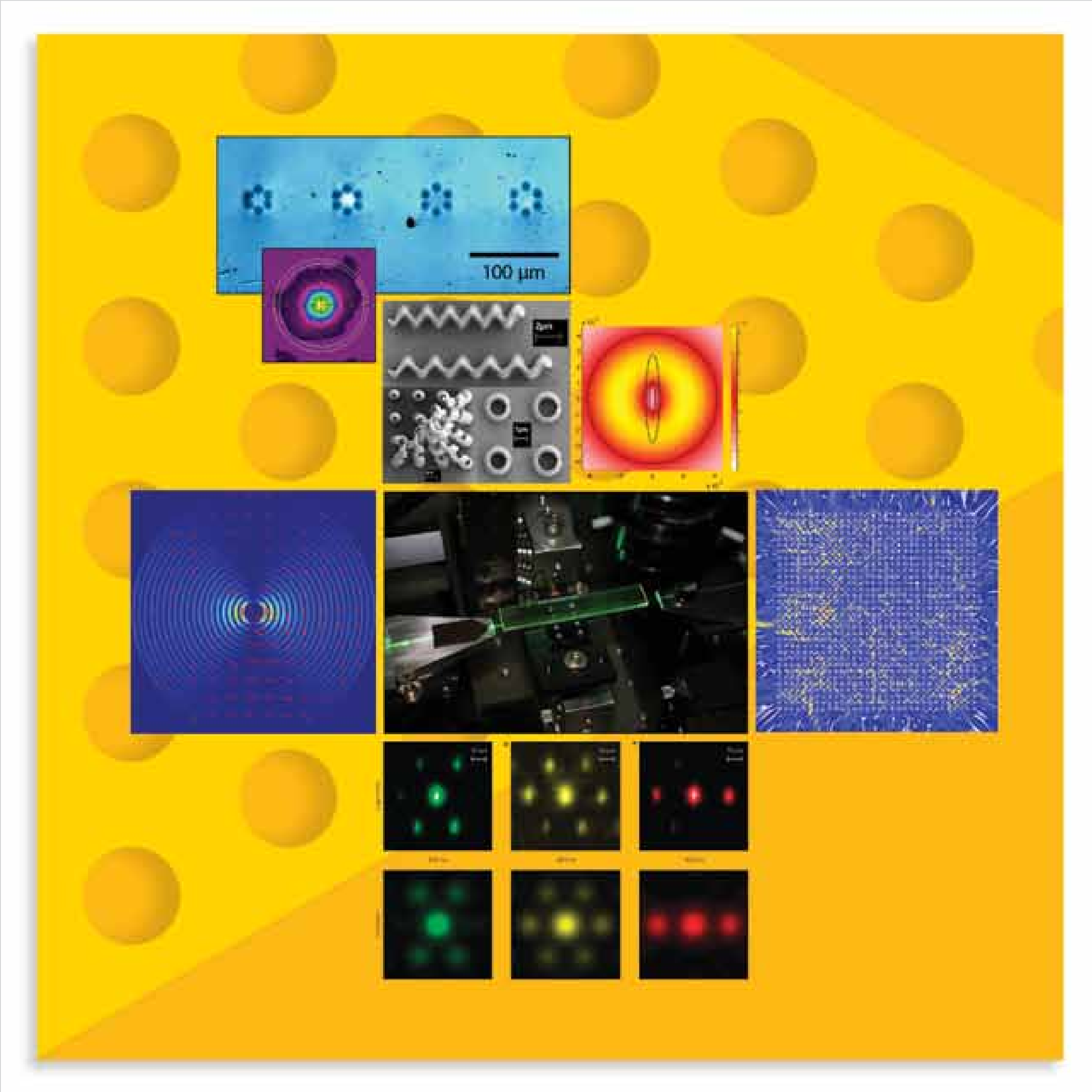
ANNUAL 2009 REPORT



CUDOS

The Centre for Ultrahigh Bandwidth Devices for Optical Systems (CUDOS)

Research in CUDOS is a team effort, but the leadership and contributions of our Chief Investigators are crucial to these team endeavours. Accordingly, we report here on the outcomes of our Flagship projects – team endeavours that draw resource from across the six CUDOS nodes – and the research activities of our Chief Investigators.

What are Flagship projects? These exemplify research in our Centre of Excellence through their scale – typically two or three nodes contribute, with more than twenty contributing staff and students – and focus, targeting projects of strategic importance within the field with the potential for significant scientific impact leading to social, economic or other societal benefit.

CUDOS established its first Flagship projects in 2004, and has added others in intervening years. In 2009 we had six Flagships, each with a dedicated Project Manager and Science Leader, with goals, research programs and outcomes reviewed yearly at a meeting attended by all Chief Investigators, Project Managers and other senior research staff in the Centre. The central role of the Flagships within the Centre is reinforced at the Annual Workshop, where each Flagship has a dedicated session comprising overviews by the Project Manager and Science Leader and typically half a dozen focused presentations by research staff or students, accompanied by invited talks from the collaborating Partner Investigators for each project.

This strategic focus and significant commitment of effort to build the necessary critical mass has yielded landmark results over the past few years, none more so than in 2009 where research outcomes of three of our Flagships were published in the highly ranked journals *Nature Photonics* (2 publications) and *Nature Physics* (1), as well as in *Advanced Materials* (1) and *Physical Review Letters* (1). These publications underline our international leadership in research into terabit per second all-optical modulation, photonic integrated circuits for quantum logic, and applications of slow light in photonic crystals as well as fundamental studies of light in photonic lattices and 3 D photonic crystals. Our impact factor for the forty most highly-ranked articles judged by publication in the journals with the highest impact factor was in excess of 5.3. This continues a trend over the lifetime of the Centre toward higher quality journal publications.

A brief overview of the research described in detail in the following sections is provided below:

Terabit per second research

The Centre's program in nonlinear signal processing built initially around nonlinear chalcogenide waveguides has provided convincing demonstrations to the international research community that error-free signal processing operations including time division multiplexing and wavelength switching can be carried out with very low system penalties at modulation rates of up to a terabit per second and beyond. The work is significant in the context of next generation optical communications research because it provides an approach that, in combination with developments in novel modulation formats based on polarisation and coherent phase detection, may lead to energy-efficient ultrafast data transmission systems required by an increasingly green and increasingly IT-reliant society over the coming decades.

As befits a project of international significance, CUDOS collaborates with large research groups elsewhere in the world to develop, demonstrate and implement these signal processing technologies. Much of the work on demonstrating ultrafast signal processing technologies is in collaboration with a leading optical communications group at the Danish Technical University (DTU) led by Prof Lief Oxenlowe, while the development of novel devices with improved performance and compatibility with silicon platforms is in collaboration with the SOFI consortium, an EU-funded team comprising academic and industrial research groups from Germany, Italy, Belgium, Switzerland and Greece, led by Prof Leuthold of Karlsruhe.

The project team achieved a number of internationally-recognised outcomes during the year, including the publication of all-optical signal demultiplexing at 640 Gb/s (a joint publication with DTU) and the publication in *Nature Photonics* of signal processing using an all-optical device to analyse and display the power spectrum of intensity fluctuations in a 320 Gb/s data signal with terahertz bandwidth. By using an optical "nanowire" waveguide in highly nonlinear chalcogenide glass to reduce the scale length of the parametric interaction on which the power spectral analysis was based, the team succeeded in reducing the length-dependent optical dispersion in the waveguide to such a degree that accurate analysis of the power spectrum was achieved over a wide range of optical wavelengths and with a measurement bandwidth of up to 2.5 GHz.

Slow Light and photonic crystals

The remarkable physical phenomenon of slow light, first observed in cooled atomic vapours, captured the public's imagination when it was described as 'Light travelling slower than a bicyclist'. It was soon realised that the spectral bandwidth over which this slowing occurred was inversely proportional to the effective refractive index responsible for the dramatic reduction in group velocity of the light pulse, meaning that the dramatic reduction of light to near-walking speed could only be achieved for an almost CW pulse of light. Much research has focused on ways to beat this delay-bandwidth limitation. At the same time, interest has been intense on ways in which this effect might be harnessed for practical applications.

Because slow light remains in the optical medium for a greater period of time – and because the slowing is necessarily accompanied by an enhancement of the intensity of the light within the medium – effects that depend on the strength of the interaction between light and medium should be enhanced. For example, the threshold for intensity-dependent nonlinearity should decrease, an effect whose application a European project team funded under the FP-7 program led by Thomas Krauss of St Andrews was established to explore. The CUDOS signal processing technology is built around such an intensity-dependent nonlinearity and so we commenced collaboration with SPLASH (the acronym for the European consortium) in 2008, with Prof Krauss joining the Centre as a Partner Investigator.

This collaboration achieved a spectacular result early in 2009, with a publication in Nature Photonics detailing the remarkable observation of third harmonic generation during the propagation of a 1.5 micrometre (µm) laser in channel in a silicon-based photonic crystal. While such a frequency-tripling process is possible, the very high optical loss at 0.5 µm make the process extremely inefficient. In the CUDOS-SPLASH experiment, light pulses were slowed to around 2% of their free space value in a photonic crystal waveguide only 80 µm long, and green light was observed by eye with pump powers of around 10 Watts, five to six orders of magnitude lower than those in previous reports of this effect! The group presented compelling evidence that this dramatic improvement was due to a combination of the higher intensity of the pump due to tight confinement of the light field in the waveguide, and the effects of slow light.

Integrated waveguides for quantum photonics applications

CUDOS researchers have world-leading capabilities in "writing" waveguides and gratings just below the surface of planar optical substrates. A femtosecond high power laser pulse is focussed into the material to reach intensities sufficiently high that at the focus, a multiphoton-induced rearrangement of the chemical arrangement of the constituent atoms occurs, leading to an increase in the local refractive index compare to the surrounding glass. By smoothly translating the substrate perpendicular to the laser beam, the team writes two dimensional waveguides and, by modulation of the output power, more complex waveguide structures including Bragg gratings.

One of the more promising approaches to quantum-based computation is based on the production of single photons. The routing of these through networks of beam splitters to form entangled "qubit" states is a new approach to computational logic that may be orders of magnitude more powerful than binary gates in present day computers. Unfortunately these optical schemes are extremely difficult to put into practice using discrete optical components. Even simple quantum logic operations require extremely complex optical layouts and the production of multi-photon qubit states becomes next to impossible. Our approach, which opens the possibility of writing complex optical circuits into a single planar substrate, has come to the attention of the quantum information community. Working in collaboration with a leader in the field of quantum information, Jeremy O'Brien of Bristol, the CUDOS team provided proof of principle demonstrations that complex quantum circuits might be produced on an optical chip written with a femtosecond laser.

During 2009 the integrated waveguide team in collaboration with Professor O'Brien fabricated directional couplers (two inputs, two outputs) in high purity fused silica and evaluated these in an experiment designed to measure the quality of the coupler in the quantum regime. The team generated pairs of identical photons at 804 nm in a parametric down-conversion process from a 402 nm laser, split these into two arms with a variable delay in one path, and directed these photon beams to the inputs of the coupler. The presence of a photon in each arm of the output was then measured as a function of the delay in the arrival at the coupler of the photons from each beam. In a quantum system each beam will contain the same entangled state of the two photons, and if these identical tangled states arrive at the coupler at the same time, two photons will emerge at one port and none at the other. This zero in the coincidence measurement at zero delay has no classical analogue, and the degree to which the coincidence signal approaches zero indicates, among other things, the quality of the coupler.

The CUDOS team conducted a series of measurements with two then three entangled photon states. The results, measured experimentally by the depth of the anti-coincidence, were comparable to those for free space couplers in the case of two entangled photons (95% extinction) and superior for the three entangled photons (84% extinction). The results provide strong support for a major new project to produce an integrated photonic chip for quantum information processing using the CUDOS direct write approach.

3D Photonic Crystals

Structures with periodic variations in refractive index in one and two dimensions are relatively straightforward to fabricate. Three dimensional structures are another matter. Our photonic crystal team has successfully fabricated 3D structures using photo polymerisation, but the materials are low refractive index (~1.5). This means that the optical properties of the crystals, and in particular the depth and angular range of the bandgaps where transmission is prohibited, are not particularly useful.

To produce photonic crystals in materials with higher refractive index we need different approaches to photo polymerization. Our researchers investigated techniques that, similar to our research in integrated waveguides, produce chemical and physical changes in the bulk of a material under high intensity ultrafast laser irradiation. We need to be able to image the laser beam to a tightly focused spot at a significant depth inside a high index material, an operation that would normally lead to substantial spherical and other aberrations. To develop dynamic imaging approaches for these conditions, we collaborated with Professor Tony Wilson of Oxford, an international expert in microscopy.

To date we have successfully produced photonic crystals with high contrast bandgaps in lithium niobate and in chalcogenide glass. We have further explored the optical properties of these new metamaterials by placing quantum dot photon sources inside the crystal and measuring the change in the fluorescence lifetime of these sources when the emission spectrum lies within the photonic bandgap. Our observation of inhibited emission was published in *Advanced Materials*. This article concluded with the statement that "this work is an important precursor step to future studies on radiative emission from PCs, and should certainly cause a stir in the field towards the further development of key photonic technologies."

Tunable Microphotonics

Tunability is a core issue for the operation of all-optical photonic devices and circuits. Highly resolved wavelength selectivity and precisely defined dispersion must be actively tuned and stabilized to be practically useful. Further, if the nonlinear response itself can be tuned then a new range of all optical switching devices may be realized. This project has attacked this challenging task both theoretically and experimentally.

We achieved dramatic reduction of the threshold power for nonlinear effects via infiltration of liquid-crystal defects into periodic structures. By placing the liquid crystal defect layer asymmetrically inside the periodic structure, we observed a nonreciprocal response. We succeeded in reversing this by using a pair of defects, one of them a nonlinear liquid crystal defect layer, and varying the input wavelength, resulting in reversible optical diode operation. In further work we have demonstrated that a one-dimensional photonic crystal with a homeotropic nematic liquid crystal defect behaves as a polarization-sensitive nonlinear all-optical device.

In further studies of liquid infiltrated photonic crystal fibres we succeeded in switching of the nonlinear behaviour of the structures from focusing to defocusing by taking advantage of the precise temperature tunability of the liquid infiltrated fibres.