camera which locks it in to the instantaneous beat frequency of the interferogram. This enables the capture of the widefield interference pattern produced by the interference of the two lasers.

**Quantum optics theory**

**Canonical quantization of electromagnetism in moving dielectrics**

S Horsley

University of St Andrews, UK

Recently, a general technique has been developed for the canonical quantization of electromagnetism within material media described in terms of ε and μ [1]. This procedure allows for any dispersion and loss you may wish to describe, so long as the Kramers-Kronig relations are satisfied, and the material can be arbitrarily
inhomogeneous and anisotropic. I will begin through reviewing this general technique and show how it may be extended to media in relative motion [2].

The description of the quantized electromagnetic field interacting with a lossy dispersive dielectric in motion turns out to have some surprising features. First of all the Hamiltonian is not necessarily positive. I will show some physical consequences of this, including the possibility to extract energy from the centre of mass motion via the vacuum fluctuations outside of the medium. I will also discuss the relation of this formalism to the controversy regarding the existence of friction in the Casimir effect when the plates are in lateral motion.


Direct determination of purity and fidelity for single-photon states

L Wright, C Soeller and B Smith

University of Oxford, UK

Individual state purity and quantum fidelity between two states are both fundamental attributes of quantum systems. These properties are not only of foundational interest, but also influence the quality of a system for quantum applications such as quantum information processing and quantum metrology. For individual photons the purity and fidelity associated with different sources directly impacts the capacity for quantum applications in which photons from different sources are interfered. Imperfect states result in reduced performance due to non-unit interference visibility. Here we present a simple method, using conventional HOM interference, to ascertain the purity and bound the fidelity of single-photon states without resorting to full quantum state tomography (QST). This method significantly improves the efficiency over QST owing to the reduced number of measurements required. This type of diagnostic is therefore expected to be useful in systems where in-situ monitoring of single-photon sources is necessary for the reliable implementation of quantum information applications.

Detecting nothing

D Oi, V Potocek and J Jeffers

1University of Strathclyde, UK, 2Czech Technical University, Prague

We show how to detect the presence or absence of the vacuum in a quantum optical field without destroying the state, implementing the ideal projections onto the respective subspaces. Detecting a vacuum is trivial, but standard quantum optical detection does not preserve the state for further interrogation. It is this feature which enables sequential measurements, useful for quantum communication.

The scheme uses a variant of V-STIRAP to enact an adiabatic conditional evolution of a probe atom. This depends on the presence or absence of photons in the target field, but is otherwise independent of the number of photons, thus avoiding any leakage of information from the non-vacuum subspace. We discuss how this may be achieved experimentally in cavity QED or circuit QED systems. The protocol can also be adapted to create unusual quantum states of light the application of the bare raising and lowering operators. These have not previously been implemented in quantum optical experiments.
Super-optimal coherent state amplification without quantum resources

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University of Strathclyde, UK

Current techniques in super-optimal quantum optical signal amplification are far from experimentally ideal. Schemes based on the quantum scissors [1,2] require single photons as a resource, which is costly in terms of count rates and therefore success probability of the device, and which limits the maximum photon number of the amplified state to 1. The maximum photon number can be increased by cascading, but the success probability drops dramatically, and the count rate even more so. Devices based on noise addition and photon subtraction do not have these limitations, but are far from perfect amplifiers [3,4].

We propose a new method for quantum signal amplification which does not suffer from either of these problems. It is a non-deterministic method, based on the interaction of a limited set of coherent states at a beam splitter followed by a photon subtraction. No quantum resources are required, and the device can amplify perfectly for a twofold gain, with a relatively high probability of success.


Quantum-state storage and processing for polarization qubits in an inhomogeneously broadened Lambda-type three-level medium

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We study the propagation of a single-photon pulse whose two polarization components are coupled with the two transitions of a coherently prepared lambda-type three-level medium, i.e., a phaseonium medium, which presents artificial inhomogeneous broadening. The propagation effects that normally exhibit this kind of system are used in combination with the controlled reversible inhomogeneous broadening (CRIB) technique to introduce novel quantum information applications [1].

On the one hand, we discuss the use of the lambda-type system as a quantum filter. This proposal is based on the fact that part of the incident pulse, the antisymmetric normal mode, which is uniquely determined by the preparation of the atoms in the phaseonium state, propagates without distortion. On the other hand, we show that the orthogonal component associated with the symmetric normal mode can be completely absorbed and retrieved in the backward direction with high efficiency using the CRIB method. In this case, the system can be used to implement a quantum sieve or, considering both orthogonal modes, a tunable polarization qubit splitter. Furthermore, we also demonstrate that both field components can be completely and independently absorbed by imposing a position dependent phase coherence in the phaseonium medium. Then, by applying the CRIB technique, both components can be recovered on-demand, thus implementing a quantum memory for polarization qubits.

**Nanophotonics and plasmonics III**

**Femtosecond phase-resolved microscopy of plasmon dynamics in individual gold nanospheres**

P Borri, F Masia and W Langbein
Cardiff University, UK

Metallic nanoparticles (NPs) exhibit morphology-dependent electromagnetic resonances also called surface plasmon resonances (SPR) which couple to propagating light. The field of “plasmonics” with metallic NPs is tremendously growing, yet the optical detection of individual metallic NPs with high spatial and temporal resolution remains a challenging endeavor. Here, we demonstrate a novel phase-sensitive four-wave mixing (FWM) microscopy technique in heterodyne detection capable to resolve the ultrafast changes in the real and imaginary part of the dielectric function of single small (< 40nm) gold NPs. The results agree well with a quantitative model of the FWM response which accounts for the transient electron temperature and density in gold via intraband and interband transitions at the SPR. Remarkably, we find that the effect of interband transitions in the excitation is important to explain not only the magnitude of the measured FWM but also its initial dynamics which is dominated by the formation of hot electrons via Auger electron-hole recombination. Beyond fundamental interest, our FWM technique offers background-free detection of the full complex susceptibility change even in a highly scattering environment and operates at power levels corresponding to negligible average photothermal heating, hence is compatible with live cell applications. Moreover it can be readily applied to any metal nanostructure. The amplitude and phase-resolved detection demonstrated here provides an intrinsic ratiometric readout which has the potential to bring unprecedented sensitivity in SPR-based applications, for example monitoring nanoscale distance changes with plasmon rulers in cells and tissues.

**Diamond nanostructures and superresolution microscopy: seeing the nanoscale!**

B Patton\(^1\), D Wildanger\(^2\), J Smith\(^1\), J P Hadden\(^3\), S Knauer\(^3\), S Hell\(^2\), J O’Brien\(^3\) and J Rarity\(^3\)

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Due to their atom-like energy spectra and ease of manipulation, defect systems in diamond are currently of interest to a wide research community. While many defects are optically active, one factor that poses a challenge to their use is the fact that, with a refractive index of 2.4, the surrounding diamond itself poses limitations to collection efficiency for centres located beneath a planar diamond surface. In the first part of the talk we present some of the fabrication methods that allow us to improve collection efficiency and obtain a tenfold increase in the number of photons we can collect from a single centre.

Having suitable samples at hand, we sought to see if diamond’s other material properties (such as thermal conductivity) could prove to be of benefit for optical measurements. Conventional microscopy relates the resolution of a given optical setup with the angle over which the final objective lens can collect light. Recent techniques allow resolution of objects smaller than this, giving rise to superresolution microscopy. We present our latest results using one such technique, Stimulated Emission Depletion (STED) imaging and show how we can now optically address objects with a resolution in the single nanometer range!
Precise depth determination of diamond defect centres using self interference spectroscopy

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Negatively charged nitrogen vacancy (NV-) colour centres in diamond are a leading candidate for applications in quantum photonics and spintronics as well as nanoscale optical imaging and magnetometry. This is because they provide a natural interface between optical photons and solid state electronic and nuclear spin states which are long lived even at room temperature. In order to fully realise the potential of this system as a spin-photon interface it is necessary to couple the NV centres to micro cavities which enhance the photonic interaction. Part of this challenge is to accurately determine the position of the target NV centre. Recently, techniques such as stimulated emission depletion [1] have allowed lateral position determination exceeding the diffraction bounds by several orders of magnitude. However axial (depth) determination is still difficult due in part to the high refractive index of diamond, which induces significant spherical aberrations.

We demonstrate how to overcome these problems by using self-interference spectroscopy [2] of single NV defects several microns from a diamond-air interface. Over the relatively wide NV centre emission spectrum (620nm-800nm), interference of the direct and reflected portions show constructive and destructive interference, encoding the distance of the emitter to the surface. Spectra analysis allows axial position determination with nanometre scale accuracy. This is an essential tool in the development of NV centre photonic devices.


Metal-glass nanocomposites for optical storage of information

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Long-term digital storage of our cultural and scientific heritage on a really durable medium is still an unsolved technological challenge. Current magnetic and optical storage media provide very high capacities and access speeds, but they require periodic replacement due to their limited lifetime of some 10 years. Safety of the data against electromagnetic shock or high temperatures is also an important issue in this context.

Here we demonstrate an all-optical data storage and readout technique on a medium that has proved to be stable over centuries - in medieval church windows - glass containing metallic nanoparticles. Using ultra-short laser pulses to persistently change the shapes of the nanoparticles dependent of the laser polarization, well-defined local dichroism in the focal volume can be produced. The latter is utilized for multi-bit encoding, where the information can be read out very fast by wavelength- and polarization-sensitive detection of the transmitted light. The technology has the potential for data capacity and access speeds superior to the currently available optical recording media, combined with unprecedented durability.
Twisted photons and twisted electrons – theory and experiment

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Twisted photons, also known as optical vortices, are special states of light containing orbital angular momentum, exemplified by the quanta of Laguerre-Gaussian and Bessel light beams. They have been studied extensively over the last two decades. In contrast, twisted electrons, also called electron vortices, represent a very recent discovery. Predicted by Bliokh et al. (K.Y. Bliokh et al., Phys. Rev. Lett. 99, 190404 (2007)), twisted electrons have been created inside electron microscopes in several laboratories. This presentation compares the two types of vortex, highlighting similarities and differences. In particular, we concentrate on the consequences of the charge and spin of the twisted electrons - features physically distinct from the case of twisted photons. Since twisted electrons are charged, they possess intrinsic electric and magnetic fields. A description of these self-fields is presented, along with the results of studies into the spin-orbit coupling of the twisted electrons with these self-fields. We also describe two different experiments involving the interaction of the two types of vortex with matter. The first experiment by Araoka et al. (F. Araoka et al., Phys. Rev. A 71, 055401 (2005)) concerns the interaction of twisted photons with molecules, and the second by Verbeeck et al. (J. Verbeeck et al., Nature 467, 301 (2010)) on electron energy loss spectroscopy of magnetised iron thin films using twisted electrons. We present theoretical analysis for each case and compare the predictions of theory with the experimental results (S. Lloyd et al., Phys. Rev. Lett. 108, 074802 (2012), S. Lloyd et al. (to be submitted)).

Detecting the azimuthal and radial content of Laguerre Gaussian beams

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The last two decades have seen widespread interest in light fields possessing orbital angular momentum, which is associated with azimuthal phase variations within the light field. In particular the orthonormal basis set of Laguerre-Gaussian (LG) beams has been of interest in this regard. An LG beam is typically characterised by two indices, namely the azimuthal index L, which denotes the number of cycles of 2pi phase around the mode circumference and the radial index P where P+1 denotes the number of rings present within the light field. In addition to the fields of sub-diffractive imaging and optical manipulation, light fields with non zero azimuthal index are of central importance in quantum information processing. They permit access to a large multi-dimensional Hilbert space. Recently, multiple methods have emerged to measure the azimuthal index of a LG light field. These include the use of computer-generated holograms, rectangular slits, arrays of circular apertures, triangular and square shaped slits to name a few. However, these methods completely neglect the radial index P and work only for a pre-determined value such as P=0. Without the measure and knowledge of the radial index, it is impossible to correctly neither deduce the orbital angular momentum of a beam nor distinguish between an optical misalignment and a complex radial behaviour. Here, we employ a set of triangular apertures and more generally random apertures to measure both the azimuthal and radial indices simultaneously. The method is generalised to include superpositions of LG beams and detect their relative amplitudes and phases.
Electron vortex propagation in magnetic fields
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While vortices and orbital angular momentum have been studied for many years now in optics, and vortex electron states are seen in condensed matter, it is only recently that electron vortices in free space were first theoretically predicted and then observed. These electron vortices have the same geometrical properties as their optical counterparts, however there are significant differences too, for instance unlike photons electrons have charge and mass, and half-integer spin. Of particular interest are the magnetic properties resulting from the circulation of electronic charge, which have no analogue in optics. Using the Schrödinger equation we investigate the interaction of electron vortices with an external magnetic field, and this allows us to reinterpret known behaviour of electrons in terms of vortex states and orbital angular momentum. Applications are anticipated in electron microscopy, where vortex beams could lead to imaging with new magnetic sensitivity.

Singularimetry – probing chiral surfaces with optical vortices
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Light is a uniquely useful tool to gather information about the structure and composition of interfaces. Ellipsometry for example uses the intensity and polarisation of reflected light to reveal information about the optical properties, such as the dielectric constant. Chiral surfaces on the other hand can be characterised by the amount they turn the plane of linear polarisation upon reflection or transmission. Because the optical probing uses a light beam of finite extent any quantity of the material obtained from an optical probing will be averaged over the beam width.

A more refined way to retrieve information about interfaces in general and chiral surfaces in particular is offered by looking at the reflection of a vortex beam, that is a light beam with a high charge optical phase singularity at its centre. Upon reflection or transmission the high charge vortex generally splits up into a characteristic constellation of single charge vortices which reveals the nature of the material. In contrast to conventional techniques, the separation of the vortices depends not only on the averaged optical properties, but also on higher order terms. We show how the reflection of a vortex beam is effectively a complex aberration, the subsequent orders of which can be tested with higher order vortex beams.

Fibre optics and wave guidelines I
Axial tamm plasmons
M Kaliteevski, C Little, R Anufriev, R Abram, I Iorsh and S Brand
1Durham University, UK, 2Unknown affiliation, 3Ioffe Institute, Russia

Tamm plasmons [1-3] are electromagnetic states that can occur localized at the interface between a metal and a Bragg reflector and which have recently attracted substantial interest as a tool for electromagnetic mode engineering and a simple way to localize light. We have shown how Tamm plasmons can be supported in systems with cylindrical symmetry and, in particular, we have used a transfer matrix method in that geometry to predict their properties. The dispersion of the modes and the distribution of the electromagnetic field have been calculated for a number of different cylindrical structures and as a result we have demonstrated that the Tamm plasmons possess properties that could be attractive for various optoelectronic applications.

Tuneable slow light in nonlinear electro-optic materials
C Denz, S Kroesen, J V Bassewitz, J Herrmann and W Horn
University of Münster, Germany

We demonstrate different approaches to control artificially structured, nonlinear electro-optic materials that allow for fast control of the delay properties by external electric fields.

On the one hand group velocity reduction is realized by a transient energy mechanism in doped photosensitive crystals with a nonlocal response using a pump probe approach. The energy transfer produces a spectral narrow gain line where a large dispersive leads to significant reduction of propagating pulses. Several aspects of this process are presented including multi-gain line configurations, phase-conjugated slow light and external electric field control, yielding group velocities of less than 1 cm/s.

On the other hand, we achieved slow light propagation in passive electro-optic materials employing all-optical and electro-optic delay reconfiguration in a one-dimensional photonic band gap produced by a volume refractive index structure. To maximize the impact on group velocity and to minimize transmission losses, phase defects are inserted into the periodic structure. Thereby, we effectively break the symmetry of the system, leading to a strong localization of modes in the defect area. We were able to demonstrate group velocity reduction of pulses at telecommunication wavelengths using phase-based superstructures as well as chirped structures to achieve closely spaced delay c-band channels with additional electro-optical control capabilities.

To allow small-scale integration and packaging into fiber communication systems, we also present the fabrication and analysis of photonic band gap structures in femtosecond laser-induced, sub-surface waveguides written into lithium niobate wafers with integrated electrodes for electric-field control.

Passive Q-switched mode-locking in a Ytterbium doped bismuthate planar waveguide laser
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A compact, passively modelocked waveguide laser in an integrated cavity is reported in a Ytterbium doped bismuthate glass. Low-loss waveguides were inscribed in the substrate using the flexible technique of ultrafast laser inscription. When pumped using a 976 nm diode laser, continuous wave (cw) lasing was obtained around 1030 nm, with a maximum output power of 314 mW for an input pump power of 478mW, resulting in an optical conversion efficiency of 66%. The high performance of the cw laser, including a slope efficiency of 78% which is close to the quantum defect limit, is attributed to the preserved fluorescence properties of the dopant ions in the waveguide core, as indicated by micro-luminescence analysis. By including a commercially available saturable output coupler with a modulation depth of 6% in the linear cavity, Q-switched mode-locked pulses were obtained with a repetition rate of 1.5 GHz; thereby representing a significant step towards the development of compact mode-locked waveguide lasers.
Tm:YAG waveguide laser fabricated by ultrafast laser inscription

Y Ren1, S Beecher1, G Brown1, A Rodenas1, A Kar1 and F Chen2

1Heriot-Watt University, UK, 2Shandong University, China

Thulium-doped YAG has drawn much attention as a suitable laser material for operation at wavelengths around 2 µm. Subsurface, depressed cladding structure waveguides were fabricated by Ultrafast Laser Inscription (ULI) in Tm3+:YAG (1at.%). To assess the quality of the ULI structures, µ-Raman confocal mapping analysis of the waveguide cross-section was performed to confirm that the waveguide core is unmodified by the inscription process, thus retaining low propagation losses and spectroscopic properties of the crystal. Low loss optical waveguiding was achieved and characterized at 1.55, 1.95 and 3.39 µm.

Dielectric mirrors were applied to the facets of the 9mm long crystal to form a laser cavity which was longitudinally pumped by a cw Ti:Sapphire laser. Lasing was obtained at 1.94 µm with a maximum output power of 70 mW for an input pump power of 720 mW and slope efficiency of 24 %. Further investigation for a range of output couplers and pumping arrangements will allow the efficiency to be further optimized.

Quantum dots I: colloidal quantum dots

Ultrafast transient absorption spectroscopy of HgTe quantum dots

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Bulk HgTe is a semi-metal with a small negative band gap (room temperature $E_g = -0.14$ eV) and thus the energies of transitions in HgTe colloidal quantum dots (CQD) are dominated by quantum confinement, which is determined by CQD diameter. This allows the absorption edge of HgTe CQD to be size-tuned across the near-infrared enabling it, for instance, to be optimised for exploitation of the solar spectrum. Recent theoretical work has also shown that the process of multiple exciton generation (MEG) should be particularly efficient in semi-metal CQD. MEG is a process by which multiple excitons can be formed following the absorption of a single photon, instead of the usual one. The additional excitons can contribute to photocurrent and thus improve the efficiency of solar cells based on CQD. However, the assessment of MEG efficiency requires an understanding of ultrafast exciton dynamics and so here we present for the first time a study of these in HgTe CQD.

Ultrafast transient absorption spectroscopy was used to study the dynamics of photo-induced transmittance changes in samples of HgTe CQD in water. Excitation produced a spectrally broad photo-induced absorption (PA) feature on to which was superimposed a narrower band-edge bleach. Both features decayed on a time-scale of a few 10s of ps. This decay was bi-exponential in the region of the band-edge, where both the PA and bleach contribute, but mono-exponential elsewhere. We also compare the experimental results with tight-binding calculations of the density of states in HgTe CQD.

Spin-flip limited exciton zero-phonon line dephasing in CdSe colloidal quantum dots

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Coherent quantum dynamics of excitons in semiconductor quantum dots (QDs) are of key interest, besides fundamental physics, for many applications ranging from quantum computing to advanced photonics devices. Significant achievements have been reported in this area, however investigating almost exclusively epitaxially-grown
QDs which are embedded in a matched defect-free crystalline environment. With the recent advances in colloidal synthesis, high-quality semiconductor nanocrystals have become more available, with the advantage of being less expensive to fabricate and easier to engineer with a large variety of sizes, shapes and compositions. Despite its importance, measuring the exciton dephasing time in colloidal nanocrystals is technically very challenging. Using an ultra-sensitive three-beam transient resonant four-wave mixing technique in heterodyne detection not affected by spectral diffusion, we have measured the ground-state exciton zero-phonon line (ZPL) dephasing time in high-quality CdSe/ZnS wurtzite colloidal QDs and in a series of quasi-type II CdSe/CdS zincblende QDs with variable core diameter and shell thickness. From the temperature dependence of the ZPL dephasing, the exciton lifetime, and the exciton thermalisation within its fine structure, we demonstrate unambiguously that the physical origin of the dephasing is the phonon-assisted spin-flip to dark exciton states. Remarkably, we show that by tailoring the exciton fine structure through its dependence on dot size and shell thickness, we control the dephasing as expected from the spin-flip mechanism. We find the longest ZPL dephasing time of 110ps at 5K in QDs with the largest core size (5.7nm) and the thinnest shell (9monolayers) in the series studied.

Optical properties of graded-alloy colloidal nanocrystal quantum dots

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We have synthesised nanocrystals with a radial gradient of chemical composition, using the rapid and simple “one-pot” method published by Bae et al.[1]. These nanocrystals are made of an alloy of Cd$_{x}$Zn$_{1-x}$Se$_{y}$S$_{1-y}$, changing smoothly from a predominantly CdSe region at the core to a predominantly ZnS (i.e. wider band-gap) region at the surface. This structure is predicted to impose a smooth confinement potential on quantum-confined electrons and holes within the nanocrystal, which may reduce both the rate of fluorescence intermittency (“blinking”) and the length of the off-period durations by reducing Auger rates [2].

The nanocrystals display a high fluorescence quantum yield of >70%, and less blinking than standard CdSe/ZnS core/shell nanoparticles, suggesting that excitons within these graded-alloy structures are effectively protected from unpassivated surface states. Single-nanocrystal fluorescence spectroscopy reveals homogeneous linewidths of 15 nm at room temperature, reducing to 3 nm at 77 K whilst retaining high photoluminescence stability and brightness.

These early results suggest that these nanocrystals could be promising materials for printable optoelectronic device applications, due to their ease of synthesis and stable emission properties; furthermore, the predicted reduction in the rate of Auger recombination suggests they may facilitate low-temperature spectroscopic study of exciton complexes in colloidal semiconductor quantum dots.


Attractive biexciton interaction energies in CdSe/CdTe/CdS type II colloidal dots

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Electrons and holes are localised in different regions of colloidal quantum dots (CQD) which have a Type II core/shell structure; in comparison, both carriers localise in the same volume in Type I CQD. Growth of different core sizes and shell thicknesses allows control of the electron-hole wavefunction overlap in a Type II CQD, and hence of various properties. In particular, it determines the magnitude and sign of the bi-exciton interaction energy; a large
positive (i.e. repulsive) interaction enables efficient optical gain in CQD whilst a large negative (i.e. attractive) interaction would reduce the threshold for multiple exciton generation and thus increase the potential efficiency of a solar cell based on CQD. To date, studies on Type II CQD have used transient photoluminescence spectroscopy (TPL) and reported large repulsive (~50-100 meV) interaction energies.

In this study, ultrafast transient absorption spectroscopy (UTAS) was used to study CdSe/CdTe/CdS core/shell/shell CQD. Unlike TPL, UTAS can be used to ensure that only relaxed bi-excitons contribute to the observed spectra. Moreover, the second CdS shell ensures that the observed spectra are free from the photo-induced absorption features associated with surface-trapping. These multi-layered CQD were synthesized from single source precursors using the hot injection method. Controlling the quantities of reagents and reaction conditions allowed varying core sizes and shell thicknesses to be synthesized. Each sample was initially characterized by steady-state absorption and photoluminescence (PL) spectroscopy, and PL lifetime spectroscopy. Analysis of the transient absorption spectra of various samples yielded large attractive interaction energies of 30-50 meV.

### Optical and quantum metrology I

**Waveguide integrated quantum photonics: superconducting single-photon detectors and autocorrelators**

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In order to scale photonic quantum information processing protocols beyond few qubits, an integrated implementation is needed. This requires integrating single-photon sources, linear circuits and single photon detectors in a single photonic chip. We have demonstrated the first waveguide single photon detectors (WSPDs) based on NbN nanowires on top of a GaAs/AlGaAs ridge waveguide and reported a quantum efficiency of ~20% for TE mode at 1300nm with a jitter of ~60ps [1]. These detectors are compatible with quantum dot single-photon sources and GaAs photonic integrated circuits.

Here we report further progress in integrated single-photon detectors, particularly polarisation independent WSPDs and integrated photon correlators. Our correlator is based on the integration of two detectors on the same ridge waveguide and enables the measurement of the second-order correlation function without external beamsplitters. It also represents the first step towards integrated photon-number-resolving detectors.

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Nano-optical measurements of novel superconducting single photon detector designs

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Superconducting nanowire single photon detectors (SNSPDs) are a highly promising emerging photon counting technology, offering infrared sensitivity, combined with low dark count rates and sub-100 ps timing jitter[1]. These devices are under consideration for a wide variety of photon counting applications, from quantum cryptography to remote sensing. Next generation device designs based on optical cavities, ultra narrow wires, parallel wire arrays and even nano-antenna enhanced devices are being evaluated to meet the demands of advanced photon counting applications. In this study we use a novel low temperature nano-optical testing setup to investigate a variety of device designs. We are able to probe the local infrared detection efficiency and timing resolution with sub-micrometre resolution. We report on the effects of nano-optical elements, the variation of timing properties with position in non-uniform nanowires [2] and the timing properties with bias of novel parallel wire devices. Enhancing detection probabilities and exploitation of varying timing dynamics with position are investigated.


Multi-pixel detector for photon-correlation measurements in position, transverse momentum and intermediate bases for an extended field of view

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We have developed a 1 x 8 linear detector array with single photon sensitivity. The front-end of the detector array consists of 8 fibres, each of a different pre-determined length. The difference in length between each successive fibre was constant. The fibres are efficiently coupled to a single photon avalanche diode (SPAD) where the arrival times between the eight channels at the SPAD were distinguishable from each other. Thus we convert the spatial position of the photons to temporal information.

Using two of these fibre arrays and two SPADs we were able to measure the correlation of photons produced by spontaneous parametric down-conversion (SPDC) at eight spatial positions simultaneously to access more of the state-space generated in SPDC.

Furthermore, we were able to observe position correlations and momentum anti-correlations of the photon pairs by using Spatial Light Modulators (SLMs) acting as variable focal length lenses to switch between measurement bases. The SLMs were positioned midway between the down-conversion crystal and the 1 x 8 fibre array. By applying different phase holograms to the reflective SLMs, we were able to switch between measurements for position (image plane), transverse momentum (far-field) and intermediate bases.

We obtain the variance product of the conditional probabilities for the position and the transverse momentum measurements, which is found to be one order of magnitude below the classical limit of separability, violating the EPR criterion.
Measuring optical frequency ratios in $^{171}\text{Yb}^+$ to study fundamental physics

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Recently, we have used a femtosecond frequency comb to measure the absolute frequency of the octupole optical clock transition in a single ion of $^{171}\text{Yb}^+$ to a fractional uncertainty of $1 \times 10^{-15}$. High-Q forbidden optical transitions make promising candidates for the next generation of optical frequency standards. However, such transitions are also of great interest for the study of fundamental physics. For example, the dimensionless ratio $R = f_{E3}/f_{E2}$ between the $^{171}\text{Yb}^+$ octupole and quadrupole optical clock transition frequencies has a high sensitivity to variations in the fine structure constant $\alpha$, scaling approximately as $\Delta R/R = -6.83 \Delta \alpha/\alpha$. Also, without the need to measure relative to the SI second, a ratio measurement benefits from the superior stability of the optical standards themselves. Therefore, ratio measurements separated by several years allow a sensitive study of $\partial \alpha/\partial t$.

To demonstrate the potential accuracy of such a ratio measurement, we present details and results from a series of comparisons between two independent frequency comb systems at NPL, based on Ti:Sapphire and Er fibre mode-locked lasers. In our previous work, the absolute frequency of a cavity-stabilised 934 nm laser was measured simultaneously using these two combs, displaying fractional agreement to better than $\pm 1 \times 10^{-17}$. The measurement setups have now been modified to allow the frequency ratio, between cavity-stabilised lasers at 934 nm and 871 nm, to be measured simultaneously using the two combs. The ratios agree at the $\pm 1 \times 10^{-18}$ level, showing that $^{171}\text{Yb}^+$ frequency ratio measurements will initially be limited by the ion standards.

Optical vortices, polarization, coherence and non-Gaussian beams II

The Pearcy Beam

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The importance of Airy beams have recently been appreciated due to their transverse acceleration and self-healing. The Airy function, which underlies these beams, is the first in a family of catastrophe integrals that describe diffraction about caustics.

The next family member is the Pearcey function. An optical Pearcey beam exhibits its own distinct properties: upon propagation it auto-focuses. This phenomenon may be understood as a generalization of the complex source approach to Gaussian beams, and extends to more complicated essential singularities in the complex propagation plane. The Pearcey beam is also self-healing, making its focus impressively robust and providing an excellent potential candidate for application in super-resolution imaging.

This talk describes the Pearcey beam, its focusing effect and underlying propagation theory, and presents recent experimental results in synthesizing Pearcey beams.
Experimental investigation of anomalous behaviour of a phase perturbed random optical field

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Scattering a laser through a highly distorted medium or reflecting a laser from a rough surface, the multiple interference of transmitted or reflected light forms a random optical field. Optical vortices which exist at the points of zero intensity with a spiral wavefront have a random distribution which is decided by the coherence area of the random optical field.

We experimentally generate a isotropic random optical field by scattering a linearly polarized He-Ne laser through a ground glass. From the interferogram of the random optical field and a reference wave, we can obtain the wavefront of the random optical field. Optical vortices then can be located and vortex distribution or density can be calculated. Furthermore, we calculate the continuous part of wavefront from the measured wavefront with a least-squares algorithm. This continuous part of wavefront can be imprinted onto a spatial light modulator (SLM) which acts as a deformable mirror to make a phase correction or a phase perturbation. When the original random optical field is reflected from the SLM surface, the continuous part of wavefront is removed or corrected.

When such a phase perturbed random optical field propagates in the free space, we find the intensity distribution changes in a different way compared with the original random optical field. Therefore, its embedded vortices also experience an anomalous transition. Properties and statistics of optical vortices are investigated as well in such a phase perturbed random optical field.

Conservation and quantization of photon angular momentum in non-uniformly polarized beams

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Beams of light can carry both spin angular momentum, S, associated with the polarization, and orbital angular momentum, L, associated with the angular dependence of the phase. For uniformly polarized beams with rotationally symmetric intensity profiles the spin, orbital, and total angular momentum of a photon are conserved and are integer multiples of Planck’s constant. Thus these quantities provide a discrete state space which can be probed in quantum optics experiments and may be useful for encoding quantum information. We derive the conservation laws and quantization conditions in more general cases where the polarization varies across the beam, using beams generated by conical diffraction in biaxial crystals as examples. The conserved angular momentum of such polarization textures derives from their symmetry under combined rotations of polarization and phase, and is a general linear combination L and S which can be measured interferometrically. We calculate the shot noise in the associated angular momentum current, and hence identify the quantum of angular momentum in such beams.

Fibre optics and wave guidelines II

Silica hollow-core photonic crystal fibres with selective bandgaps in the 2 to 3.6µm mid-infrared region

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In this work we present silica hollow core photonic crystal fibres (HC-PCF) with guidance from 2 to 3.6µm. By carefully controlling parameters during the fibre drawing process, the bandgap of the fibres can be adjusted to a specific wavelength and therefore be tailored to a certain application or laser wavelength. The light is confined inside the core due to the surrounding periodical structure of air holes and fused silica providing a band gap effect.
This leads to a very small overlap of the E-M waves with the glass and therefore the high intrinsic loss of fused silica at this wavelength regime can be overcome. As silica is bio-inert, chemically stable and mechanically robust, these fibres have significant potential advantages over other multi-component, non-silica optical fibres designed to guide in this wavelength regime. We have shown that these fibres have low bend sensitivity, a single-mode like output and high energy pulse delivery capability. All these factors are ideal conditions for a highly flexible delivery system. In particular, we present the characterisation and performance of these fibres at 2.94 µm, the wavelength of an Er:YAG laser. However, the practical implementation of this type of hollow core fibre for surgical applications is a significant challenge and hence novel methods for developing hermetically sealed fibre end tips will also be presented.

Adiabatic passage and spectral filtering of light in CMOS-compatible silicon oxide integrated rib waveguides

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A fully complementary metal-oxide-semiconductor (CMOS)-compatible adiabatic passage of light in the visible range that can be monolithically implemented together with other integrated devices is presented. We experimentally demonstrate that a system of three total internal reflection waveguides, defined by using non-stoichiometric silicon oxide, with a particular variable distance along their propagation direction allows for a highly efficient transfer of light between the outermost waveguides by adiabatically following one eigenmode of the system. Furthermore, we experimentally check its robustness against geometrical variations of the system, a feature that common directional couplers do not exhibit. The measured relative fraction of intensity transferred between the outermost waveguides ranges from 0.87 to values above 0.99 for variations of the geometry parameter values between 20% and 35% [1].

Moreover, we report the first experimental realization of a light spectral filter based on the adiabatic passage technique. We demonstrate that triple-waveguide systems can be used simultaneously as a low and a high-pass spectral filter within a range of wavelengths between 400 and 950 nm. After light is injected into the right waveguide and propagates along the system, long wavelengths are transferred into the left output whereas short wavelengths end into the right and central outputs. The stopband reaches values up to -11 dB for the left output, and around -20 dB for the right plus central outputs. The passband values are close to 0 dB for both cases.


Characterisation of a long period grating refractive index profile through correlation analysis

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The theoretical analysis of long period gratings (LPG) is often limited by poor characterisation of the refractive index profile within the core of the fibre. LPGs are often manufactured with a known period (to provide particular wavelength loss bands) but with poorly characterised UV induced core refractive index change and, often, uncertainly in length. The model is further complicated by the potential for a d.c. component in the LPG core refractive index through the UV inscription and annealing processes. Presented is a novel technique for characterising the refractive index profile of a un-apodized LPG based on the correlation between theoretical models of the loss bands and their side lobes. It is demonstrated that, with a priori knowledge of the cladding refractive index and LPG period, the amplitude and length can be calculated with accuracies of better than 10⁻⁵ RIU and 10⁻⁴ m respectively. Results illustrating the excellent match between theoretical and experimental transmission spectra of an LPG are presented and the potential error based on the uncertainty of the LPG period is discussed.
Direct integration of electro-optically tunable waveguide bragg gratings in lithium niobate by femtosecond laserwriting

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We demonstrate direct integration of electro-optically tunable, type-II waveguide Bragg gratings in lithium niobate by femtosecond laserwriting. A maximum tuning of the reflection maximum by $\Delta \lambda = 625$ pm is observed.

Fabrication of waveguide elements in bulk optical materials by nonlinear absorption of femtosecond radiation has significance for prototyping integrated optics. One of the most attractive aspects of femtosecond integration is the feasibility of producing three-dimensional refractive index changes to fabricate complex networks of photonic structures. Hence, a variety of optical elements such as waveguides, splitters and Bragg Gratings have already been realized. Besides integration in undoped silica glasses it is often desirable to access the unique advantage of high-speed response in electro-optic materials. By integrating waveguide gratings in lithium niobate, the spectral response function can be reconfigured with nanosecond response by an applied electric field. However, up to now waveguide Bragg gratings have not been realized in electro-optic materials.

In this contribution we demonstrate integration of multi-wavelength narrowband Bragg gratings in lithium niobate. The samples are butt-coupled to a cleaved fiber and the spectrum of the grating is read out in reflection. The structure is characterized under different crystallographic orientations and readout polarizations. The central reflection wavelength is adjusted to frequencies inside the C-band to ensure compatibility with fiber communication optics; a reflection bandwidth of $\Delta \lambda = 0.8$ nm to $\Delta \lambda = 1.4$ nm is obtained with maximum power reflection of up to 17%. The filter response is tuned by approximately a half width by an applied electric field.

Ultrafast laser inscription of low loss mid-infrared waveguides in polycrystalline ZnSe

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A directly laser written single mode mid-IR waveguide has been successfully demonstrated in ZnSe with low propagation losses of 1.9 dB·cm$^{-1}$ at 3.39 μm. This is comparable to the losses associated with directly laser written waveguides for near-IR light in Cr$^{2+}$: ZnSe and other crystalline materials. Utilising a negative change in refractive index, the cladding structure of a waveguide was fabricated with the desired dimensions to achieve a chosen waveguide cross-section. Single mode guiding was achieved at 3.39 μm with near symmetric Gaussian distribution and mode field of diameter of 25 x 36 μm. This result represents a significant milestone for the realisation of compact waveguide lasers and high power waveguide amplifiers in Cr$^{2+}$: ZnSe with a view to power scaling the currently available sources.

Multi-beam interference from lensed multicore fibre probes

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Multicore fibre (MCF) is an emerging platform for optical communications and optical sensing. A lensed four core fibre has been fabricated using a conventional fusion splicer. The end-shaping enables overlap in the far field of the output from diagonal cores. The longitudinal position of the crossing point depends on the surrounding material. In air this was found to be 250μm from the tip of the fibre where as in water this extends to 500μm. High contrast fringes are produced at the overlap that can be swept by manipulation of the MCF. A fringe spacing of 2μm was measured that was found to be in agreement with simulation. These fringes could be used for optical trapping in
Quantum dots II: self-assembled quantum dots
Understanding exciton-phonon interactions in driven quantum dots
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The recent experimental characterisation of exciton-phonon interactions in a coherently-driven semiconductor quantum dot (QD), and their interpretation in terms of a two-level system in contact with a bosonic environment, have demonstrated that QDs offer a natural platform in which to explore dissipative dynamics in the solid-state. In particular, the interplay between laser-driven coherent excitonic oscillations and incoherent phonon-induced processes leads to a rich dynamical behaviour, with the driven exciton oscillation frequency and damping rate depending sensitively on the energy scales of both the driven QD and the bulk phonon modes.

In this presentation, I shall outline various master equation approaches to studying exciton-phonon interactions in driven QDs. Quantum master equations are attractive as they naturally relate the system evolution with environmental parameters in an intuitive way, while they are also generally computationally inexpensive. Beginning with the simplest weak exciton-phonon coupling approximation, I shall explore the strengths and limitations of such an approach. Going beyond weak-coupling, I shall present a polaron transform method, which works for stronger exciton-phonon couplings, but which in turn imposes restrictions on the coherent driving strength.

Finally, I shall introduce a recently developed variational master equation technique, derived through a combination of a variationally optimised unitary transformation and the time-local projection operator method. In those limits appropriate for either a weak-coupling or polaron treatment I shall show that the variational master equation yields similar results, but it is also able to capture the excitonic dynamics over a much wider range of parameters where such simpler treatments fail. The accuracy of the variational master equation is verified by its excellent agreement with numerically converged Feynman integral calculations.

Electro-elastic control of self-assembled InGaAs quantum dots
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We demonstrate electrical and strain-driven manipulation of single particles in self-assembled InGaAs quantum dots (QDs). Two samples (A and B) with identical structure design but different dot growth procedures are glued to piezoelectric lead zirconate titanate stacks to allow uniaxial stress along the [110] crystallographic axis. Polarisation dependent photoluminescence on QDs embedded in a charge-tunable heterostructure is performed as a function of both applied sample and piezo bias ($V_{\text{PZT}}$).

We find a large variation in the excitonic response of individual QDs to the applied stress. In Sample A, the majority of excitons blue-shift in energy (between -0.1 and +0.8 $\mu$eV/$V_{\text{PZT}}$). In Sample B, all excitons red-shift in energy (between -0.2 and -2.0 $\mu$eV/$V_{\text{PZT}}$). Furthermore, the applied stress changes the gate bias at which an electron tunnels into the dot due to the change in the electron confinement energy. Using a perturbative Coulomb blockade model, we find the confinement energy in the conduction (valence) band increases (decreases) significantly with
tensile stress, although the absolute values vary from QD to QD. We observe tuning of the confinement energies as large as 13 meV in our experimental setup, much larger than the exciton tuning. These results highlight the sensitivity of the response to strain on each QD’s inherent shape, size and composition. Additionally, the fine-structure splitting is tuned with applied strain. Finally, we show that the different response of two adjacent QDs to stress can be exploited to tune multiple QDs into resonance on the same chip.

**Spectroscopy of charge tunable quantum dots at telecom wavelengths**

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We investigate a single layer of self-assembled InAs quantum dots in an In$_{0.15}$Ga$_{0.85}$As quantum well which emit at $1150<\lambda<1300$ nm at cryogenic temperatures. In order to increase the extraction efficiency, we use a cubic-zirconia super solid-immersion lens. Under non-resonant excitation, we measure the photoluminescence and obtain saturation counts up to ~300 counts/s on a liquid-nitrogen cooled InGaAs detector array, a significant improvement over previous reports [1].

Furthermore, we obtain deterministic charging in the quantum dots. We embed the quantum dots in a charge tunable structure [2] and collect the photoluminescence as a function of applied voltage. Discrete jumps in the emission wavelengths of single quantum dots are visible when varying the applied voltage, a signature of the emission from different charged excitons. We unambiguously identify the excitonic states in the spectra and, by applying the Coulomb blockade model [3], we can extract the electron confinement energy and the Coulomb energies between electrons and holes.

Through polarization dependent analysis, we also measure fine structure splitting on the neutral exciton lines between 34 and 106 µeV, values a factor 3 smaller than previously reported for quantum dots at similar wavelengths [4]. This is promising for entangled photon generation at telecom wavelengths.


**Optical and quantum metrology II**

**Observation of spatial correlated photon pairs in position and momentum with an electron multiplying CCD camera**

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Applications in Quantum Information Processing (QIP) and Quantum Communication would benefit from the large information capacity provided by the ability to access a large state-space. Until now the transverse spatial degrees of freedom (DOF) of correlated photon pairs have mostly been measured by scanning a single-photon avalanche diode (SPAD) or by using detector arrays with a small amount of available pixels, limiting the information capacity. Electron multiplying CCD (EMCCD) cameras with many pixels in an array are more suitable for this type of measurement due to the increased number of available “detectors”. EMCCD cameras offer single photon sensitivity, quantum efficiencies in excess of 90% and are commercially available.

We report the observation of spatial correlations from spontaneous parametric down-conversion (SPDC) with an EMCCD camera in the image plane and far field of a type-I β-Barium Borate (BBO) crystal, showing position
correlation and momentum anti-correlation respectively. The 5mm long BBO crystal, cut for degeneracy and angled for near-collinear output, was pumped with the third harmonic of a Nd:YAG laser (\(\lambda = 355\,\text{nm}\)) to produce a source of down-converted photons (\(\lambda = 710\,\text{nm}\)). The photon flux at the EMCCD camera was 0.02 photons per pixel per image.

After background subtraction, the variance products for the position and momentum marginal correlations in the x-direction and in the y-direction are three orders of magnitude below the classical limit of separability, indicating entanglement of the photon pairs in both transverse dimensions. Furthermore, we show the strength of the spatial correlations violates the EPR criterion.

**Measuring protein concentration with entangled light in an opto-fluidic chip**

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Measurement lies at the heart of all science and technology. Currently, a commonly deployed method for sensing optical path length—for example, physical distance, sample concentration or birefringence—is to use interferometry with classical coherent light.

The prospect of quantum enhanced sensing promises practical applications that notably include measuring light sensitive samples and experiments where the measurement apparatus itself is altered by light. Micro-fluidics offers an accurate means to deliver small volumes of fluid into integrated optics for biological and chemical sensing with interferometry.

Here we report quantum interference of two-photon “NOON” entanglement in an opto-fluidic chip. The chip comprises an integrated circuit of waveguides and a micro-fluidic channel containing room temperature biological samples. The resulting quantum interference enables us to directly measure the concentration of protein (Bovine Serum Albumin) via correlated photon detection statistics.

Both the waveguides and the micro-fluidics are fabricated with laser inscription, which provides an attractive platform to realize practical, miniaturized quantum enhanced sensing devices.

The high visibility interference we observe, despite imperfections of micro-fluidic channel and the presence of a biological sample, supports the promise of integrated optics for realising practical quantum enhanced sensing tools.

**Practical photon number detection using electric field-modulated silicon avalanche photodiodes**

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Here we demonstrate a practical photon number resolving detector, based on a fast-gated silicon avalanche photodiode in which the lateral electric field is strongly modulated. In these devices the in-plane doping profile is engineered to produce discrete pockets of highly doped material, thus dividing a small-area device into a few smaller zones, each of which is sensitive to single photons and coupled electrically through a single semiconducting layer. By applying sub-nanosecond voltage pulses to prevent the total device current from saturating we are able to realise high-speed spatially multiplexed detection.

We first use emission microscopy to probe the lateral electric field profile in these devices. We then investigate the single and multi-photon detection properties in a fast-gated mode with \(f = 0.5\,\text{GHz}\), using the self-differencing technique to resolve the unsaturated detector signals. We clearly distinguish signals arising from optical pulses containing up to 4 photons and we characterise the uncertainty in determining the detected photon number from
the output voltage by modelling the photon number states with the Poissonian statistics of the source. We obtain errors for 0 - 2 photons of \( \varepsilon_0 = 2.2 \times 10^{-10} \), \( \varepsilon_1 = 1.1 \times 10^{-4} \) and \( \varepsilon_0 = 4.3 \times 10^{-5} \), showing the states to be clearly resolved.

We show that using short voltage gates we are able to completely suppress cross-talk, and because all high-field zones are sensitive to single photons during every detector bias cycle electric field-modulated silicon avalanche photodiodes are an excellent candidate for applications in quantum information processing.

*Kilometre range single-photon depth imaging system at 1560 nm wavelength*

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We have developed a state-of-the-art scanning time-of-flight depth imaging system, based on time-correlated single-photon counting (TCSPC), employing a 1560 nm source (50 MHz mode-locked fibre laser) and a superconducting nanowire single-photon detector (SNSPD). Infrared operation is advantageous in terms of improved eye safety and reduced solar background. The SNSPD system detection efficiency is 17.5\% at 1 kHz dark count rates for 1560 nm and the system timing jitter is <100 ps FWHM. Depth profiling measurements were successfully performed under bright daylight conditions on a variety of targets. Depth resolutions of +/- 0.8 mm, 1.1 mm, and 1.5 mm were achieved at standoff distances of 325 m, 910 m, and 4400 m with pixel dwell times of 1 ms, 10 ms, and 2 s, respectively using an output illumination with an average optical output power of less than 250 \( \mu \)W. Uniquely, the performance of the system enabled a 1 mrad field-of-view depth profile movie of a moving object to be recorded at a standoff distance of 325 m using a pixel dwell time of 1 ms. A four-second movie with centimetre resolution in xyz was captured at 10 frames per second, each frame having 10 × 10 pixels. This system has a range of potential applications in the areas of geosciences and atmospheric sensing.
Poster presentation abstracts

Poster session I

Active and adaptive optics

P.01 - Performance evaluation of a liquid crystal based 3D autostereoscopic display

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Over the last few years, many experimental and theoretical research groups, worldwide, have been actively working to demonstrate the use of liquid crystals (LC) as adaptive lenses for image generation, waveform shaping or non-mechanical focusing applications. Particular achievements in the field have concerned the development of alternative solutions for 3D vision.

The aim of this work has been focused on evaluating the electrooptic response of a LC based 3D autostereoscopic display prototype. The strategy for achieving 3D vision has been implemented by including a cylindrical LC lens array, placed in front of a display acting as a lenticular sheet with tunable focal length and controlling the birefringence electrically.

Experiments have been mainly directed to assess the device performance from two viewpoints. On one hand, initial tests led to quantify the angular position of the viewing zones for two-view architectures. The left and right eye views consisted of 2D low resolution images of alphanumeric symbols, specially combined on the display for mimicking a flipping effect before evaluating the reproduction of real 3D illusion. Theoretical predictions were verified by these experiments where values of viewing angles, are within the 3D vision requirements (viewing angles typically smaller than 15° for small displays over short distances). On the other hand, the performance evaluation of the 3D device was tested in terms of angular luminance and image deflections, crosstalk and 3D contrast, within a simulated environment. These measurements were carried out by an autostereoscopic 3D display characterization equipment (angular resolution 0.03°).

P.02 - Measurement of the M2 laser propagation factor using a liquid lens

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The accepted M² measurement methodology detailed in ISO 11146-1 involves sampling the beam width at several positions along the direction of propagation using a camera which is translated with respect to the source. However this approach can be slow and typically requires a large measurement setup which is not practical in many situations. A number of other techniques have been proposed and implemented in commercial instruments; each having limitations in terms of size or performance. In this paper we describe a compact device which incorporates a liquid lens to allow fast, accurate and flexible measurement of M². The measurements from this device are compared against those obtained using the standard technique. Finally we discuss the limitations of this new method and other potential applications.
P.03 - Femtosecond microfabrication using an adaptive optics addressed microlens array

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Direct laser writing is becoming a useful tool in the fabrication of a range of micron scale structures. Typically, a femtosecond laser is focused into a suitable substrate, where multiphoton absorption and avalanche effects cause permanent material changes localised to the focal region. However, the required structures need to be written sequentially, which can lead to long fabrication times. One method of reducing processing times is to insert a microlens array into the beam to create multiple foci. Here we couple a liquid-crystal spatial light modulator (SLM) to a microlens array in order to address individual lenses simultaneously. Individual foci can be effectively switched on or off for fabrication and steered from their natural focus, allowing for the fabrication of aperiodic structures. In addition, the intensity of individual spots can be adjusted and aberrations compensated, enabling a high degree of uniformity across the array. The fabrication of large arrays of voids for volume optics is demonstrated.

Advances in imaging and lasers

P.04 - Low noise InAs electron avalanche photodiodes for imaging applications

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InAs can detect light from the visible up to 3.5µm with good quantum efficiency. This is useful for applications such as active imaging, gas sensing and free space communication. The proven single carrier multiplication characteristics allow InAs electron-avalanche photodiodes (e-APDs) to provide high sensitivity with its low-noise avalanche gain. However due to its narrow bandgap, low operating temperature is often necessary to sufficiently suppress the leakage current. Thus the knowledge of the way in which dark current and impact ionisation vary with temperatures would be useful.

In this work, we measure the dark current, avalanche gain (M) and excess noise factor in InAs e-APDs as functions of temperature. The total leakage current reduces substantially as the temperature decreases from 295 to 77K. The bulk and surface leakage components of the leakage current at each temperature are extracted to allow the calculation of the total leakage current for different dimensions of InAs e-APDs. A study on the temperature dependence of M was also carried out from 77 to 295K and the corresponding electron ionisation coefficients were derived. Across this temperature range, the pure electron initiated multiplication noise (F_e) was also measured up to M~25 to verify that holes do not impact ionise. There is no clear dependence of F_e on temperature and it remains consistently low, varying between 1.45 and 1.6. Having the responsivity of InAs e-APDs, the signal to noise ratio at a particular temperature, bias voltage and radiation wavelength can then be calculated.

Biophotonics

P.05 - Phase sensitive-optical low coherence reflectometry for bio-sensing applications

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LNE developed a Phase Sensitive-Optical Low Coherence Interferometer (PS-OLCI) to metrologically characterize any type of optical fiber. The set-up consists of two Michelson interferometers: one to characterize the device under test and one to sample the acquisition, thus it allows to get information in the spatial domain, on the spatial
transmittance, as well as in the spectral domain through Fourier transform. Therefore, it gives also access to spectral transmittance and to the phase of the device under investigation as a function of the wavelength.

Since there is a lack of reference technique in the biological domain to measure very low concentration of molecules, LNE adapted its PS-OLCI to characterize optical biosensors response, helping development of new interrogation techniques.

An optical biosensor based on polymeric material, composed of a planar cyclic micro-resonator in the shape of a racetrack vertically coupled to a straight waveguide is currently under investigation.

The micro-resonator has been completely characterized by PS-OLCI, then surface glucose sensing has been performed. From spatial measurement the opto-geometric parameters of the micro-resonator are calculated. The spectral measurements show a resonant wavelength shift on the modulus, and an evolution of the slope of the phase signal as the concentration of glucose changes. A relationship between the molecule concentration and the measured optical parameter can be set to get the molecule concentration. A sensitivity of 0.1 pg/mm² has been reached on glucose detection from phase measurements. This demonstrates the interest of the PS-OLCR as a part of the interrogation tool also.

P.06 - Light-sheet tomography for in vivo Imaging of arabidopsis root

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Meeting future global food demand will require designing new plant phenotypes better able to adapt to non-optimal soil types. The ability of a plant’s root system to interact with the microenvironment of soil determines how effectively it can extract water and nutrients. Hence, in order to develop the fast and cost effective phenotyping techniques needed to develop efficient root structures, in vivo imaging in soil is required. To date this has not been possible due to high density of scatterers and absorbers in soil or because transparent soils do not sufficiently model the heterogeneity of a soil’s microenvironment. We present here a new form of transparent soil containing a wide range of refractive index matched particles such that imaging of plant roots is possible in vivo with minimal scattering or absorption in the soil. Due to the low density of root structures, i.e. relatively large spaces between adjacent roots, we are able to show a new form of lightsheet imaging which does not rely on fluorescence, but which relies solely on scattering from root surfaces in order to build up a three dimensional image of the plant roots.

P.07 - Optical designs to improve opto-electronic neural stimulation with micro-LED arrays

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The breakthrough discovery of a nanoscale optically gated ion channel protein, Channelrhodopsin 2, allowed the genetic re-engineering of neuron cells to be photosensitive. Combined with an genetically expressed ion pump, Halorhodopsin, it became possible to directly stimulate and inhibit individual action potentials with light. This work reports developments undertaken as part of the European project, Optoneuro, which is developing ultra-bright electronically controlled optical array sources with enhanced light gated ion channels and pumps for use in systems to further our understanding of both brain and visual function.

Micro-LED arrays permit spatio-temporal control of neuron stimulation on sub-millisecond timescales. However they are disadvantaged by the light emission distribution of the LEDs and the fill factor that can be achieved in array
form. We present the design and implementation of a projection system combining a micro-LED array with micro-optics that improves the fill-factor by collecting a larger proportion of the LED emission and directing it correctly to the sample plane. This approach allows low fill factor arrays to be used effectively, which in turn has benefits in terms of thermal management and electrical drive from CMOS backplane electronics. The entire projection system is integrated into a microscope prototype, which provides stimulation spots at the same size as the neuron cell body.

P.08 - Nanothermometry: Quantum dots for temperature sensing in biological environments

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Bridging the realms of physics and materials science with the life sciences, nanoparticles have spent many years at the forefront of biological and medical research. Quantum dots can be fabricated to have particular emission properties and can be labelled to target specific binding sites in biological samples to act as biomarkers[1]. A class of QDs made from cadmium telluride show a peak emission wavelength which increases linearly with temperature[2] and have potential to become useful biological nanothermometers.

We use optical traps to generate localised heat in samples and measure this heating using cadmium telluride (CdTe) QDs. A conventional optical tweezer system was modified to incorporate a number of different sources to controllably heat our sample, an excitation source and spectrometer. Using samples which contained CdTe QDs in solution, we optically trapped particles using laser sources of different wavelengths and trapping powers whilst recording the emission spectrum of the CdTe QDs. Shift in emission spectra indicated temperature shift within and nearby the optical trap. Commercially available 2.3nm diameter CdTe QDs, em λ=540nm at 25°C,(Plasma Chem) which exhibit an emission shift of 0.6nm/°C were used to quantify localised heating by focused laser beams in a variety of samples. We discuss the limitations of the technique including quenching by surrounding liquid and cytotoxicity.

We have demonstrated the use of CdTe QDs as nanothermometers to measure heating in samples due to a focused laser beam with sensitivities of 0.6˚C. These particles hold promise for performing temperature measurements with high spatial resolution in biological environments.


P.09 - Cavity Enhanced Absorption Spectroscopy (CEAS) as a detection technique for microfluidic devices

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The detection sensitivity of conventional absorption spectroscopy for microfluidic devices is poor due to short optical path lengths through the sample. One way of increasing the effective optical path length is by using cavity enhanced absorption spectroscopy (CEAS), in which a microfluidic device is placed between two highly reflecting mirrors to achieve multiple passes of a laser beam through the sample. The effectiveness of the approach is largely determined by the extent to which scattering and absorption losses introduced by the microfluidic device can be minimised.

This work investigates the effective optical path length and detection sensitivity in CEAS measurements employing microfluidic devices made using various materials (e.g. fused silica, Zeonor®, anti-reflection coated PMMA, tinted PMMA, clear PMMA) and fabrication techniques (e.g. double sided adhesive, photoresist bonding and milling).
The microfluidic device was placed inside a 13 cm long optical cavity formed from two concave mirrors (R_{400-800 nm} = 99±0.3%, radius of curvature 1 m) at normal incidence to the laser beam propagation axis. A broadband light source (≈500–1800 nm) and a fibre-coupled spectrometer were employed. The effective path length and detection limit for various microfluidic devices were estimated through absorption measurements on aqueous solutions of potassium permanganate. The intensity of the light beam existing the cavity output may be related directly to the cavity losses, and therefore used to estimate scattering and absorption losses of the microfluidic devices. Future work will focus on using CEAS for studying chemical reaction kinetics using the microfluidic device with the highest detection sensitivity.

**P.10 - Catadioptric micro-optics**

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We present a novel class of single-component optical systems manufactured through a combination of precision diamond machining and metallic coating processes. These systems combine multiple refractive and reflective surfaces, allowing the fabrication of miniature, complex optical systems. The design of such a compact optical system leads to very tight tolerances required for surface separation and alignment which would be difficult at best to achieve in a multi-component system. Manufacturing a single component, multiple surface optical system allows us to utilise the intrinsic positional accuracy of diamond machining technology to achieve these rather challenging mechanical tolerances.

To illustrate this, we present designs for the Extremely Small Microscope, a catadioptric objective lens designed for use in endoscopic microscopy, and the Extremely Small Telescope, believed to be the world’s smallest Cassegrain telescope.

**P.11 - Novel nanotechnologies for multiple spatially and temporally resolved live single cell membrane sampling and analysis**

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Studying biology at the single cell level is of profound importance as the very concept of cellular heterogeneity within supposed ‘identical cell populations’ is the basis for how many diseases develop, especially cancer. No cancer or disease is ever diagnosed at the first cancer or diseased cell level, but having a platform that can analyse and compare components of a diseased cell’s proteome relative to that of a normal cell within the same cell population would be a huge step in that direction.

Using a system where optical traps are generated holographically with a spatial light modulator (SLM), we can accurately control multiple mono-disperse lipid-coated microbeads (or Smart Droplet Microtools, SDMs) within a microfluidic cell culture environment. We are able to spatially and temporally resolve sampling of various membrane associated fluorescently tagged proteins from multiple individual adherent viable cells and cell lines in a microfluidic culture environment and can sample repeatedly if necessary both before and after the addition of various biological and chemical reagents. This technology has the potential for subsequent downstream processing of the SDMs and their cargo for quantitative analysis and for delivering stimuli and other reagents to the cells.
Diffractive optics

P.12 - Design and fabrication of transmissive and reflective diffractive optical components for mass replication

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Diffractive micro-optics is a mature technology capable of producing optical functionalities that cannot be replicated easily using other optical manipulation techniques. The standard method of fabrication used in the manufacture of components on glass substrates is a combination of multiple exposure photolithography and dry (reactive ion) etching. This fabrication technology, which has been used to produce ultra high efficiency (>95%) diffractive optical elements, is not ideally suited to the production of large numbers of devices as it is time consuming and subject to non-reproducible errors due to misalignments and etch errors in the total surface relief profile. A potential method of overcoming this drawback is the replacement of the multi-stage fabrication cycle with a single, direct written process. This would remove the majority of the errors associated with the mastering as well as significantly reducing the overall fabrication time. The direct written substrates, which can be created with up to 256 greyscale levels, can then be etched, using a standard RIE process, to produce a high fidelity glass master suitable for mass replication using one of the polymer mass replication techniques, such as micro-embossing.

In this paper, we will present high fidelity diffractive optical elements suitable for use within a mass replication process. The additional considerations, such as profile reversal, polymer surface conformism and substrate shrinkage, that must be accounted for during the transfer from simple glass master to final polymer device will be studied in detail and methods for the mitigation of these effects presented.

Optical tweezing and micro-manipulation

P.13 - Optical control of microparticle morphology in the liquid phase

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Since Ashkin's pioneering work, optical tools, and particularly Gaussian beam traps, have been employed in the manipulation of microscopic particles across the sciences.

However, in the vast majority of cases, the particles in question are limited in shape. For liquid microdroplets, an area-minimising surface tension imposes a spherical interface. For solid particles, morphological constraints may also result from a natural crystalline form. Typical existing procedures for sculpting arbitrary shapes, such as two-photon optical etching, are serial, time-consuming and require high-power lasers.

We demonstrate that systems of conventional optical traps are able to deform oil-in-water emulsion drops displaying ultralow surface tension. Furthermore, this is achieved using a simple bench-top dual-trap system at high numerical aperture and moderate optical power. Indeed, the introduction of holographic diffractive elements would extend this to an arbitrary number of traps as required.

By developing specific surfactant formulations, deformation of a range of different oils and monomer droplets will be made accessible. After deformation, in-situ polymerisation will allow the particles to retain an aspherical shape. In combination with microfluidic droplet production, this offers a route to high-throughput manufacture of shape-adapted polymer microbeads.
P.14 - Measuring the interaction between Uvr proteins and DNA using an optically-controlled force probe

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DNA repair begins with the identification of DNA damage sites, the dynamics of which are not presently understood. Here we apply a novel single molecule manipulation technique to study how the Uvr family of proteins locate damage. We use a nanofabricated probe to measure the binding interaction between single protein molecules and DNA. This ‘nanoprobe’ is optically trapped at three locations on its structure and has a protruding tip 200 nm wide\textsuperscript{1}. By scanning the DNA with the tip, rotational deflections provide an accurate measure of the resistive forces experienced when a bound protein is encountered.

To achieve force measurements with sub pico-Newton resolution and a 10 kHz sampling rate, we use a custom CMOS sensor and control electronics\textsuperscript{2}. Force values are derived from the change in probe position using bright field imaging and laser tweezers calibration.

To permit successful introduction of the probes into a biologically compatible environment, we have developed a unique flow cell that allows components to be added in controlled microlitre volumes\textsuperscript{3}. In addition to high speed probe imaging, fluorescence imaging is used to observe the complete ensemble of the nanoprobe and quantum-dot labelled proteins bound to DNA. This provides confirmation of the underlying process, which involves scanning over immobile proteins or dragging individual proteins along the DNA.


P.15 - Optical trapping with optical spirals containing orbital angular momentum

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We explore the use of optical spiral patterns that contain orbital angular momentum (OAM) to trap airborne particles. The use of optical traps for airborne particles is often complicated by the fact that aerosols within the trapping chamber have a reasonable probability of coalescing with a trapped particle as an experiment is being undertaken. The use of optical ‘shields’ has previously been used to help protect traps under these circumstances. We examine the ability of spiral traps to both shield and load particles as required. We show that the behavior of such traps, in terms of the sizes of trapped particles, the overall ability to trap and the particle dynamics within the trap are highly dependent on the trapping power, and that the OAM can be used to aid trap loading. We also examine the use of such traps to confine and rotate very large objects such as lycopodium particles (> 50 microns in diameter, for example) in a fluid medium.

P.16 - Arduino controlled optical tweezers

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The ability to make small form optical tweezers with simple control systems is useful for integration of low cost instrumentation in, for example, teaching laboratories. We demonstrate the use of a low cost programmable microcontroller that can act as a laser driver and data analysis device for a simple optical tweezers system with a quadrant photodetector to enable trap calibration. Our choice of device is the Arduino board, which costs around £20,
and is used to drive two low power laser diodes. In addition to cheap electronic control and analysis we make use of simple beam shaping optics and an aspheric lens with a high numerical aperture (around 0.55). Although modest compared to standard tweezers this is sufficient to achieve trapping. We show trapping and power spectrum analysis from such a system and discuss the technical challenges of working with such devices and the trades off that must be made in comparison to using a high specification or commercial device.

P.17 - Optical red blood cell sorting
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Cell based therapies are becoming a reality and hold great promise in applications as wide ranging as eye surgery and blood transfusion. In the latter, large numbers of industrially generated red blood cells need to be monitored and/or sorted to remove the risk of the teratomas which are associated with non-fully differentiated stem cells. Because of the volumes of cells involved, and their subsequent in vivo use, a passive monitoring/sorting approach is needed which does not rely on cell labelling.

We have previously shown that optical techniques have the ability to sort according to size-dependant polarisability: i.e. between different particles depending on their intrinsic properties, i.e. size, shape, and refractive index. We exploit this passive sorting ability to sort stem cell derived RBC models made of both inert and biological content: i) using polymer spheres and ii) using an HL60 cell line. The latter is a cell model being used to develop the scaling up RBC production. Hence, the results of the HL6 experiments can be used as a good indicator of how red blood cells will perform under similar conditions.

P.18 - Expanding the toolbox for optical manipulation of metal nanoparticles with holographic optical tweezers
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Optical tweezers have emerged as a tool to optically manipulate metal nanoparticles, reaching beyond their conventional application of trapping transparent microscopic objects. We present a holographic tweezers workstation to optically trap, move and characterise metal nanoparticles. We investigate the trapped nanoparticles spectroscopically and monitor their plasmonic interactions.

Our advanced darkfield imaging system enables us to simultaneously image and trap individual metal nanoparticles without compromising the high numerical aperture of our trapping objective. The versatility of holographic tweezers allows us to create multiple traps while the beamshaping abilities of the spatial light modulator are able to correct for aberrations of the trapping optics. We monitor the improvement of the optical trap with video-based nanoparticle tracking. Furthermore we theoretically assess the capabilities and limitations of video-based tracking for nanoparticle position detection, in particular with respect to acquisition frequencies below the corner frequency.

P.19 - Microsoft kinect interface for controlling holographic optical manipulation
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Initially a tool for physicists, optical tweezers have become widely used in many research fields, most notably within the life sciences. As with most scientific instruments, optical tweezers were initially constructed in research labs; however, due to their increasing popularity, more “user friendly” systems are now in demand in order to allow the
many advantages of optical tweezers to be exploited without a prior grounding in optics and optical technique. This drive to develop more intuitive ways of control has also been a major driving force in the gaming industry, where high-end, low-cost components now allow the user to fully interact with a virtual world, rather than with the traditional joystick. Systems such as the Microsoft Kinect have given the user a more instinctive method of control. Here, we present a holographic optical tweezers system that can be controlled using a low cost Microsoft Kinect. Multiple spots can be generated and manipulated, either individually or together, through a series of pre-programmed gestures. We also draw comparisons between the Q-value of holographic spots controlled by the Kinect and by a pre-programmed holographic sequence.

P.20 - Acousto-optically generated potential energy landscapes: potential mapping using colloids under flow
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One dimensional optical potential energy landscapes created using acousto-optical deflectors are characterized using colloidal particles driven by a solvent flow. The full optical potential of both single optical traps and complex landscapes composed of multiple overlapping traps are determined using a simple force balance argument. The potential of a single trap is shown to be well described by a Gaussian well and the magnitude of the trap stiffness is found to be consistent with those obtained by thermal equilibrium methods. We also directly obtain the depth of the optical trap, which is shown to vary linearly with the laser power, as is the trap stiffness. Finally, various complex optical landscapes are generated from individually controlled optical traps. The optical landscapes are very well described by a sum of single Gaussian optical traps. This offers the potential for the fully controlled design of any potential landscapes, constructed from single basic optical traps.

P.21 - Single aerosol trapping with an annular beam
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In this work we demonstrate the trapping of aerosol droplets using an annular beam, formed by blocking the central portion of a Gaussian beam, and explore the improvements over conventional Gaussian beam traps. Recent work on the modelling of single particle dynamics within an optical tweezer trap has indicated that the use of annular beams can increase the range of particles which can be trapped. [1] We now experimentally verify the findings of this model and show the trapping improvements which can be achieved with this beam type. We confirm that the annular beam does allow smaller droplets to be trapped when compared to the Gaussian beam, and that these droplets may be trapped at higher powers without being displaced out of focus or lost from the trap due to the increased scattering forces. We also use back focal plane interferometry to confirm a significant increase in the axial to lateral trap stiffness ratio when an annular beam is used.

Silicon and carbon photonics

P.22 - Electronic structure and optoelectronic properties of strained Ge nanowires with different orientations
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The interest in semiconductor nanowires is driven by the continued need for downscaling of electronic devices. For all but extremely thin nanowires, their conduction band quantised states can be obtained reliably using the effective mass method, which produces independent sets of bound states associated with each valley. With an anisotropic effective mass describing the X and L-valleys, the reciprocal mass tensor, expressed in the wire's natural coordinate system, takes different forms, depending on the wire orientation, and may lead to lifting of the degeneracy of some of the equivalent valleys. Ge is an indirect band gap semiconductor, but with ~ 0.2 eV difference between its direct (\(\Gamma\)), and indirect (X and L) valleys, hence the character of low-lying quantized states sensitively depends on both the strain conditions and the wire orientation, and both can be employed to tune the wire electronic structure for a particular application, similar to the case of Ge quantum wells. The electronic structure is calculated for germanium nanowires of different growth directions embedded in an insulator, and the results are then used to investigate the prospects of employing Ge nanowires in an injection laser. In particular, the required doping density for filling the low-lying indirect valleys and the electron injection efficiency into the direct valley are calculated, and compared to the case of Ge quantum wells.

P.23 - Photonic crystal cavity based cascaded modulators and demodulators for a WDM system
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Wavelength division multiplexing (WDM) and demultiplexing are the key functions of any optical interconnect. In conventional on-chip interconnects, multiple lasers are modulated separately and multiplexed into a single channel using a complex AWG system. At the receiver end, each channel is detected separately after demultiplexing. Such schemes incur significant optical losses due to large number of interfaces; furthermore, due to system complexity, such circuits requires very precise fabrication technology.

Here, we present a new system based on photonic crystal cavities vertically coupled to a low refractive index contrast bus waveguide that offer a solution to this challenging problem. The low mode volume of the photonic crystal nanocavity offers very low switching energies when used as a modulator. With the incorporation of defects into the silicon host material, a wavelength selective photodetector can also be created as the ideal counterpart to the cavity modulator. By cascading such nanocavities, each with a unique resonance wavelength, a simple and highly effective WDM system can be created which may be scaled up to terabit data transmission with relative ease.

As a preliminary demonstration, we have achieved a modulation speed of 1Gbps by forward biasing a pin diode embedded in the photonic crystal cavity. The use of a large bus waveguide with low refractive index enables us to achieve a low fibre-to-fibre insertion loss of 2.8dB. The same modulator is then used as a detector by implanting defects into silicon.
Density matrix modelling of Ge/GeSi quantum cascade terahertz lasers

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The prospect of making silicon-based quantum cascade lasers (QCLs) has attracted considerable research interest in recent years, due to their significant potential advantages including a mature Si processing technology, the prospect of integration with Si microelectronics, and superior thermal performance to that of III–V devices. Amongst various proposed designs, with different material compositions and substrate orientations, (001)-oriented n-type Ge/GeSi structures utilising L-valley intersubband transitions appear to be the most promising due to a small quantisation effective mass, and hence large optical matrix elements, and practically realisable layer widths. While all the previous simulations for group IV-based QCLs used the rate equation model, this neglects the coherence effects and is of limited usefulness for predicting QCL performance, particularly in the terahertz range. In this work, a quantum-mechanics transport model for Ge/SiGe QCL simulation has been developed, using the density matrix (DM) approach. In contrast to the existing DM formulations which have been used to simulate III–V based QCLs, the present model accounts for the role of all the QCL states in coherent transport, or in optical transitions, or both. The simulator includes all the principal scattering mechanisms in Ge/SiGe heterostructures: intravalley scattering due to interface roughness, alloy disorder, ionized impurities, electron-acoustic phonon and optical phonon interactions, and intervalley phonon scattering. It was used in conjunction with a semi-automated optimization algorithm to identify heterostructure designs for bound-to-continuum Ge/GeSi QCLs, and to compensate for the gain-reduction associated with diffuse Ge/GeSi interfaces.

Incandescent emission from graphene films

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Incandescent emission from graphene has been the subject of much recent interest. For example, Yu et al have demonstrated incandescent emission from large area graphene (0.5 cm²), both on a quartz substrate and free standing. An effective blackbody temperature of up to 1700 K was extracted from the measured emission spectra. Freitag et al investigated the thermal emission from large (55 μm) back-gated transistors made from exfoliated graphene. They showed that the measured spatial variation of the IR emission can be used to extract the temperature distribution, carrier densities and spatial location of the Dirac point in the graphene. The graphene also acted as a grey body emitted (Planck’s law, modified by an emissivity), with an emissivity of ~1.6%.

The aim of this work is to investigate incandescent emission from graphene and few layer graphite, produced either by manual exfoliation from high quality graphenium flakes, or grown onto Cu by CVD and transferred onto Si/SiO₂ wafers. Gold contacts were deposited on the active area of the samples, which ranged from ~100μm² to 1mm². Spectral and spatial characteristics of the emission were measured, with samples mounted in an evacuated chamber, as a function of current through the graphene. The emission properties of the different samples are discussed with reference to the calculated emission from a blackbody source.

Room temperature 2 micron fluorescence from Tm³⁺ doped silicon thin film

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In a silicon host, fluorescence from rare earth dopants such as Tm³⁺ is difficult to detect at room temperature due to quenching. This is due to the clustering of the rare earth ions, resulting in increased non-radiative decay pathways at temperatures approaching ambient. In this study we report Tm³⁺ doped silicon thin films fabricated using
femtosecond pulsed laser deposition (fs-PLD) and demonstrate the Tm$^{3+}$; $3\text{F}_4$ to $3\text{H}_6$ transition to be active at room temperature. The doped film was excited using an 808 nm laser and a broadband 2.04 µm fluorescence is recorded with an FWHM of 164 nm and a decay lifetime of 250 µs. Structural characterisation of the film was carried out using SEM and AFM. Analysis using Raman spectroscopy indicates a mixture of crystalline and amorphous silicon nanoparticles existing within the film. By controlling deposition parameters such as substrate temperature it is possible design films with a given amorphous to crystalline ratio. High rare earth doping concentrations in silicon can be achieved via the fs-PLD process employed in this research.

Channel waveguides were later fabricated using laser micromachining of the thin films. Such microfabricated Tm$^{3+}$ doped thin films and waveguides can form the platform of a compact device with integrated optical and electrical functionalities operating in the 2 µm region. Such devices have applications in identifying gasses, organic liquids and biological samples.

**P.27 - Group IV photonic devices and modulation predictions**


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Mid-infrared (MIR) group IV photonics has attracted increasing attention in the last few years. It is driven mainly by the lure of possible applications such as chemical-bio-physical sensing, free-space communications, thermal imaging and infrared countermeasures. In this paper we present experimental results for passive MIR photonic devices realised in different material platforms. Propagation losses of 0.6-0.7 dB/cm for silicon-on-insulator (SOI) rib waveguides, 3.6 dB/cm for silicon-on-sapphire and 3.9 dB/cm for silicon-on-porous silicon strip waveguides demonstrate the possibility for low loss waveguiding at 3.39 µm wavelength. SOI rib and strip waveguides have also been characterised at wavelengths longer than 3.7 µm. Propagation losses of 1.5 dB/cm at 3.73 µm and 1.8 dB/cm at 3.8 µm have been measured for rib waveguides, whilst submicron strip waveguides exhibited propagation losses of 5.9 dB/cm at a wavelength of 3.74 µm. 1×2 multimode interference (MMI) splitters and racetrack resonators based on submicron SOI strip waveguides have been experimentally examined in the 3.72-3.88 µm wavelength range. Optical losses of 3.6 dB/MMI and a ring Q-value of 7.1 k were obtained at 3.74 µm. We also present predictions for electroabsorption and electrorefraction in silicon and germanium using the free charge-carrier plasma dispersion effect over the 1.2-14 µm wavelength range. Electro-absorption modulation is calculated from impurity-doping spectra taken from the literature, and a Kramers-Kronig analysis of these spectra is used to predict electro-refraction modulation. The predictions suggest that electroabsorption modulators will be more effective at wavelengths longer than 4 µm.

**P.28 - Charge transport efficiency in Ge/Si single-photon avalanche diodes**

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Avalanche photodetectors (APDs) designed around a Ge/Si heterojunction provide a number of benefits to device operation, not least of which is their compatibility with existing cost-efficient manufacturing infrastructure and the ease with which absorbing and avalanche regions may be separately optimised. However, as with similar devices grown from other material systems, the introduction of the heterojunction requires consideration of an additional issue: transport of the optically-generated charge over the heterointerface. The efficiency of such a process is of significantly greater relevance in Geiger-mode devices, also known as single-photon avalanche diodes (SPADs), where poor performance will lead not simply to a proportional reduction in the amplitude of the detected electrical signal but to a fraction of incident photons not being detected.
A stochastic Monte Carlo multi-band transport simulation is applied to determine the impact of heterojunction-limited charge transport on electron-triggered Ge/Si SPAD structures. This method enables the variation of heterojunction transport efficiency with biasing and background impurities of various magnitudes and types to be analysed, including the probabilistic distribution of the transport process. Comparison of the relative importance of different quantum-mechanical and semi-classical transport processes leads to potential routes for device optimisation, which must be considered in the context of design constraints such as the quality of available material and dark current levels.

**Advances in laser science**

**P.34 - Excess noise induced by optical feedback in 6.1-um quantum cascade lasers under well-defined conditions**

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For the application of distributed-feedback quantum cascade lasers (QCLs), it is necessary to understand excess noise under optical feedback from external components. We have measured the excess noise under well-defined conditions: A 6.1-um QCL with a cavity length of 2 mm operating at room temperature was used in the experiments, whose a-factor, evaluated by using the self-mixing technique, was -1.7. The fraction of the reflected field coupling back coherently into the lasing mode, f, which was difficult to know in the mid-infrared region due to the unavailability of optical fibers, was estimated to be more than 0.6% by also employing the self-mixing method. No coherence collapse was observed, even in such a comparatively-high f. In the experiments, the output light from the QCL collimated with an antireflection-coated Ge lens was divided in two with a beam splitter. A reflecting mirror moving with a vice coil was placed at the end of one arm, and the light was returned to the QCL. The other beam transmitting the beam splitter was focused onto a photovoltaic detector. At first, relative intensity noise was measured at 30 MHz with the moving mirror being stopped. Then, without changing the setup, the moving mirror was oscillated, and the self-mixing waveform appearing at the anode of the QCL was monitored. We were able to obtain the so-called feedback parameter from it and estimated the f. The characteristic of high resistance to the feedback light was due to a relatively-small a-factor and the long cavity length.

**P.35 - Graphene based Q-switched thulium-doped fibre lasers at 2 micron**

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Q-switched thulium-doped fibre lasers (TDFLs) oscillating in the eye-safe wavelength range of 1.8-2.1 micron offer significant advantages for many important applications, such as remote sensing, LIDAR and medical surgeries. We report our numerical and experimental investigation of graphene based passively Q-switched TDFLs. The characteristics of saturable absorption of graphene films at 2 micron were studied in order to develop passive Q-switches of high performance. The numerical simulation of Q-switched TDFLs is based on the coupled rate equations. The laser output characteristics including pulse width, pulse energy and repetition frequency are calculated for different levels of pump power and fibre lengths. The effects of the number of layers of the graphene films on the performance of Q-switching are investigated. Using the numerical simulation results, the designs of Q-switched TDFLs are optimized. The experimental results of the Q-switched TDFLs will be presented.
P.36 - Direct measurement of the junction temperature of a DFB laser diode used in tunable diode laser spectroscopy

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Correct thermal characterisation of distributed feedback (DFB) laser diodes is important for their stable and efficient operation. Laser diode spectral, electrical and dynamic parameters are all dependent on device temperature. For gas detection using tunable diode laser spectroscopy (TDLS), the emission wavelength is tuned across a gas absorption line by altering the diode’s injection current and / or its setpoint temperature. The device temperature is nominally set using a thermistor attached to a Peltier element, however this sensor does not necessarily have good thermal contact with the laser cavity and is relatively unaffected by additional heating of the cavity by the injection current.

We have investigated techniques previously developed to measure the junction temperature of devices including LEDs, high power laser diodes and low power GaN laser diodes. In the first technique, the device is driven with a narrow current pulse while measuring the diode forward voltage. In the second technique, the device is operated under continuous wave (CW) conditions and the junction temperature is related to changes in the emission wavelength at different injection currents and nominal operating temperatures.

These techniques have been applied to a quantum well InGaAsP-based DFB laser diode used in TDLS, for the first time. Compared to previous studies, our DFB laser has a lower forward voltage, and the effects of temperature variation are reduced, nevertheless repeatable measurements have been made. Results will be presented for a 1651nm DFB laser, comparing the measured junction temperature with that measured using the standard packaged thermistor.

P.37 - The increase of the output power value of gas ion lasers in presence of noble gas additions

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In the paper authors will present their research results on phenomenon of advantageous influence of noble gas additions on the output parameters of gas ion lasers, especially argon and krypton ion lasers. In theirs previously published papers authors noticed that small additions of argon can increase the output power value of several KrII laser lines of the krypton laser up to 30% in comparison to output power of laser filled with pure krypton. Authors recognized these results as very promising and worthy further researches. In this paper authors will present following results of their investigations. Authors have observed that influence of small neon additions to the krypton discharge causes much stronger increase of the output power of KrII laser lines in krypton laser that previously observed for argon additions. Moreover the neon additions increase the output power of several ArII lines in argon ion laser too.

The magnitude of power increase depends among others on laser line wavelength. Authors will present results of their measurements and will try to explain this phenomenon. In authors’ opinion this phenomenon results from compound of several effects important for laser action in gas ion lasers: the gas pumping effect which occurs in gas ion lasers and different speeds of this effect for active gas and admixture gas, the influence of the ion concentration on the laser generation parameters, differences of ionization energy value of particular noble gases. Measurements for individual laser lines were performed in full range of gas pressures, mixture compositions and supply conditions. Because ion gas lasers are still important sources of high quality laser radiation in the visible range as well in the ultraviolet range, this phenomenon could find the practical usage in these ion lasers applications where the output power value is the important parameter.
Metamaterials and cloaking

P.38 - Maxwell’s Fishpond

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Maxwell’s Fishpond is a remarkable transformation device which has the property of perfectly imaging from any point on its surface, exactly as happens on the surface of a sphere (at least in the ray-optics limit). However, building one where the wave dynamics are clearly visible, so that it is useful as a demonstration - rather than only for an experiment - is a demanding task. Here we show how we demonstrate some of the remarkable features of transformation optics with a water-wave version of the fisheye - the ‘Maxwell’s Fishpond’. Our Maxwell’s Fishpond is capable of reforming a disturbance up to five times, although such a feat required taking considerable care, close observation, and a little luck. This success suggests other wave versions of similar optical devices, such as the Eaton or Luneburg Lenses should be useful demonstrators, and we will discuss the necessary requirements. Indeed, our current Maxwell’s Fishpond is giving good service as an experimental third-year undergraduate project.

Nanophotonics and plasmonics

P.39 - Homogenous silver-glass nanocomposite

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Glasses and other dielectrics containing metal nanoparticles are of interest due to their unique linear and nonlinear optical properties. These properties are dominated by the strong surface plasmon resonances (SPRs) of the metal nanoparticles. The spectral position and shape of these SPRs can be designed within a wide spectral range throughout the visible and near-infrared spectra by choice of the metal and the dielectric matrix or by manipulation of the size and spatial distribution of the metal clusters. Therefore, these compound materials are promising candidates for many applications in the field of photonics.

We present a dry process for controllable generation of silver nanoparticles in glass matrix. The embedded nanoparticles show a characteristic optical absorption band around 420nm, which is caused by SRR. The optical absorbance of the produced samples has been measured. This allows inferring what amount of silver nanoparticles has formed inside the glass, and what size they have. Thin slices of the cross section of the samples have been prepared, and optical absorbance spectra have been measured in different distances from the surface. From this the depth profile of the layer containing silver nanoparticles can be analysed.

P.40 - Light backscattering in plasmonic films for enhanced gas and vapour sensing

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Based on recent experimental and theoretical results obtained with gold-glass nanocomposite films, we propose a plasmonic device which uses the backscattering of light in order to make a highly sensitive gas/vapour sensor. The backscattered reflectance is used as sensing signal since it has been shown that this component of the diffracted light is much more sensitive to a change of refractive index in the surrounding medium than the specular component. In addition, the backscattering of light presents an azimuthal angular dependency which is viewed as an advantage for practical implementation.
The device consists of three planar layers. First, a glass substrate acting as incidence medium. Then a layer with a reduced refractive index with respect to the substrate is added. This layer acts as a leaky-waveguide in order to maximize light coupling into the third sensing layer. The third layer is composed of gold nanopillars embedded in a SiO$_2$ matrix. Through numerical simulations, 2D periodic square and hexagonal arrays of gold nanopillars are compared in order to point out the influence of the nanocomposite arrangement in the photonic response. Moreover, disorder is introduced into these arrays in order to highlight the robustness of the sensing principle with respect to defects in the particle arrangement and size. For the purpose of gas/vapour sensing, we study the backscattered reflectance as it changes according to modifications in the dielectric environment at the external surface due to adsorption from gas/vapour. We determine the optimized device parameters and incidence angles.

**P.41 - Optics of nanometer-scale structures**

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It is shown that of the optical parameters of the nanometer-scale layers of materials depend strongly on their thicknesses. The dimension resonance takes place, where an index of refraction has a maximum and coefficient of absorption has a minimum.

The dimension dependencies of the optical parameters of absorbing and conducting materials are obtained (Ge, Si, Se, Te, Ag, Al), using the existing experimental data on refractivity and transparency and our analogues of the Fresnel formulas and Snell's law for absorbing and conducting media. It is shown that in the stationary case, when absorption, currents and charges in a medium take place, the laws of the energy conservation hold both for TE- and TM- polarization of light.

In thin conducting films, the negative refraction can occur due to surface current, in the case of all positive optical parameters. It is possible only in the case of TM- polarization. In thin degenerate semiconductors the “wrong” refraction can take place only in the IR region of spectrum, and in metals with a high conductivity (Ag, Au, Al), it can be observed in the visible region.

Light emission in thin films is possible for the thicknesses, which is multiple to the wavelength of light in a medium: 

\[
(2*\pi*d_{\text{eff}})/2=\lambda*m=(\lambda_0/n)*m, \text{ where } m=1,2,\ldots
\]

The visible luminescence of the porous silicon can be explained by their emission at dimension resonance.


**P.42 - A columnar thin film as a surface-plasmonic-polaritonic optical sensor**

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A columnar thin film (CTF) consists of a parallel array of columnar nanowires, grown on a substrate by vapour deposition. The void regions between the columns may be infiltrated by a fluid. The porosity of CTFs, along with their optical properties, may be tailored to order. Accordingly, these are attractive candidates for optical sensing applications. For example, a CTF coated by a thin layer of metal may be envisaged as a surface-plasmonic-polaritonic (SPP)-based optical sensor. Our study investigated this possible application theoretically. We used a higher-order homogenization technique, based on an extended version of the second-order strong-permittivity-fluctuation theory, which accommodates both the size and statistical distribution of the component particles that make up the infiltrated CTF. We considered two SPP scenarios, (i) a canonical scenario wherein the SPP wave is
guided by the planar interface of a CTF half-space and a metal half-space; and (ii) a realistic scenario for SPP wave
excitation based on a modification of the Kretschmann configuration. The performance parameters of the envisaged
SPP-based CTF sensor, as revealed by our study, are promising.

P.43 - Polarization-resolved absorption and scattering microspectroscopy of individual silver nanoparticles
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The field of “plasmonics” with metallic nanoparticles (NPs) is growing beyond fundamental interest into a range of
applications from sensors to optoelectronics. For many of these applications, the quantitative characterization of the
optical response of single metallic NPs is crucial.

We measure the scattering and absorption properties of individual silver NPs (AgNPs) covalently bound to glass
coverslips, using dark-field and transmission microscopy and spectroscopy. Bare AgNPs, of nominally 80nm and
40nm diameter, were bound to thiol-functionalized glass coverslips. Alternatively, AgNPs were functionalized with
4-mercaptobenzoic acid and immobilized onto an amine-terminated coverslip. Binding was characterized with dark-
field microscopy using a 40x0.95NA dry objective and a 1.4NA oil condenser equipped with a 1.2-1.4NA dark-field
ring. Single AgNPs appear blue in dark-field corresponding to their localized surface plasmon resonance at
~420nm. The extinction cross-section was measured in bright-field transmission by quantitative comparison of
images of the AgNPs in and out of the plane of focus. Full color images were acquired with a Canon 40D camera
and split into the red (570-640)nm, green (470-575)nm and blue (420-500)nm channels to obtain a spectrally-
resolved extinction. For an isolated AgNP of nominally 80nm diameter we measured extinction cross-
sections of $(6\pm3)\times10^3$ nm$^2$, $(12\pm6)\times10^3$ nm$^2$ and $(18\pm6)\times10^3$ nm$^2$, in the red, green and blue, respectively. These values compare
well to the literature, and the variations include the ±9% spread of manufacturer specified particle sizes (80±7)nm. Polarization-resolved transmission and full scattering and extinction spectra will also be shown.

P.44 - Polarization-degenerate quantum dot emission in photonic crystal cavities
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Self-assembled quantum dots (QDs) placed in photonic crystal cavities (PCCs) have long been proposed as a key
component in quantum computing architectures. Many of the specific applications of these QDs rely on the transfer
of information between the polarization of a photon and the carrier spin in exciton states: the biexciton decay,
entangled photon pair generation, or a spin-photon interface to transfer the polarization information from a photon
to the spin state of an exciton. In all cases, it is the phase difference between two linearly polarized photon states
that contains the entire qubit superposition state. However, due to the symmetry of the PCC, the polarization
transfer is highly dependent on QD position, which usually experiences a highly linearly polarized near field. This
means that the full phase information cannot be stored on a photon polarization qubit in these cavities.

Here, we present a method to numerically calculate polarization dependent spin-photon transfer for any QD position
for any cavity design. We apply this technique to the doubly degenerate “dipole” mode of an “H1” PCC and identify
several regions of polarization independent enhancement. We also show that a QD spin in the centre will couple to
two degenerate modes, which act as states on the “near-field” version of a Poincare-like sphere, thus demonstrating
that for a H1 cavity, one may store a photon polarization superposition state inside the cavity, a necessary
requirement for many of the applications discussed above.
P.45 - Balanced detection for interferometry with a noisy source
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Measuring the optical properties of individual nanoparticles is challenging, due to small absorption and scattering cross sections. Interferometry is a technique where by multiplying a small optical signal by a stronger reference beam small signals can be detected with an excellent signal to noise (SNR) ratio. The optical properties of nanostructures are frequency dependant according to material, local surroundings, geometry and size suggesting a need for broadband interferometric detection.

Supercontinuum light sources can produce a visible light spectrum. These are however intrinsically noisy – typical rms noise is 1 – 5%. Since interferometric detection relies on multiplying the signal by a reference from the same source; noise will be present in the detected interferometric signal from the nanostructure.

Balanced detection is a method to reduce noise – the photocurrent from two detectors is subtracted, thereby greatly reducing common noise and increasing the SNR. We have developed a method of optical auto – balancing. To achieve perfect balance the laser power (and noise) incident on one detector is adjusted with a feedback mechanism. We have found that our method works effectively at reference powers as little as tens of microwatts. At a single wavelength the noise from a commercial Fianium Supercontinuum source is removed in excess of 40dB. Combining this with interferometry, we have detected signals as small as 0.01pW.

We are extending our method of noise reduction to all wavelengths, and will show our progress towards detecting broadband optical spectra of individual nanostructures.

P.46 - Enhancement of radiation from dielectric waveguides using resonant plasmonic cores/shells
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Optical waveguides can be combined with plasmonics elements such as antennas, metallic nanoparticle chains or plasmon waveguides in order to provide new possibilities for subwavelength integrated photonic circuits for telecommunications and optical logic applications. One of the problems with using Silicon waveguides is achieving efficient coupling of the waveguide mode to radiation modes in a small footprint and with good directivity. In the present work, we investigate numerically a method of power extraction from a dielectric waveguide using a core-shell particle with a plasmonic shell in proximity of the waveguide end. Through numerical simulations we demonstrate that a core-shell particle placed near the output of the waveguide results in an improvement in the impedance matching between the dielectric waveguide and the free space when the core-shell particle undergoes resonance. Additionally we observe that the reflected energy in the waveguide is strongly dependent on the distance between the particle and the waveguide output. This permits us to sense the distance between the particle and the waveguide by monitoring the reflected energy.

P.47 - Cross resonant antennas for controlling emission polarization of organic emitters
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Over the last years, optical antennas have become key elements for the engineering of enhanced and confined electromagnetic fields, giving rise to large local intensity enhancement factors. Several plasmonic nanoantenna geometries are being investigated to enhance the luminescence emission of fluorescent molecules or quantum dots.
Specifically, cross resonant antennas have recently been proposed for polarization control of light-matter interactions. In the present work, we have studied experimentally and numerically the possibility of using asymmetric cross antennas, consisting of two perpendicular nanosized gold dipole antennas with different lengths and a common feed gap structure, to provide two different energy resonances that can be selectively excited by controlling light polarization. In addition, the cross antenna configuration would allow to independently probe the effect of an enhancement in either the absorption or the emission cross section of a specific fluorescent dye.

P.48 - Plasmonic photovoltaics: new concepts for absorption enhancements in III-V solar cells

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Research into plasmonic photovoltaics has recently attracted a great deal of attention owing to the potential for improved efficiencies, which derive from optical absorption enhancements based on the mechanisms of near-field confinement, scattering and coupling into waveguide modes. Such techniques are particularly attractive for thin-film applications since plasmonic absorption enhancements permit the fabrication of structures in which the optical absorption depth is significantly larger than the physical thickness of the absorbing layer. Applying plasmonic structures to solar cells could therefore reduce the amount of raw semiconductor material required and hence the cost of production, without compromising on efficiency. To reach this goal however, a good understanding of the fundamental processes that govern the interaction of plasmons and solar cells is required.

To that end we have developed a 3D modelling framework that bridges electromagnetic and electronic calculations to provide a complete set of parameters describing the optical and electronic response of a solar cell. Using this simulation tool, in combination with experiments on GaAs-based plasmonic solar cells, we will present an in-depth investigation into the parameters affecting absorption enhancements. We will show that the choice of metal employed is crucial to optimise scattering efficiency and minimise parasitic absorption. Furthermore we will demonstrate the effect of controlling the periodicity of nanoparticle arrays in diffracting incident light into laterally propagating modes within the absorbing layer. Based on this work we show that in principle it is possible to improve light conversion efficiency in a 500 nm GaAs solar cell by more than 45%.

P.49 - Silicon-based plasmonic coupler

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Power transmission coupling efficiency in a metallised tapered silicon waveguide is investigated using finite element simulations. The structure is symmetrically corrugated with rectangular grooves which excite surface plasmon polaritons (SPPs) when illuminated by light entering from a broad input opening. The SPPs are then focussed into a narrow silicon slit at the apex of the taper. The angle and the period of the grooves is chosen to enhance the SPP field propagating towards the slit while suppressing the outgoing SPPs, hence improving the coupling efficiency. The structure is intended to be compatible with a standard silicon-on-insulator photonics platform. Furthermore, a simplified transfer matrix model was developed to understand the factors which affect the optical transmission into the slit. Optimisation of the structure with respect to the width, depth and number of grooves was carried out. For a structure comprising four and seven grooves on each side of the taper, a maximum efficiency of ~60% was predicted for coupling from a 6.4μm and a 10.5μm aperture into both a 30nm plasmon waveguide and a 300nm silicon-on-insulator waveguide. Such a structure hence offers an efficient means of coupling directly from an on-chip fibre grating to a plasmonic optical circuit.
P.50 - Optimised plasmonic structures for thin film solar cells

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Over the last decade there has been a growing interest in the use of plasmonic features to enhance the efficiency of solar cells via light trapping within the active layer. Using optical modelling techniques (FDTD) we have built upon several established methods, developing new approaches to optimise these for thin film devices. Novel structures have been shown both to increase scattering into guided modes within the substrate and to excite plasmonic modes at the rear electrode. Both approaches should increase the optical path length of light within the cells leading to increased absorption and thereby device efficiency.

There have been two distinct approaches taken within our group. Firstly, by structuring nanoparticle (NP) scatterers and their dielectric environment we have been able to promote strong scattering at large angles, thus directly coupling more light into the guided modes of the substrate. We have found that by placing NP's in a simple photonic structure above the cell, which can be tuned to suit a variety of materials, we can control both the scattering pattern and the extinction peak.

A second approach is to engineer nano-scale featured electrodes to excite plasmonic modes at the electrode interface. These bring about increased near-field and enhanced scattering thus leading to higher absorption. We are currently developing a novel fabrication technique which will permit a high level of control over the nano-scale features.

Both approaches demonstrate a large potential for surpassing existing techniques and opening up new avenues of research in this field.

P.51 - Collective effects in 2D spaser lattices

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The problem of create intensive directional nano-source of coherent radiation exist enough time. A spaser which was proposed Stockman [1] is not directional source. A lasing spaser [2] is limited by the radiated power. We report about a new kind of intensive directional nano-source of coherent radiation based on effect superradiation. We investigated 2D plane of lasers have overlapping pump sources. Due to overlapping pump sources different phase relations between dipole moments of neighboring spasers becoming no equivalent. In other words, at the system begins the competition modes. The strongest mode is the mode of spasers oscillating in-phase. Because of this superradiance begins at the system. Beginning of the SI leads to an increase the intensity of radiation and the emergence of direction of in the radiation spectrum. We emphasize that method synchronization dipole moments neighboring particles due to competition modes was became possible only after the creation of spaser.

Nonlinear photonics

P.52 - Two-colour spatial optical solitons: new stability analyses for off-axis propagation

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Two-colour spatial optical solitons comprise a pair of stationary continuous-wave light beams at two well-separated temporal frequencies. The components overlap in the propagation plane and are coupled through system nonlinearity (e.g., the Kerr-type response in the host material of a planar waveguide) [Opt. Commun. 88, 419 (1992)]. Such configurations have huge potential for future photonic device applications such as multi-channel waveguiding [Opt. Lett. 19, 945 (1994)]. To date, analyses of such geometries have been mainly within the arena of paraxial wave optics.

Our research goes beyond the slowly-varying envelope approximation, into regimes where two-colour light fields may propagate and interact off-axis at arbitrary angles and orientations. The coupled governing equations are of the nonlinear Helmholtz (as opposed to Schrödinger) type [Phys. Rev. E 74, 066612 (2006)]. In an essential way, this more general system involves the interplay between nonlinear (self- and cross-focusing) processes and, crucially, fully two-dimensional diffraction.

We will present the first analysis of off-axis two-colour light fields. Four families of exact analytical two-colour soliton (bright-bright and bright-dark for a focusing Kerr nonlinearity; dark-bright and dark-dark for defocusing) have been derived, each of which has co- and counter-propagation classes that are related by geometrical transformations. Solution of the plane wave modulational instability problem, obtained by generalizing our established Helmholtz linearization techniques [J. Phys. A 39, 1535 (2006)] to vector regimes, has provided further insight into the propagation properties of those two-colour solitons with dark-type components. Unexpected regions of stability, mediated by cross-focusing, have been uncovered in certain parameter regimes.

P.53 - Helmholtz dark spatial solitons in waveguides with defocusing saturable materials

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Presented by C Bostock

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Angular configurations play a fundamental role in essentially all nonlinear photonic architectures: from beam multiplexing applications, to scattering at a single interface, to evolution inside patterned optical structures. Equations of the nonlinear Helmholtz type are ideally suited to describing scalar oblique-propagation contexts. Knowledge of their exact solitons facilitates novel device designs, and the pursuit of these classes of solution is a key research objective of our collaboration.

Saturation under high-intensity illumination is a property of many photonic materials. Phenomenological descriptions of a saturable refractive index must go beyond polynomial-type expansions in the (local) light intensity [e.g., the cubic-quintic approximation (Pushkarov et al., Quantum Electron. 11, 471 (1979)), which eventually break down. However, such approaches almost always result in a governing equation that does not possess exact soliton solutions. A notable exception is the model proposed by Wood et al. [Opt. Commun. 69, 156 (1988)].

We will present, for the first time, exact dark spatial solitons for a Helmholtz equation with a self-defocusing saturable nonlinearity. These novel solutions have been obtained by deploying a unified combination of analytical techniques (symmetry reduction, coordinate transformations, and direct integration). Multi-parameter asymptotic analysis recovers the predictions of conventional (paraxial) theory [Krolikowski and Luther-Davies, Opt. Lett. 18, 188 (1993)], while convergence to its Kerr counterpart [Chamorro-Posada and McDonald, Opt. Lett. 28, 825]
(2003)] has been found in the limit of low light intensities. Computations involving perturbed initial-value problems have demonstrated that Helmholtz saturable dark solitons are highly robust nonlinear waves surrounded by wide basins of attraction.

**P.54 - Optical manipulation of BEC momentum states via non-normality**
F Papoff and G R M Robb
University of Strathclyde, UK

We propose an alternative method of control of a BEC momentum distribution, in which atomic momentum states are modulated simply by injection of light at frequencies far from resonance into an optical cavity containing a BEC. This exploits the fact that we can find conditions in which the response to an external modulation can be very large even far from resonance and the largest possible response of the system may be made up by variables that are not modulated. The results presented offer the possibility of new methods for modulating momentum state populations at rates $10^6 \text{s}^{-1}$, significantly faster than would be possible by modulating e.g. a magnetic trapping potential.

**P.55 - Control of response of exciton polariton confined in GaAs thin films by controlling pump and probe pulses**
O Kojima$^1$, S Ohta$^1$, T Kita$^1$ and T Isu$^2$
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Optical control of exciton states is an important research area to realize the new devices for ultrafast optical communication and quantum information technologies. We have investigated the temporal response of the exciton polariton confined in the GaAs thin films with the thickness close to the light wavelength by the four-wave-mixing and pump-probe techniques with ultrashort pulses [1-3]. More recent research for the transient profile of the excitons demonstrates the interesting variation by controlling the spectral shape of the probe pulse due to the excitonic quantum beat oscillation [4]. In the present work, we report the control of the exciton response due to independently controlling both of the pump and probe beams by a pump-probe technique.

The sample used was the double heterostructure thin films with three periods of GaAs (110 nm)/Al$_{0.3}$Ga$_{0.7}$As (5 nm) on a (001) GaAs substrate grown by molecular beam epitaxy. The center-of-mass motion of excitons is confined in the GaAs layers. The exciton response was measured by a time-resolved reflection-type pump probe technique. We used two sets of a grating and a slit to change the spectral shape for the pump and probe pulses. The control of the spectral shape of the pump pulse shows the change of the exciton response probed by the controlled pulse even under the nonresonant excitation conditions. These results originate from the change of coupling exciton with light fields.

P.56 - Effect of phase, amplitude and spacing on neighboring soliton pulses
A Antwiwaa and S Prince
SRM University, India

Optical solitons are essentially stable pulses that travel without changing their shape; they do not disperse and can resist perturbation in the physical medium. In order to achieve stability, there should be a balanced between the group velocity dispersion (GVD) which causes pulse broadening and the self phase modulation (SPM) which causes spectrum broadening. After balancing the GVD and SPM, there is a need to take into consideration the relative phase, relative amplitude and the spacing between neighboring soliton pulse.

In this paper we have conducted various simulation experiments using matlab to investigate the interaction between two neighboring solitons of equal amplitude and unequal amplitude by varying the phase between them. We have also investigated into the interaction between neighboring soliton by varying the spacing and amplitude.

The simulation results shows that care must be taken when choosing the amplitude, phase and spacing in order to avoid to avoid interaction since interaction affects the efficiency of soliton propagation.

P.57 - Spatiotemporal soliton formation in arrays of silicon waveguides
A Gorbach, O Staines, D Skryabin, G Hobbs, W Wadsworth and J Knight
University of Bath, UK

We present theoretical studies of spatiotemporal solitons in arrays of coupled silicon nanowaveguides conducted at pump wavelengths greater than 2µm where two-photon absorption (TPA) effects in silicon is substantially reduced. The arrays consist of five 220nm thick and 800nm wide waveguides with wall-to-wall separation of 900nm and length 15mm, designed such that the characteristic dispersion and coupling lengths are approximately matched at our pump wavelength, and are small enough with regards to the waveguide length.

The system is modelled by coupled nonlinear Schrödinger type equations. The important aspect of this model is the dispersion of coupling, which becomes particularly strong in our system at wavelengths greater than 2µm. The coupling-induced dispersion results in a considerable variation of group velocities among five linear guided modes, as well as of their dispersions.

The system supports three classes of solitons based on the wire in which they are localized. Group velocities of all the solitons are different from those of any of the linear modes, which is the direct result of the group velocity variation among the modes. This strongly affects position of Cherenkov peaks emitted by the solitons, and we confirm this finding by performing numerical propagation. Another important result of the coupling induced dispersion is the new mechanism of spectral broadening. If viewed as an ensemble of different guided modes being propagated at the same group velocity, a soliton spectrum is stretched due to different linear modes having spectral peaks at different wavelengths.
The resolution of far-field imaging is restricted by Abbe’s diffraction limit and alternative techniques are required to image structures smaller than this limit. One technique uses Bessel beams that do not diffract and are known solutions of the linear paraxial equation of propagation. Here we employ self-focusing of optical beams in nonlinear media to achieve the diffraction and sub-diffraction regimes.

Since Gaussian beams are the most commonly used in optics, we address the re-shaping of these beams when entering a nonlinear material. By using the Nonlinear Schrödinger equation (NLSE), we show that beam reshaping is accompanied by shedding of energy before a narrow, stable and self-focused profile with a typical sech² shape is attained and propagates without diffracting. The results change significantly when full nonlinear saturation is included in the NLSE (which is necessary for 2D simulation) and the change in refractive index saturates at a given intensity. We describe two branches of stable solutions in this case, depending on the nonlinear coefficient of the medium. In regimes of spatially oscillating self-focused beams, the energy shedding is enhanced until the power is reduced to that of the lower stable branch. Although the energy shed is small compared to the total power and well below the intensity required to excite fluorophores, an optimal choice of media for sub-diffractive imaging depends on the interplay of nonlinearity and the process of energy shedding described here.

We first present results of simulations with Gaussian and Bessel input beams applied to realistic configuration of optical far-field imaging. We then generalise the analysis to include dispersion for the case of ultra-short pulses.
Poster session II

Advances in terahertz technology

P.01 - A theoretical framework for chemometric analysis of amorphous materials

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In broadband dielectric spectroscopy studies of amorphous materials that lack discernible Lorentzian, Debye or Drude responses, we tend to observe a Jonscher-like admittance response of fractional order as a function of frequency. We propose to model such response using a 3-dimensional random network of resistors and capacitors. An incidence matrix analysis is used to model a network of branches with nodes consisting of resistive and capacitive elements distributed across several interconnected layers. An identification study of these networks is performed to infer the admittance response using integral and fractional order models of reduced order. A fractional order model with 17 optimized parameters, as initialized by an integral order model of 4th order, can accurately describe the responses of networks composed of more than 70 nodes and 200 branches with 100 resistors and 100 capacitors. Admittance response results from several simulations of such networks with different composition of capacitors will be presented. In a Chemometrics context, the reduced order models enable a parsimonious representation of the network dynamics, thus providing us with the opportunity to perform classification studies that can infer the composition of the materials. This is of interest from a quality control perspective. The proposed analysis provides an interpretation of results obtained through the well-established methodology of processing the spectra, where a known background is ratioed with the sample spectrum to infer a complex insertion loss function across a range of frequencies. The modelling process can lead to better understanding of charge migration processes in amorphous materials.

P.02 - Quasi-optical antenna phase measurements using homodyne detectors

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Experimental difficulties at high frequencies (above 1 THz) preclude the possibility of using conventional phase pattern measurement techniques and therefore, a new phase retrieval technique has been developed. In the proposed method, the output from the source, an optically pumped passively stabilised far-infrared (FIR) ring laser, is split to give two mutually coherent co-polar sources S1 and S2, each launching a beam towards the test antenna at slightly different angles q and q + qs, where qs is the angle subtended by the two sources. By blocking first one source and then the other, the output voltages V1 and V2, representing power pattern measurements for every angle q are measured. Using V12 to represent the corresponding output voltage when both sources simultaneously launch a beam towards the test antenna, the phase relation of the two electric fields arriving at the detector is extracted from the recorded antenna power patterns after monitoring the output voltages for each angle. A measurement example of a whisker contacted GaAs Schottky barrier diode mounted on a cube corner reflector, with amplitude and phase antenna pattern measurements in the E-plane at 1.3971 THz is provided. Phase information can be retrieved even in regions where the power patterns show poor signal to noise ratio. The sensitivity of the technique to measurement errors will be discussed at the conference.
A one-port de-embedding technique that requires the use of shorted waveguides of the same size but of different lengths, is utilised to calculate S-parameters and a waveguide's complex propagation constant. The precision of a quasi-optical null-balance bridge reflectometer in measuring waveguide characteristic impedance and attenuation using this de-embedding technique is analysed after taking into account alignment errors between the device under test and the instruments’ test port. The analysis is based on the propagation of errors after assuming imperfect coupling of two fundamental Gaussian beams due to rotationally displaced modes, as well as errors due to laterally and axially displaced modes. The asymmetric diffractive spreading of the beam in one of the two arms of the interferometer is also taken explicitly into account. As there is a need to make 8 measurements with 4 different waveguide lengths in order to de-embed the characteristic impedance, the required precision in repositioning the samples at the instruments’ test-port is discussed. The proposed technique is suitable for micro-spectroscopy applications where the dielectric constants of materials placed inside waveguides needs to be measured as well as for de-embedding quasi-optically measured impedance in antenna structures. An advantage of the method is that it obviates the necessity of utilizing a six-port for the measurements so it can be used at frequencies where no TRL or other S-parameter de-embedding techniques are currently available. It further allows for the use of a non-linear detector without compromising the precision in the measurements.

Terahertz time-domain imaging has demonstrated to have a range of application areas including security, medical, pharmaceutical and non-destructive test of industrial processes and products [1]. Most THz imaging experiments have been performed by raster scanning the object relative to a focused THz beam. Consequently, a complete image usually takes minutes or even hours to acquire, depending on the total number of pixels and the required spectral range/resolution. This is a major limiting factor for real-time applications such as in vivo medical and security imaging, or for on-line industrial process monitoring.

Recently Chan et al. [2] and Shen et al. [3] reported a new terahertz imaging procedure that is based on the concept of compressive sensing (CS). This CS-THz imaging system could significantly reduce the number of terahertz measurements, thus speed up terahertz imaging process [2-4]. Up to now, all these CS implementations have been performed on 2D THz images. In this presentation we report the first implementation of direct 3D compressive THz imaging by using random sampling. We demonstrate that only 8% of the 3D THz data is necessary to reconstruct all 3D THz images, indicating its huge potential in significantly speeding up the THz measurements and reducing the required data storages.

P.05 - Double bosonic stimulation of THz radiative transitions

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The rate of spontaneous emission for THz photons can be additionally increased by bosonic stimulation if a radiative transition occurs into a condensate of bosons. [APL 97, 201111]. Quantum mechanical description of the interacting system of THz photons and microcavity polaritons system can be developed on the basis of on the generalized Lindblad equation for the density matrix [PRL107, 027401]. Polaritons exhibit pronounced non-linear properties at low excitation level a, and therefore system of interacting THz photon and polaritons demonstrates a variety of intriguing nonlinear effects, including bistability, THz switching, and generation of short THz wavelets. Various designs of microcavity structures providing radiative THz transitions are investigated.

Fibre optic and waveguides

P.06 - Comparative studies of the thulium and erbium doped from 1480-1650 nm with different host materials as optical fiber amplifiers

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This work describes the comparison of the amplification characteristics (gain) and the Noise figure (NF) of the Thulium and Erbium in three different host materials which Yttria Alumina-Silica glass, Fluoride and Tellurite fiber glass. The gain using these host materials covers the range 1.45-1.65 μm. TDFAs operated in the region of wavelength (1480-1510 nm) which is called S-band. TDFAs are pumped at 1.04 and 1.55 μm which creates population inversion between 3F4 (upper laser level) and 3H4 (lower laser level), and EDFA operated in the region (1510-1650 nm) which is called L-band with the pump wavelength 980 nm. It is found that the erbium doped yttria-alumina silicate fiber amplifier exhibits a maximum gain of 40.3 dB at the central wavelength 1540 nm and minimum noise figure 14 dB, but the broadening in the gain curve is 20 nm. Also it is found that the thulium doped yttria-alumina silicate fiber amplifier exhibits a maximum gain of 27.5 dB at the central wavelength 1467 nm and minimum noise figure 2.5 dB, with the broadening in the gain curve is 41 nm. Gain flatness was investigated and the results strongly confirm the feasibility of using different hosts’ glass doped with Thulium in practical ultralarge capacity WDM networks.

Fibre optic sensors

P.07 - Long term stability of fibre Bragg gratings embedded in polymeric structures using additive layer manufacturing technology

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Additive Layer Manufacturing (ALM) technology is rapidly maturing from a tool for visualisation and model building to a versatile manufacturing solution for bespoke components in a large variety of materials.

In this paper we present results from a long term cyclic loading experiment on a polymeric tensile test object (Nylon 12) with an embedded fibre Bragg grating for in-situ strain monitoring. The experiment has been in progress for nearly 2 years in Feb ‘12 and is continuing. The test specimen is loaded every 100 seconds for 100 seconds by a force of ~40 N resulting in an extension of ~1600 με (microstrain) which is monitored by the embedded FBG inside
the specimen and the measurements are compared to an attached extensometer and a conventional electrical strain gauge on the outside of the specimen.

The recorded strain values from all three sensors show an excellent correlation with the expected strain values based on the applied tensile load and some marginal changes in geometry (curvature) of the test specimen under load. The date also reveal a very slow permanent elongation of the specimen due to load induced creep, as is expected in many polymeric materials, however the embedded strain sensing fibre is not creeping relative to the specimen and records the true elongation.

The paper presents a discussion on benefits, disadvantages and problems observed in initial trials and during the extended trial period representing >300,000 load cycles.

Some ALM processes utilise glass filled materials to achieve require mechanical performance, however FBGs embedded into this class of materials are not performing well. The effect of the fibre jacket material on performance is discussed.

P.08 - The development of a POF based distributed sensor and its application to environmental monitoring

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Plastic Optical Fibres (POF) offer a low cost and flexible route for the development of serially distributed sensors. When combined with optical time domain reflectometry, the response from specifically positioned sensors along the POF can be attained. Recent work carried out on the response of chemically sensitised or decladded fibers for moisture has shown that using a continuous optical source operating at a suitable wavelength allows for the recording, characterisation, and calibration of the obtained moisture within a given medium including water, sand, foam, and soil. Work is now in progress to include further environmental variables such as pH levels. This distributed sensor modality shows applicability in a number of areas related to sensing.

A simple distributed sensor is first assessed using a forward optical setup where a pulsed light source feeds a photosensor through the POF directly with no reflection. The results show that for a POF with 3 sensitised regions, the moisture levels obtained through the measurement medium are cumulative. Also, quantitatively, each 5cm decladded sensing region affects the incoming light pulse in a similar fashion. These effects are demonstrated by exposing the sensitised region in succession to a specific environmental quantity such as moisture.

Using dedicated multiple phase locking and measurement software, individual regions of the time domain waveform collected from the photosensor are extracted, signal processed, prior to display/analysis in real time. By constructing a time domain reflectometer, analysis of an arbitrary number of distributed sensors can be demonstrated.

P.09 - Optical fibre cantilever sensors fabricated using ps-laser machining

J Li, F Albri, R J Maier, W N MacPherson and D P Hand

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Micro-fabricated cantilevers have been demonstrated for use as miniaturized, rapid response, ultrasensitive sensors for a wide variety of applications including biological and chemical monitoring. However, the alignment of the cantilever structure with the read-out system is challenging and often the overall system is large to accommodate bulk optics and detectors.
In this work we use cantilevers aligned to the core of a standard communication optical fibre as a means to address this issue. Fibre cantilevers have been reported elsewhere, but here we propose a novel fabrication route using a two step ps-laser machining process. First, a ridge is fabricated onto one end of an optical fibre by directly machining along the fibre axis. Subsequent machining from the side allows the formation of a Fabry-Perot cavity. The interference generated by the cantilever and fibre surface is directly measured using light in the fibre hence no subsequent mechanical alignment is needed.

We demonstrate a potential ‘low-cost’ readout system using a miniature spectrometer and halogen lamp source. This is used to interrogate the interferometric fringes generated by fibre and cantilever surface. The wavelength based interrogation is immune to any power fluctuation along the connecting fibre, which makes the sensor more reliable. Experimental results demonstrate the ability to measure cantilever displacement with around 50nm resolution over a 7000nm range.

Optical and quantum metrology

P.10 - Quantum metrology with fibre sources

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For any interferometric measurement of an optical phase \( \theta \), quantum mechanics places a fundamental limit on its precision through shot-noise; \( n \) detections of independent photons implies a statistical uncertainty \( \sqrt{n} \), and the precision is limited by the standard quantum limit (SQL) \( \Delta \theta \geq 1/\sqrt{n} \). However, using entangled photons it is possible to beat the SQL and reach the Heisenberg limit \( \Delta \theta \geq 1/n \).

Experiments with parametric downconversion sources have used non-classical interference to produce path-entangled states of indistinguishable photons, beating the SQL with two and four photons [1]. Instead, we generate path-entanglement between disparate wavelengths using a non-degenerate source inside a Sagnac interferometer. The source is a length of photonic crystal fibre pumped by coherent pulses at 722nm, generating pairs of photons at 625nm and 860nm through four-wave-mixing. When one pair is generated in either path of the interferometer with equal probability, the state is maximally entangled, and as the relative delay varies the state evolves with a total phase approximately double that of the classical pump. This compares well to 2-NOON downconversion experiments where the period is equal to that of the pump laser.

We will present results comparing classical interference to a two photon fringe with a visibility 89%, well above the threshold to beat the SQL. By generating two pairs we demonstrate oscillation at 4 times the pump frequency with visibility >80%. We will also show results extending this to three pairs, with oscillations at 6 times the pump frequency.


P.11 - Towards single photon avalanche diode detectors using narrow bandgap InAs

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The ability to efficiently detect ultra-low light levels is becoming increasingly important for numerous applications in communications, imaging, security, medicine and metrology. For this reason, research into properties of novel semiconductor-based optical detectors for use in these emerging application areas is vital. In photon-starved applications, conventional semiconductor photodiodes have a limited sensitivity, and hence avalanche photodiodes...
APDs are often the most appropriate solution. InAs is a III-V semiconductor that shows excellent potential for APD operation in the infrared range, possessing a narrow bandgap ($E_g = 0.36$eV) that can be used to detect photons efficiently at wavelengths of up to 3.5µm (covering the 1.3µm and 1.55µm telecommunication windows). The main properties that make InAs a unique material are the excellent multiplication characteristics and the disparate impact ionisation coefficients, $\alpha$ and $\beta$ ($\beta \sim 0$). A conventional APD (with similar $\alpha$ and $\beta$) biased beyond avalanche breakdown outputs a detectable current pulse from the self-sustaining avalanche current created by a single incident photon. However, because only electrons contribute to the avalanche, an InAs detector can operate at high gain with lower jitter and has the potential of photon-number resolving capabilities (i.e. can differentiate between one, two, or more photons at the same time). We design, fabricate, and characterise high gain InAs APD for photon counting applications.

P.12 - High-resolution single-photon spectroscopy at telecom wavelengths
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Photonic sources operating at the single-photon level are useful for a range of quantum optical technologies [1]. Spectroscopy is an essential technique for investigating and optimising such sources. Specific applications include producing entangled photon sources by tuning polarisation splitting [2] and spectral filtering [3]. As devices become more sophisticated, higher spectroscopic resolution is needed over wider ranges.

We have developed a high-performance instrument that addresses a gap in current spectroscopy systems. Scanning Fabry-Perot interferometers (SFPIs) can achieve high resolution, but at the cost of limited free spectral range. Conversely, spectrometers offer a wide spectral range, but with lower resolution. Our design strikes a unique balance, simultaneously providing $\sim 10x$ the resolution achievable with spectrometers [6] and at least $10x$ the free spectral range of conventional SFPIs [5], across the telecoms wavelength band. It is based on a stable, tuneable cavity with a 600 MHz (2.4 µeV) linewidth, 150 GHz free spectral range and finesse $F = 250$, and uses a superconducting nanowire detector for single-photon sensitivity at telecom wavelengths [4]. The principle of the interferometer could be applied throughout the visible spectrum.

Initial plans include spectral investigations of telecom wavelength sources of single photons. The construction, testing and first use of this system will be reported, and results to date will be presented.

This work is supported by the UK National Measurement Office, European Metrology Research Programme and EPSRC Engineering Doctorate Scheme.

P.13 - Uncooled GaSb/InAs type II superlattice photodiode for radiation thermometry

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Radiation thermometers have been used as a contactless measurement of temperature by measuring the photons emitted by an object at a finite temperature. They can be used in applications such as monitoring the growth temperature of semiconductor wafers and monitoring the temperature of molten iron. Typical infrared detectors currently used for radiation thermometry include thermal detectors, such as thermopiles and pyroelectrics, and photon detectors, such as Si and Ge diodes.

In this work we investigated the potential of using a GaSb/InAs type II superlattice photodiode for radiation thermometry. The effective bandgap of GaSb/InAs type II superlattice is determined by the thickness of the constituent GaSb and InAs layers such that wavelengths ranging from infrared wavelengths from 2 to 30 mm can be detected. Our type II superlattice photodiodes were designed to detect wavelengths from 2 to 5.3 μm at room temperature. The dark current density at room temperature is ~1x10⁻³ A/cm².

In the thermometry measurement, we chopped the radiation from a calibrated black body source, amplified the photocurrent using a transimpedance amplifier and measured the amplified signal using a lock-in amplifier. We obtained good response at black body temperatures from 150 to 1000°C. Measurement at lower temperature was compromised by the relatively high dark current. Therefore cooled GaSb/InAs type II superlattice may potentially offer lower temperature detection.

P.14 - FPGA based flexible instrumentation for photon counting and time tagging

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Characterisation and typical experimental uses of a new flexible event timing instrument will be presented, as well as an overview of the instrument itself. We will present three instrument realisations of this low cost FPGA based device: a Time Correlated Single Photon Counter (TCSPC), an 8 channel narrow window coincidence counter capable of recording all possible coincidence combinations, and a multi-channel Time to Digital Converter (TDC).

An early prototype, originally developed for the Bristol free space Quantum Key Distribution system has been developed into this flexible instrument. In the time tagging mode the instrument is capable of time tagging to a resolution of 30.5 ps, with a time measurement certainty of 19 ps and is capable of a sustained tagging rate of 5 MHz. The coincidence counter currently has an adjustable 1 to 5 ns coincidence window, and updates at 2 Hz. All instruments are implemented on a common FPGA hardware platform and are self-calibrating, negating the associated costs of analogue timing electronics.

The instrument is now being tested in various photonics experiments at Bristol. We will describe its application in a 4-photon cluster state generation experiment, where for the state tomography eight detector inputs are used and all fourfold and twofold coincidence subsets are selected and counted along with the four singles rates.

However such a device has wide applications outside the field of Quantum Photonics, in Fluorescence Lifetime Imaging (FLIM), LIDAR, clock recovery in communication systems and more general counting and timing applications.
Temporal variation of residual amplitude modulation in electro-optic phase modulators

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The electro-optic modulator (EOM) is a key optical component used for phase modulating an incident field in optical frequency references and gravity wave detectors. However, all EOMs generate unwanted residual amplitude modulation (RAM) which limits the sensitivity and resolution in these ultra sensitive applications. While the origins of RAM are not fully understood, measurements reveal that it can be suppressed to the $10^{-5}$ level through adequate control of beam and medium properties. Although a practical and useful outcome, our understanding of RAM is not complete and observations such as its irreproducible temporal behaviour remain unexplained and prevent further suppression of this noise.

This study describes a comprehensive experimental evaluation of the time dependence of RAM and its dependence on input intensity. These measurements were performed with a continuous wave 532 nm Nd:YAG laser that was phase modulated with an MgO doped lithium niobate EOM, with the output measured by a phase sensitive detector. The results presented here demonstrate that both the magnitude and phase of the modulator RAM varied with time. Our results show that the observed temporal fluctuations in RAM level are tied to the medium’s nonlinear optical properties and in particular, to the continual evolution of the self-defocusing refractive index changes that occur in the photorefractive medium. Using the results of this study, beam properties are identified that minimize the RAM temporal fluctuations, which are important in low noise applications where RAM stability is demanded.

Optical diagnostics in engineering

P.16 - Comparative analysis of digital demodulation approaches in optical coherence tomography

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Optical Coherence Tomography (OCT) is a non-invasive high-resolution imaging technique based on low-coherence interferometry. Nowadays not only it is widely used in the field of biomedical diagnostics, but it also shows a high potential in other applications, e.g. within the field of non-destructive testing (NDT). In a standard intensity-based OCT system, the demodulation function is typically implemented by fixed analog electronics, which is inflexible and noise-making. Therefore, this paper aims at using digital signal processing methods to provide increased demodulation accuracy, improved flexibility, and decreased system cost. A variety of demodulation approaches, e.g. Coherence, Hilbert Transform, Wavelet Filtering, etc. are investigated, firstly with the simulated signal. Then using a Time-Domain OCT system developed for material characterization experimental results are processed using the developed algorithms. The samples tested include coatings and glass-fibre composites. Finally comparative analysis is presented to evaluate the validity of each demodulation method for material testing with OCT.

P.17 - Characterization of tablet coatings using infrared optical coherency tomography

C Li, Y Dong and Y Shen
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Tablet coatings have been widely used by the pharmaceutical industry to control the release rate of active pharmaceutical ingredient in human body. It is hence of great importance to characterize coating properties such as coating thickness and coating uniformity for the purpose of quality control and quality assurance. Terahertz technology has been demonstrated as one of the most powerful method for nondestructive quantification of
pharmaceutical tablet coatings. Tablets with a coating thickness above 40 microns can be accurately and routinely determined using terahertz technology [1].

Optical coherence tomography (OCT) is a prevalent interferometry technique to perform non-contact cross sectional imaging with achievable micrometer axial resolution in numerous disciplines. Very recently we and other groups have shown that thinner coatings with a thickness down to 10 microns could be determined nondestructively by using infrared OCT [2-4]. In this work, we report the development of a full-field OCT system for non-invasively characterising pharmaceutical tablet coatings. We will present experimental results obtained on 190 biconvex tablets (19 batches, 10 tablets each batch). The extracted coating thickness will be compared with that obtained using terahertz imaging and near infrared spectroscopy methods.


Singularities, optical vortices, polarization, coherence and non-Gaussian beams

P.18 - Angular momentum of quasimonochromatic Guassian Beam

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The relation for Poynting vector of quasimonochromatic wave is presented. It is shown that the total angular momentum of quasimonochromatic wave may be divided on the orbital and spin ones. On the example of Gaussian beam it is shown that value of the spin angular momentum connects with coherence characteristics of the beam.

P.19 - Testing of the angular position- orbital angular momentum uncertainty relationship based on entropy

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The accuracies to which two non-commuting variables can be known are fundamentally limited by uncertainty principles. Various uncertainty relationships are often expressed in terms of the standard deviations of the associated variables. Alternatively, formulating uncertainty relationships using entropies gives a useful insight into the information content of the system whilst also, in the angular regime, bypassing the issue of angular periodicity and standard deviation.

In this work we experimentally tested the entropic formulation of the uncertainty relationship between angular position and orbital angular momentum (OAM) and demonstrated a good correspondence between theoretical predictions and experimental measurements. We demonstrate this relation by limiting the angular position of an incident Gaussian laser beam using an angular aperture and measuring the resultant spread in the OAM distribution. We measure the OAM spectrum by using a forked hologram and coupling the diffracted beam into a single mode fibre. By using an SLM to display a superposition of both the aperture and the forked hologram we have built a compact and stable measurement system giving the high discrimination between OAM states required to demonstrate angular uncertainty relationships.
P.20 - Control of the amplitude and polarisation distributions of focussed high NA beams using holograms on spatial light modulators

J Clegg, M Lenz and M Neil
Imperial College London, UK

When a laser is focussed by a high numerical aperture lens, the fields in the focal region can have significant components in all three directions. The exact polarisation produced at the focus is important for microscopy applications such as probing plasmonic systems, investigating molecular orientation and re-orientation inside living cells and for super-resolution techniques. Control of the two-dimensional polarisation in the back focal plane of the lens can therefore be crucial for proper control of these field components.

Here we demonstrate the use of programmable diffractive optical elements on reflective spatial light modulators (SLMs) to control the phase and polarisation pattern of light beams. When focused by a high numerical aperture lens these patterns give rise to a variety of point spread functions. Phase control also allows for aberration correction.

We describe two separate techniques that achieve this control. In the first, a parallel-aligned nematic SLM is used. This is attractive because the optical setup is simple and the holograms can be blazed, allowing for high diffraction efficiency. The second technique uses a ferroelectric liquid crystal SLM (FLCSLM). The 1 kHz update frequency of the FLCSLM is beneficial to applications requiring high speed, for example adaptive optics or laser scanning confocal microscopy.

P.21 - A novel method for generating electron vortex beams.

F Trindade, C Greenshields, D MacLaren, S McVitie and R Stamps
University of Glasgow, UK

The generation of electron vortex beams is a relatively new subject area. In Optics, however, vortex beams have been extensively investigated. There are many similarities between electron and optical vortex beams, and also some essential differences due to the electron's mass, charge and half-integer spin. In this work novel methods for generating electron vortex beams are discussed and results from TEM experiments will be presented. We show that certain designs allow us increased sensitivity to specific material properties as compared to conventional TEM analysis. Prospects for gaining new insights into electron vortex states and interactions with materials are discussed.

P.22 - Intensity and phase profile measurements of vortex beams at millimetre wavelengths

S Maccalli\(^1\), G Pisano\(^1\), P Schemmel\(^1\), S Colafrancesco\(^2\), B Maffei\(^1\), M W R Ng\(^1\) and M Gray\(^1\)
\(^1\)The University of Manchester, UK, \(^2\)University of the Witwatersrand, South Africa

In 1992 Allen and his colleagues discovered that optical beams with complex wavefront structures, called optical vortices, carry Orbital Angular Momentum (OAM), in addition to Spin Angular Momentum (SAM) \cite{2}. In a vortex wave, the phase fronts are no longer parallel, but form a helical structure about the axis of propagation. It can be demonstrated that the accumulative phase difference around the axis of the vortex is \(2\pi l\), where \(l\) is the topological charge of the vortex and can be any integer number between \(-\infty\) and \(+\infty\) \cite{2}.

Light that carries OAM has a huge potential, both for scientific and technological applications. Until now most of the experimental work has been done at optical frequencies. This has resulted in advances for quantum encoding, optical tweezers and coronagraphy. However, new devices and experimental techniques are needed in order to manipulate OAM states at radio frequencies for applications in telecommunications and astronomy.
In this work we demonstrate how to characterize a vortex beam produced with a $l = \pm 2$ q-plate [3] designed to work at $\lambda = 3$ mm. The q-plate was simulated and optimized with HFSS 13.0, Finite Element Analysis software by Ansoft. The manufacturing technique consists of creating artificial birefringence in a dielectric material by machining grooves into the surface with a specified geometry. The q-plate may be quickly redesigned for any radio frequency required.

By measuring both intensity and phase, the far field beam profile is reconstructed. Intensity and phase data was obtained by compiling several transverse beam scans at various rotation angles. A map of the local 2 phase-shift induced on the field by the device was obtained by making a planar scan at a small distance from the q-plate. All measurements were performed by use of a Vector Network Analyzer. The experimental data is in good agreement with the simulation predictions.

**Quantum coherent control**

**P.23 - Energy sharing in the two-electron attosecond streak camera**

H Price¹, A Emmanouilidou¹ and A Staudte²

¹University College London, UK, ²University of Ottawa, Canada

Using the recently developed concept of the two-electron streak camera (see Emmanouilidou et al. [1]), we studied the energy sharing between the two ionizing electrons in single-photon double ionization of He(1s2s) [2]. We found that the most symmetric and asymmetric energy sharings correspond to different ionization dynamics with the ion’s Coulomb potential significantly influencing the latter. This different dynamics for the two extreme energy sharings gives rise to different patterns in asymptotic observables and different time delays between the emission of the two electrons. We show that the two-electron streak camera resolves the time delays between the emission of the two electrons for different energy sharings.


**P.24 - 2D Holographic optical lattices for single atoms manipulation**

L Beguin, A Vernier, T Lahaye and A Browaeys

Institut d’Optique, France

Two-dimensional lattices of single atoms are a promising environment allowing fine control of the atomic interactions in a mesoscopic ensemble. We propose an experiment to study the long range dipole-dipole interactions in the system working in the Rydberg blockade regime. The versatility of holographically generated 2D arrays of single atoms should allow us to achieve arbitrary geometries as well as site-to-site addressability, thus enabling the tunability of the interactions within the system.
P.25 - Reduced-density-operator description of single-photon and multi-photon processes in quantized many-electron systems

V Jacobs
Naval Research Laboratory, USA

A reduced-density-matrix description is developed for single-photon and multi-photon processes in quantized many-electron systems, taking into account environmental electron-photon and electron-phonon interactions. A general treatment for the spectral line shapes is provided, which is based on the derivation of precise expressions for the tetradic matrix elements of the frequency-domain Liouville-space self-energy operator. Using a perturbation expansion of the frequency-domain Liouville-space self-energy operator, a detailed evaluation of the spectral-line widths and shifts is carried out in the isolated-line, short-memory-time (Markov), and lowest-order (Born) approximations. Applications of interest include spectral simulations for single-photon and two-photon absorption processes in atomic, molecular, and solid-state systems.

P.26 - Dynamics of correlations in the fermi problem

M Borrelli¹, C Sabin², G Adesso³, F Plastina⁴ and S Maniscalco¹
¹Heriot-Watt University, UK, ²Instituto de Física Fundamental, Spain, ³University of Nottingham, UK, ⁴Università della Calabria, Italy

Since its conception the two-atom Fermi problem has always been at the center of an intense academic debate. The core of such a debate lies in the simple question of whether quantum mechanical probabilities respect or not microcausality. Several solutions have been proposed, mostly providing a positive answer [1]-[2]. However, what about correlations? In a recent paper [3] it was shown that the entanglement between the two atoms starts increasing outside the light cone as a consequence of zero-point-energy fluctuations. In this work we study the dynamics of a wider class of quantum and classical correlations in the same model and make a comparison between their time-dependent behavior. The results obtained generalize what was previously found for entanglement and suggest the possibility of detecting quantum correlations outside the light cone.


P.27 - Strange change of CsCdCl₃-excitation spectra with temperature

R Demirbilek¹, A Çelik Bozdoğan¹, M Çalışkan¹, G Asan¹ and G Özen²
¹Yıldız Technical University, Turkey, ²Istanbul Technical University, Turkey

We have grown CsCdCl₃-crystal and measured its intrinsic excitations and emissions spectra.

Using these spectra we constructed an electronic energy level diagram of CsCdCl₃ [1]. The excitation spectrum changes in temperature range from 16 K to 20 K, which reverses at about 80K. We will present and discuss our results about this interesting change.

Several halide perovskites like CsCdBr$_3$ are important for investigation of physical processes such as ion-ion interactions, doping-ion and host crystal interaction resulting in up-conversion and energy transfer. CsMgCl$_3$, CsMgBr$_3$, CsMgI$_3$ and CsCdBr$_3$ are in this point of view similar, since they all consist from $[MX_6]^{4-}$ octahedrons. Such crystals crystallize in the hexagonal space group P6$_3$/mmc and the site symmetry of Mg$^{2+}$ or Cd$^{2+}$ ion is D$_{3d}$[1-3].

The low temperature (10K) excitation and emission spectra of CsMgCl$_3$, CsMgBr$_3$, CsMgI$_3$ crystals were measured in order to determine their electronic energy levels. An analysis of the excitation and emission spectra of these crystals will be presented.


**P.29 - Enhancement of collective atomic recoil lasing by electromagnetically induced transparency**

J Mckelvie and G Robb

University of Strathclyde, UK

Collective Atomic Recoil Lasing (CARL), which involves simultaneous amplification of scattered light and atomic density gratings, has been observed in Bose Einstein condensates (BEC) and in cold atomic gases typically at or below sub-Doppler temperatures.

To date, models of CARL have considered only two-level atoms. We have developed a model of cold three-level atoms interacting with optical fields where both internal atomic degrees of freedom and the motion of the atoms are described. This model allows us to investigate the interplay between recoil-induced effects such as CARL with effects associated with 3-level atoms such as Electromagnetically Induced Transparency (EIT) and stimulated Raman scattering.

We will present results showing linear stability analysis and nonlinear simulations of the atoms and optical fields in various configurations. Our results demonstrate that EIT can result in a significant enhancement of the CARL amplification process. The optical dipole forces which govern the formation of the atomic gratings responsible for CARL are strongly affected by the modified absorptive and dispersive behaviour of the three-level atoms due to EIT. A possible consequence of this is that EIT could allow the observation of CARL instabilities and related phenomena in gases at temperatures much higher than have been possible to date. Parameters for possible experiments to demonstrate these effects will be proposed.

**P.30 - Nonlinear dynamics of Bose-Einstein condensates in optical cavities**

M Diver, G Robb and G-L Oppo

University of Strathclyde, UK

Recent experimental and theoretical studies of a Bose-Einstein condensate (BEC) enclosed within a Fabry-Perot cavity [F. Brennecke et al. Science 322, 235 (2008)] demonstrated nonlinear effects including bistability and nonlinear oscillations. Theoretical models of this BEC-cavity system to date have described the coupling between
the BEC and the optical cavity field, but the atom-atom interactions in the BEC have been neglected and the modification of the BEC wavefunction due to its interaction with the cavity field has been assumed to be small.

We have developed a model of the BEC-cavity system that fully describes the spatio-temporal dynamics of the BEC wavefunction in the optical cavity and includes the atom-atom interactions of the BEC i.e. finite scattering lengths. Using this model we demonstrate the effect of the atom-atom interactions on the nonlinear dynamics of the BEC-cavity system, both for repulsive condensates such as the rubidium BEC studied by Brennecke et al. and for attractive condensates such as a caesium BEC. The results presented will be relevant to experiments under construction involving a caesium BEC enclosed in a Fabry-Perot cavity.

P.31 - Spatial opto-mechanical structures in cold atomic gases
E Tesio, T Ackemann, G Robb, W Firth and G-L Oppo
University of Strathclyde, UK

Spontaneous self-organisation in nonlinear systems far from equilibrium is a research topic that cuts across many areas of physics and science. In the context of transverse nonlinear optics, saturation of electronic transitions in an atomic medium creates a nonlinear response to the incoming radiation. If a positive feedback loop is created, this response provides an instability mechanism leading to spatial structures of the light intensity in the plane transverse to the propagation. Such structures are also encoded in the spatial distribution of the internal degrees of freedom of the sample, namely the coherences and the populations of the medium.

We investigate here a different mechanism for the formation of transverse structures, studying the case of a laser-cooled, two-level atomic sample inserted in a planar ring cavity. In this case, the opto-mechanical coupling between light and the centre-of-mass degrees of freedom of the medium mediated by the intensity-dependent dipole forces affects the atomic density distribution. The nonlinear interplay between opto-mechanical forces and the density modulations that they create is shown to effectively provide a new pattern-forming mechanism for the system via atomic bunching. Such a mechanism is shown to lead to a novel spontaneous self-organisation in the transverse plane that becomes dominant when lowering the temperature of the ensemble to a few times the Doppler limit. Theory and simulations for parameters experimentally accessible in Rubidium vapours are presented.

P.32 - An optical Isolator using atomic vapour in the hyperfine paschen-back regime
M Zentile¹, K Kleinbach¹, L Weller¹, C Adams¹, I Hughes¹ and S Knappe²
¹Durham University, UK, ²National Institute of Standards and Technology, USA

Optical isolators are essential for the vast majority of experiments involving lasers. Using a model for the electric susceptibility of an alkali metal vapour we are able to predict the temperature and magnetic field needed to produce the required 45 degree Faraday rotation. Our model includes absolute absorption [1], dipole-dipole interactions [2], magnetic fields [3], and allows us to fully characterize the absorption and dispersion for both pulses [4] and continuous light [3].

Here we demonstrate experimentally that it is possible to make a light, compact optical isolator by using a 1mm long atomic Rb87 vapour cell [5] and a small permanent magnet. We achieve magnetic fields of around ~0.6 Tesla which force a large splitting in the transition frequencies, giving a region of high transmission and large dispersion. At these high fields we enter the Paschen-Back regime where the angular momentum state of the atom is best described in the uncoupled basis as the total coupled angular momentum, F, is no longer a good quantum number.

There is excellent agreement between theory and experiment for the absorption spectrum and the Faraday rotation as a function of frequency.
Quantum dots

P.33 - Photon correlation spectroscopy of ZnO quantum dots - a tool for investigating size dispersions and inter-particle forces
M Shortell, E Jaatinen and E Waclawik
Queensland University of Technology, Australia

Understanding the relationship between the optical properties of quantum dots and their morphology is important for the design of quantum dot based optical devices. ZnO is a particularly important material due to its wide bandgap, unique surface chemistry, and large nonlinear susceptibility. However due to the small exciton bohr radius of ZnO, ZnO QDs have to be made very small in order to see a blue shift in the bandgap. The small size of ZnO QDs leads to a very high surface energy making them relatively unstable in most environments.

Capping ZnO QDs with organic ligands is usually used to create more stable nanoparticles but due to the very small size there is usually a large excess volume available for solvent molecule infiltra-p- tion limiting the stability of the nanoparticles. This also means the volume of the organic capping layer is the same order or larger than the volume of the ZnO core. This in combination with the low refractive index of ZnO results in difficulties in interpreting photon correlation spectroscopy results. This usually results in overestimating the size of ZnO QDs.

Photon correlation spectroscopy was used to measure the diffusion coefficient of ZnO nanoparticles of different sizes. The relationship between stability and nanoparticle size was investigated by measuring the diffusion coefficient at different ZnO concentrations. Assuming rayleigh scattering of spherical core-shell nanoparticles, different calculations to convert intensity weighted to volume weighted particle size distributions was examined and compared to other techniques such as ultraviolet absorption spectroscopy and transmission electron microscopy.

Quantum information

P.34 - Quantum measurement with chaotic apparatus
M Everitt, W Munro and T Spiller
1Loughborough University, UK, 2NTT Basic Research Laboratories, Japan, 3University of Leeds, UK

We study a dissipative quantum mechanical model of the projective measurement of a qubit. We demonstrate how a correspondence limit, damped quantum oscillator can realise chaotic-like or periodic trajectories that emerge in sympathy with the projection of the qubit state, providing a model of the measurement process.
P.35 - Polaractivation of noisy optical quantum channels

L Gyongyosi and S Imre
Budapest University of Technology and Economics, Hungary

Polar channel coding is a revolutionary encoding and decoding scheme that makes possible the construction of codewords to achieve the symmetric capacity of noisy communication channels. The polaractivation is the polar encoding based superactivation of noisy quantum channels. The superactivation is an extreme violation of the additivity of quantum channel capacities and enables the use of zero-capacity quantum channels for communication. Polaractivation of an optical quantum channel means the ability of achieving positive capacity for a noisy optical quantum channel that initially had zero capacity. The polaractivation is based on the quantum polar encoding and the result is similar to the superactivation effect — positive capacity can be achieved with quantum channels that were initially completely useless for communication. However, our polaractivation differs from superactivation since it does not stand any preliminary conditions on the initial private capacity of the channel or on the maps of the other channels in the joint channel structure. Applying our polar encoding scheme, the noisy quantum channel with zero private and quantum capacity will be able to transmit private classical and quantum information. The proposed polaractivation effect requires only the use of our quantum polar encoding scheme and in comparison to superactivation, the polaractivation can be implemented easier in practice. Our work also demonstrates that the private classical capacity and the quantum capacity of noisy optical quantum channels are polaractive.

P.36 - Transmission of classical information over zero-capacity optical quantum channels

L Gyongyosi and S Imre
Budapest University of Technology and Economics, Hungary

In the first decade of the 21st century, many revolutionary properties of quantum channels were discovered. The superactivation of zero-capacity quantum channels makes it possible to use two zero-capacity quantum channels with a positive joint capacity for their output. The phenomenon called superactivation is rooted in the extreme violation of additivity of the channel capacities of quantum channels. It was found that in some very special cases quantum information can be transmitted in a similar scenario, however the most general question — the transmission of classical information — over such a structure was an unsolvable problem. Sending classical information over a channel combination in which each channel has not the ability to transmit classical information seemed to be impossible. As we have proven, the superactivation of classical capacity of optical quantum channels is also possible and requires the most natural physical process that occurs during stimulated emission. Before our work, the superactivation of the classical capacity of quantum channels was an open question and seemed to be completely impossible. We show that classical information can also be transmitted over the combination of zero-capacity optical quantum channels.
Future long-distance quantum communication networks based on quantum repeater systems enable the secure exchange of confidential quantum information. Photons are ideal carriers of such quantum information, however, they experience decoherence as transmission distances increase [1]. Therefore, transmitted quantum information requires rectification in order to ensure the unscathed retrieval of the initially sent quantum state.

We present a programmable memory-based beam splitter that equips quantum repeaters based on quantum memories with such functionality [2]. Based on the principle of photon subtraction, stored quantum information, can be distilled by continuously retrieving tiny amounts from the stored excitation [3]. This feat is achieved by using the far off-resonant Raman interaction [4], which allows light fields not participating in the memory interaction to travel through the interaction medium without being changed.

Furthermore, we demonstrate a multi-read feature, which facilitates the complete retrieval of stored quantum information in subsequent time bins, where each bin can be programmed individually by adjusting the power of the read pulses. This technique enables the distribution of a single signal pulse into multiple and paves the way for simple light-matter-entanglement.

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P.39 - Direct optical experimental verification of Yang-Baxter equation

G L Long, C Zheng, J Li and S-Y Song
Tsinghua University, China

Yang-Baxter equation is an important mathematical physics theory as its many applications in various fields of physics. In this Letter, we present a direct experimental verification of Yang-Baxter equation using linear quantum optics. A two-dimensional Yang-Baxter equation is realized and both the equality of the Yang-Baxter equation and the parameter transformation relation are demonstrated directly for the first time.

Quantum optics

P.40 - Quantum-classical crossover of a field mode

M Everitt1, W Munro2 and T Spiller3

1Loughborough University, UK, 2NTT Basic Research Laboratories, Japan, 3University of Leeds, UK

We explore the quantum-classical crossover in the behavior of a quantum field mode. The quantum behavior of a two-state system—a qubit—coupled to the field is used as a probe. Collapse and revival of the qubit inversion form the signature for quantum behavior of the field and continuous Rabi oscillations form the signature for classical behavior of the field. We demonstrate both limits in a single model for the full coupled system, for field states with the same average field strength, and so for qubits with the same Rabi frequency.

P.41 - Super-optimal coherent state amplification without quantum resources

E Eleftheriadou and J Jeffers
University of Strathclyde, UK

Current techniques in super-optimal quantum optical signal amplification are far from experimentally ideal. Schemes based on the quantum scissors [1,2] require single photons as a resource, which is costly in terms of count rates and therefore success probability of the device, and which limits the maximum photon number of the amplified state to 1. The maximum photon number can be increased by cascading, but the success probability drops dramatically, and the count rate even more so. Devices based on noise addition and photon subtraction do not have these limitations, but are far from perfect amplifiers [3,4].

We propose a new method for quantum signal amplification which does not suffer from either of these problems. It is a non-deterministic method, based on the interaction of a limited set of coherent states at a beam splitter followed by a photon subtraction. No quantum resources are required, and the device can amplify perfectly for a twofold gain, with a relatively high probability of success.

P.42 - Tapered distributed feedback pillar cavity in diamond

M Taverne, S Knauer, S Kannan, D Y-L Ho, M Cryan and J G Rarity
University of Bristol, UK

NV centres in diamonds provide a photo stable room temperature single photon source. The well known problem of low extraction efficiency in such sources especially in its zero phonon line is usually mitigated by coupling the emission to wavelength scale structures (pillar microcavity with distributed bragg mirrors (DBR) for III-V semiconductors and solid immersion lenses for group IV semiconductors are recent examples). In this paper, pillar/waveguide structures using novel surface etched distributed feedback mirrors (DFB) are proposed, and recent modeling results using finite difference time domain modeling (FDTD) are presented.

Two single mode, periodically thickened DFB mirrors of 340nm diameter with 100nm high fins are studied. The first such structure consists of a regular untapered grating, with period $\lambda/(2n)$ and cavity length $\lambda/n$ (diamond $n=2.4$, $\lambda=637$ nm). The second structure is an ‘adiabatic’ cavity tapered by shortening the DBR periods on either side of the cavity. Both structures have 30, 25 fins respectively for preferential emission in one direction with tapers included in the pair count.

Using a transverse dipole impulse excitation with source at the cavity’s centre we calculate the electromagnetic ringdown. The Fourier transform of this ringdown shows cavity resonance peaks with $Q$-factors given by the ratio of centre frequency to width $\omega/\Delta \omega_{\text{FWHM}}$. We observe that such novel tapering improves the $Q$ factor by 50% from 1738 to 2567. We are presently optimising our models and will present latest results and preliminary focussed ion beam etched structures at the conference.

P.43 - Photon pair quantum interference with 2x2 multimode interference devices

K Poulios¹, D Fry¹, A Politi², N Ismail³, K Worhoff³, M Thompson¹ and J O’Brien¹
¹University of Bristol, UK, ²University of California, USA, ³University of Twente, The Netherlands

Integrated quantum photonics provide a route to realising large, complex circuits for quantum information and computation schemes, offering miniaturisation and inherent interferometric stability.

Multimode interference (MMI) devices can be used to naturally implement NxM optical multi-ports. In comparison to single-mode based devices, such as evanescently coupled waveguides, MMI devices support multiple guided modes while exhibiting improved robustness to fabrication errors and deviations in experimental parameters, such as wavelength variations.

In this work we study the behaviour of 2x2 MMI devices as beam splitter for quantum optics applications. We perform a theoretical investigation into quantum interference of photon pairs in 2x2 MMI devices and present an expression for the Hong-Ou-Mandel interference visibility, considering the dynamics of the MMI device. We show that without heavy filtering near unity non-classical interference visibilities can be attained.

We experimentally confirm the theoretical analysis characterizing MMI devices fabricated in silicon oxynitride (SiON), a platform that enables high refractive index contrast and therefore the ability to make more compact devices, minimising the adverse effects of intermodal dispersion. We observe visibilities of two-photon quantum interference up to 97.7% without additional narrow-band filtering (2nm bandwidth photons).
These results demonstrate that 2x2 MMI devices can be fabricated in a repeated fashion and concatenated, providing a viable basis for scalable integrated quantum-photonic networks towards large scale quantum information processing.

Structured optical materials

P.44 - Helmholtz spatial solitons and oblique propagation in coupled-waveguide arrays

J Christian¹, E McCoy¹, G McDonald¹, J Sanchez-Curto² and P Chamorro-Posada²

¹University of Salford, UK, ²Universidad de Valladolid, Spain

The interaction between light waves and layered host media is a fundamental class of problem in nonlinear photonics. For example, the interest may lie with studying the behaviour of a spatial optical soliton: (i) at the planar boundary between otherwise homogeneous materials [Aceves et al., Phys. Rev. A 39, 1809 (1989)], or (ii) coupling from a homogeneous medium into a waveguide array (an optical structure with periodic refractive-index modulations). In the latter case, one typically considers head-on or side-coupling geometries [Mandelik et al., Phys. Rev. Lett. 92, 093904 (2004)].

Oblique (off-axis) propagation effects play a central role in essentially all photonic device architectures, and they lie at the heart of interface and coupled-waveguide contexts (where, in the laboratory frame, light may encounter an optical boundary at any angle). Previously, Helmholtz soliton theory has provided an ideal mathematical platform for fully capturing the angular degrees-of-freedom associated with single-interface problems [Sánchez-Curto et al., Opt. Lett. 32, 1127 (2007); 35, 1347 (2010)].

We will present an overview of what is, to the best of our knowledge, the first nonparaxial model capable of describing arbitrary-angle evolution in coupled-waveguide arrays. Paraxial theory, with its small-angle limitations, cannot facilitate such general analyses. The governing envelope equation is of the scalar Helmholtz type with a Kerr nonlinearity, and exact spatial solitons [Chamorro-Posada et al., J. Mod. Opt. 45, 1111 (1998)] have been used as basis functions. Extensive computations have predicted a wide range of new qualitative phenomena when combining structural periodicity with non-trivial beam propagation angles.

P.45 - A hidden sector photon search using photonic band gap structures

N Woollett¹, ⁴, I Bailey¹, R Seviour² and P Williams¹, ⁴

¹Lancaster University, UK, ²University of Huddersfield, UK, ³STFC Daresbury Laboratory, UK, ⁴Cockcroft Institute, UK

Currently there are a number of ‘Light Shining Through Wall’ (LSW) experiments taking place which are searching for hidden sector photons (HSP). The HSP is a hypothetical sub-eV particle which may be detectable if it has a coupling to the Standard Model photon. Such couplings may be present even though the HSP does not couple to electric charge, and can therefore propagate freely through metallic or dielectric boundaries. At microwave wavelengths the LSW experiments employ copper or superconducting cavities to act as emitters and detectors for HSPs. The sensitivity of these cavities is restricted by practical considerations, such as the obtainable quality factor and geometries.

In this poster we propose an alternative approach to the LSW experiment through the use of a photonic structure (PC). By placing defects within a PC we can confine specific electromagnetic state within the band-gap of the PC for long periods while allowing other modes to propagate away. Altering the physical characteristics of the lattice enables a range of frequencies to be tested, whilst still maintaining the frequency matching between defect regions. The ability to place multiple defects within a structure permits the design of novel experimental setups which would be difficult using conventional cavities, especially at high frequencies.
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For more information about the exhibitors, please consult the Exhibition Catalogue in your Photon12 participant pack.
Cover image: Polarization interferogram for a liquid crystal wavefront corrector under variable voltage and frequency conditions