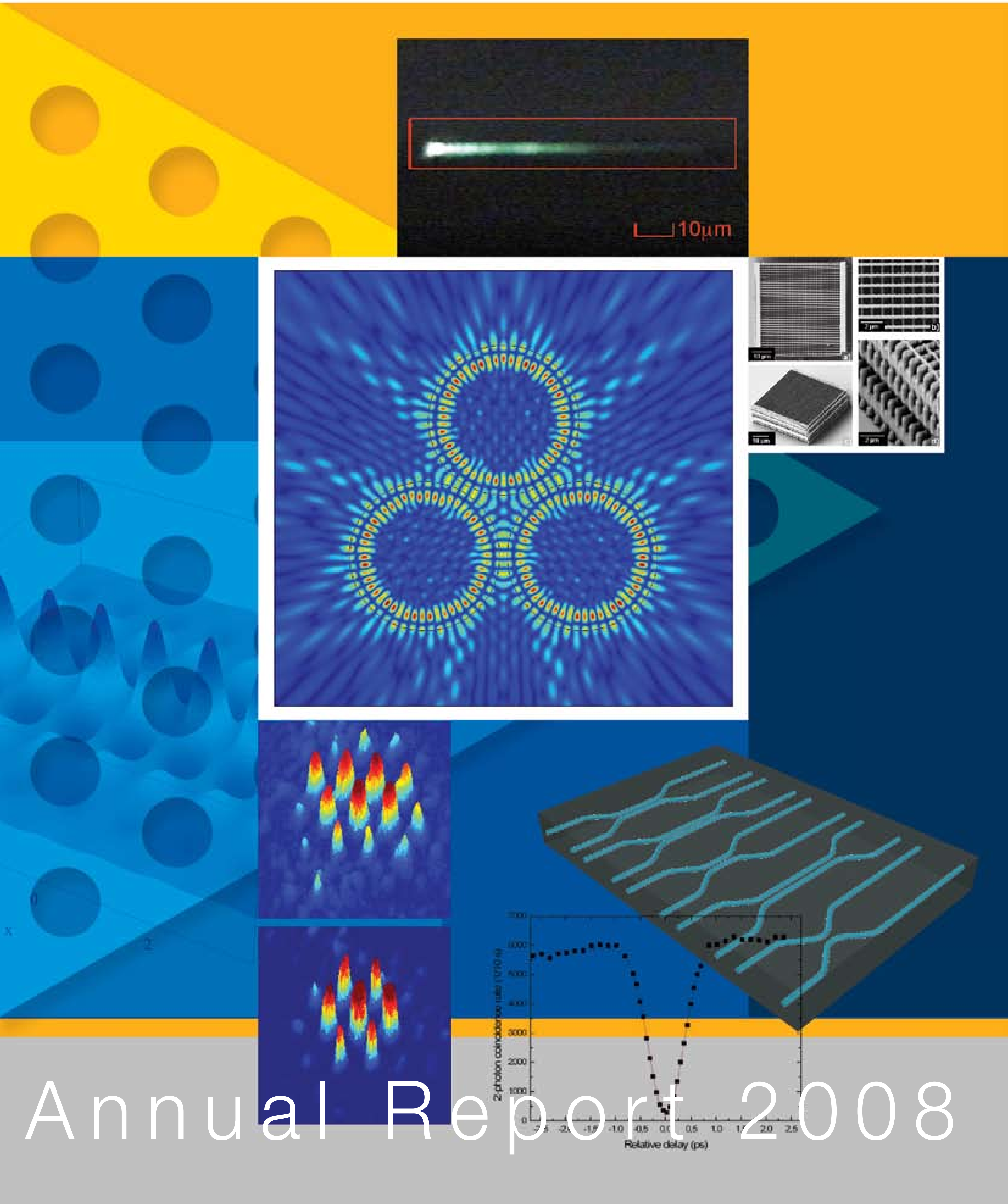
CUDOS

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



Annual Report 2008

3D BANDGAP CONFINEMENT

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Four year vision/long term goal and motivation

The long-term goal for this project is to develop and characterise three-dimensional (3D) photonic crystals (PCs) possessing complete bandgaps and novel nonlinear properties with the aim to realise miniaturised all-optical devices for a range of innovative photonic applications. This aim addresses the CUDOS vision of a highly integrated photonic chip with a significantly increased processing capacity by the addition of an extra dimension in space. Various components such as PC waveguides and superprisms are needed to demonstrate such compact 3D PC photonic chip architectures. Most important of all, active elements including low threshold and directional emitters are the key to a practical device. We placed nanometre-sized quantum dots (QDs) and nanodiamonds inside 3D PCs and investigated their radiation dynamics.

CUDOS strategy/competitive advantage

Materials with high refractive index contrast are critical to realising a complete bandgap in a 3D lattice. However this direct approach has huge technical challenges. Our approach has been in two steps: (1) demonstrate useful passive and active photonic devices in low refractive-index materials, such as polymer and opals. These possess only partial bandgaps but allow us to develop and accumulate expertise in material science, fabrication and device design. (2) Transplant the knowledge obtained from low-index PCs to high index 3D PCs with complete bandgaps and realise the 3D PC photonic chip architectures.

Three dimensional Photonic Bandgaps team.

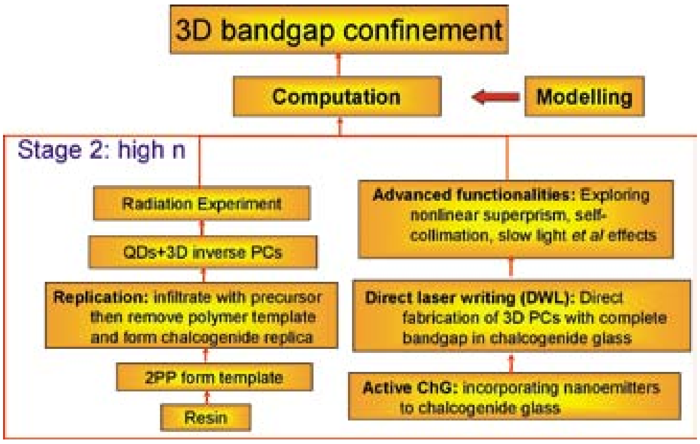


Fig 1. A schematic diagram illustrates the CUDOS approach to the 3D bandgap confinement project, the second phase: high refractive index 3D PCs

CUDOS possesses unique expertise in theoretical simulations, material science, photonic design and world-class facilities across its participating universities to conduct cutting-edge research in this flagship project. With regard to computational modelling, we have significant expertise in FDTD and semi-analytic modelling, as well as good access to supercomputing facilities at the APAC National Facility. Experimentally, we use state-of-the-art nanofabrication techniques based on Direct Laser Writing (DLW) and self-assembly methods for the fabrication of 3D PCs with bandgaps in the visible and near infrared (NIR) wavelength regime (Fig. 2).

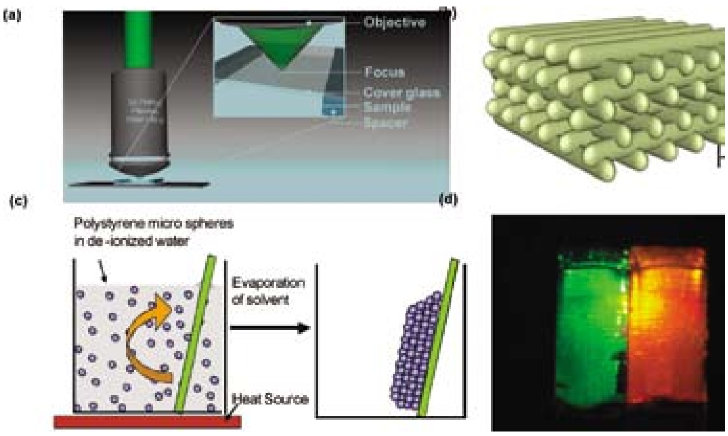


Fig 2. Schematic drawing of (a) the DLW setup and (b) a woodpile 3D PC generated by DLW. (c) Self-assembly setup and (d) two opal PCs generated by self-assembly.

Chalcogenide glasses were selected as the building platform for 3D PCs because of their high index, which enables a complete bandgap to be achieved and their superior nonlinear properties, which add extra functionalities. The application of these novel materials allows for the integration of the 3D PC components with diverse chalcogenide-based elements built by other CUDOS nodes to form a functional photonic chip. Using our expertise in material science, we successfully incorporated novel emitters, including QDs and nanodiamonds into 3D PCs to control the spontaneous emission by the versatile bandgap materials and to redistribute the energy to a desirable format.

Collaborative links

The internal collaboration in this flagship project within CUDOS involves researchers from five Universities and has been reinforced through frequent tele-conferences and focused discussion symposia. Theoreticians at University of Technology, Sydney (UTS), and University of Sydney have developed a model for the temporal and spatial features of the radiation dynamics of nanometric emitters embedded in the 3D photonic bandgap materials. Experimental implementations are carried out in both Macquarie University (MQ) and Swinburne University of Technology (Swinburne). The material scientists at Australian National University (ANU) provide valuable support and chalcogenide wafers for experiment.

Externally, the long term collaboration with Prof. Tony Wilson (CUDOS PI) and Dr. Martin Booth on adaptive optics was enhanced by Dr. Martin Booth's visit to Swinburne in March 2008 and Dr. Guangyong Zhou's and Mr. Ben Cumming's visits to Oxford in June 2008 and January 2009. These were supported by two joint international collaboration grants (Investigators: Gu, Wilson, Booth, Zhou) from the *Leverhulme Trust* (UK) and *ARC Linkage International.* Significant progress in the experimental adaptive compensation of aberration is detailed in the 'Achievement highlights' section.

The collaborative link with Prof. Daniel Jaque's group at Universidad Autónoma de Madrid, Spain on PC fabrication in rare-earth ion doped lithium niobate has been fruitful. In 2008 a paper was published in Applied Physics Letters and another one was accepted for publication in Advanced Materials in 2009. This collaboration was consolidated by Dr. Guangyong Zhou's visit to Spain in June 2008 (supported by travel grant from Australian Academic of Science). It will be further enhanced in 2009 after Prof. Jaque and his PhD student visit Swinburne.

The collaboration with Prof. Xue-Hua Wang's group in Sun Yat-Sen University, China, has been further strengthened through the award of a joint ARC Discovery grant to Dr. Baohua Jia and Prof. Wang (PI) for three years (2009-2011).

A new collaborative link with Prof. Chunlei Du from Institute of Optics and Electronics, Chinese Academic of Sciences, China was initiated in 2008 in the field of plasmonics nanophotonics. Prof. Chunlei Du has a well-recognized reputation in the field of micro/nano fabrication, and optical components/ systems design. In Oct. 2008 Prof. Du visited Swinburne for three months. Another new collaboration with Prof. Yunlong Sheng's group from University Laval, Canada was also initiated on the plasmonic effect of PCs in 2008.

Working with Martyn Pemble of the Tyndall Institute, the Macquarie group incorporated rare earth ions (Europium) into opals to control the light emission in the red wavelength spectrum. Stacked Langmuir Blodgett films with 2D regularity and robust structure were explored. In March 2008, Dr Frank Dillon visited Macquarie for 3 weeks, and worked with PhD student Luke Stewart to fabricate silica microspheres of specific size distributions with various impurities incorporated into the microspheres. The size distribution of the microspheres governs the regularity of the opal, as well as the bandgap wavelength.

In collaboration with Dr Jim Rabeau and Dr Yan-Hua Zhai of Macquarie University, the Macquarie group incorporated nitrogen vacancy (N-V) centres in nanodiamonds into the interstices of the lattice of polymer opals, either randomly distributed throughout the opal, or in a layer on top or within the opal.

Goals for 2008

Based on the long-term strategy of this project, the goals for 2008 were: first of all, further experimental and theoretical investigation of radiation dynamics of nano-emitters inside 3D low refractive index PCs. In particular, we aimed to experimentally map the 3D lifetime distribution of embedded emitters in 3D PCs. We also aimed to model as well as demonstrate experimentally 3D PC waveguides and cavities and other components. In 3D PCs of high-index material we aimed to demonstrate complete bandgap and to produce active chalcogenide nanocomposite materials.

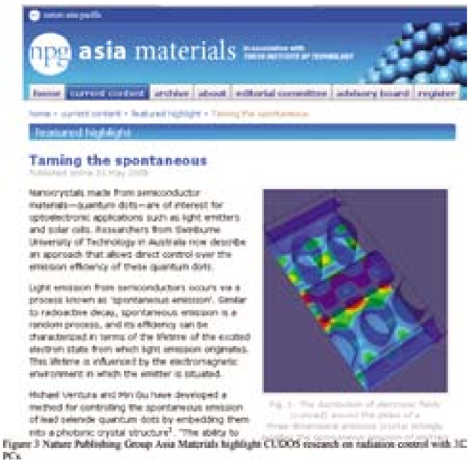


Fig 3. Nature Publishing Group Asia Materials highlight CUDOS research on radiation control with 3D PCs.

Achievements and highlights for 2008

Spontaneous emission control with polymer 3D PCs

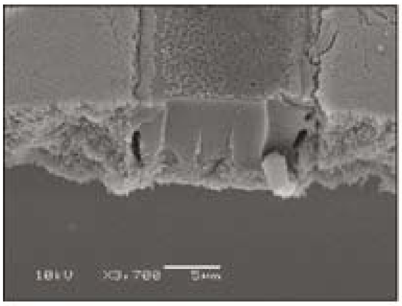
Nature Publishing Group Asia Materials highlighted a recent CUDOS publication in an article entitled 'Taming the Spontaneous' in May 2008. The highlighted paper was published in Advanced Materials and is titled "Engineering spontaneous emission in a quantum-dot-doped polymer nanocomposite with three-dimensional photonic crystals" by Michael J. Ventura and Min Gu [1]. It describes the modification of the spontaneous emission rate of lead-selenide quantum dots embedded in a three-dimensional woodpile photonic crystal.

As a further step to this experiment, Dr. Ventura is working on the 3D mapping of the lifetime distributions of embedded emitters in 3D PCs.

Radiation dynamics in opals and inverse opals

Using self-assembled opals, the Macquarie group created large size structures in silica and polystyrene with few defects and excellent optical properties across mm scale dimensions (Fig. 2(d)). Using both rare earth ions and nitrogen-vacancy centres in nano-diamonds as optical emitters, we investigated the effects of the opal stopgap on the spectrum of the light emission, the angular spread of the emission, and the radiative lifetime of the emission. We found that nano-diamond centres are promising single photon emitters for quantum optics. Waveguides were incorporated into the opals to enable the light guiding and collecting from the emitters, and thus to design and construct devices incorporating light emitters embedded in the opals, and to couple light into and out of the opals.

During 2008 a number of experiments were conducted with the aim of controlling light propagating within 3D photonic crystals. The emission of light from nitrogen vacancy (N-V) centres in nano-diamonds and rare earth dopant ions in opals were investigated. The effects of annealing were studied, with a controllable stopgap peak wavelength being observed in the opal as a function of annealing temperature. We also observed stopgap effects for light guided within waveguides fabricated with SU-8 photoresist embedded in silica opals.



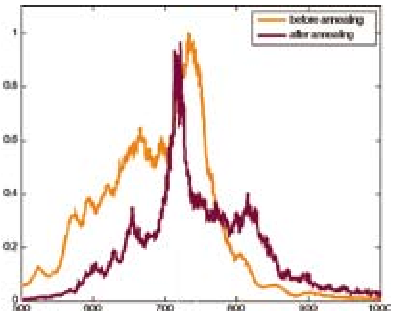


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Fig 4. (a) Scanning electron micrograph of 3D silica opal grown around and on a multimode SU-8 waveguide.
(b) Waveguide transmission spectra for a waveguide embedded in an opal before and after annealing (to shift the stopband of the opal). The spectral peak at 730 nm shifts to 710 on annealing, consistent with the optical properties of annealed opal.

We chose to work with opals, self-assembled 3D photonic crystals, because they are large-area photonic devices and are relatively quick to fabricate. Since they are low refractive-index contrast opals we observe stopgaps or partial bandgaps rather than complete bandgaps in the opals or inverse opals. We can produce high-quality opals with tailored bandgaps by selecting the initial microsphere size distribution. The microspheres self-assemble by settling onto a vertically mounted glass or silicon substrate in a liquid suspension maintained at a constant temperature (Fig. 2(c)). Inverse opals of good quality have also been fabricated by infiltration of silica sol-gel solutions into the initial polystyrene opal structure and then removal of the polystyrene microspheres by pyrolysis. Silica microspheres are fabricated at both Tyndall and Macquarie using the Stöber reaction process.

We achieved tunable and controlled adjustment of the opal stopgap by annealing the opals. Accurate measurement of the stopgap peak wavelength enabled us to characterise the silica refractive index using measurements of the microsphere diameter. We inferred that the microspheres shrunk slightly and increased their refractive index during annealing.

Waveguides of SU-8 were incorporated into the photonic crystals to couple light into and out of the opals. We created high quality multimode optical waveguides, as shown in Fig. 4(a), and measured their transmission/reflection spectra. We successfully assembled opals around and above the waveguides using self-assembly. Working with University of Sydney student Darran Wu and researcher Dr Jeremy Bolger we observed differences in the light propagation in the waveguides with and without the opal (Fig. 4 (b)). We also observed that when the stopgap of the opal changes for example due to annealing, the transmission spectra of the waveguide change in a similar way [2]. Modelling to understand the light propagation (which is complicated by the presence of many modes and uncertainty in the opal orientation) is underway using the RSoft suite.

Nitrogen vacancy (N-V) centres in nanodiamonds have been incorporated into the interstices of the lattice of polymer opals, either randomly distributed throughout the opal, or in a layer on top or within the opal. The spectral changes due to the presence of the opal were measured (Fig. 5), and the lifetime of the emission, as a function of depth in the opal, and particle size of the nanodiamond were characterised [3-5].

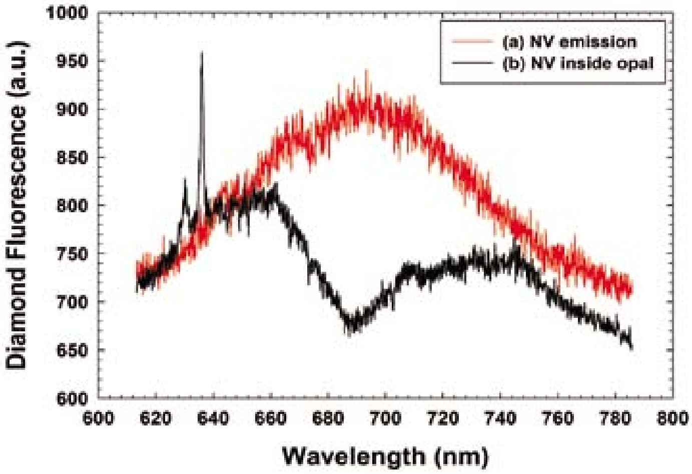

Fig 5. Emission spectra of N-V centres in nanodiamonds on a silica substrate and incorporated into a silica opal with stopgap ~690 nm.

Theoretical modelling

Numerical modelling was used to understand how to design optimised planar defects in PCs. Planar defect modes in woodpile PCs were modelled using the supercomputer at the NCI National Facility using a combination of software developed at UTS and the RSoft Fullwave FDTD code. The dependence of defect mode frequency on crystal defect geometry was determined, and optimised accordingly. The dependence of defect mode Q-factor on the number of layers in the woodpile PC was also characterised. A typical transmittance spectrum for a woodpile with planar defect is shown in Fig. 6.

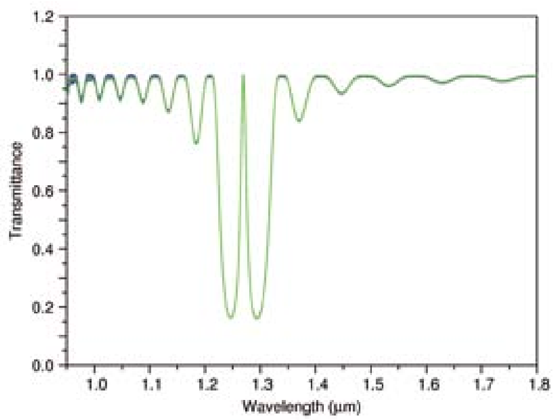

Fig 6. Transmittance spectrum for a woodpile consisting of 40 layers of polymer rods on either side of an air-gap defect. The size of the air-gap has been optimised so that the frequency of the defect mode occurs at the centre of the bandgap for the woodpile.

In the current year substantial progress was made in modelling woodpile photonic crystals using the Bloch mode multipole formulation, starting with the development of a set of tests to verify the consistency and accuracy of the computer codes. Calculations now completed include field reconstructions and the Bloch mode transfer matrix approach for transmission calculations for a woodpile composed of a unit cell containing multiple scatterers. The developed modules were applied to calculate the band structure and to characterise planar and point defects for woodpile photonic crystals. The Q-factors were calculated as functions of defect size and strength of the perturbation. The dependence of defects on incidence angle was also calculated. The obtained results will be used in the design of low loss slow light waveguides.

3D photonic crystals in Chalcogenide glasses

The other remarkable milestone achieved in 2008 was the first demonstration of 3D high-index photonic crystals with higher-order stop gaps in the NIR wavelength range (Figs. 7(a,b)). This important piece of work has been published in Optics Letters and highlighted by the MRS Bulletin [6,7]. Simulation demonstrated that through optimising the structural parameters complete bandgaps can be opened as shown in Fig. 7(c).

Towards active chalcogenide 3D PCs, the surface of the chalcogenide glasses has been functionalised with home-developed luminescent core/shell QDs emitting in the NIR region. The final goal is to match the NIR emission wavelengths of QDs with the bandgap of ChG 3D PCs to achieve spontaneous emission control.

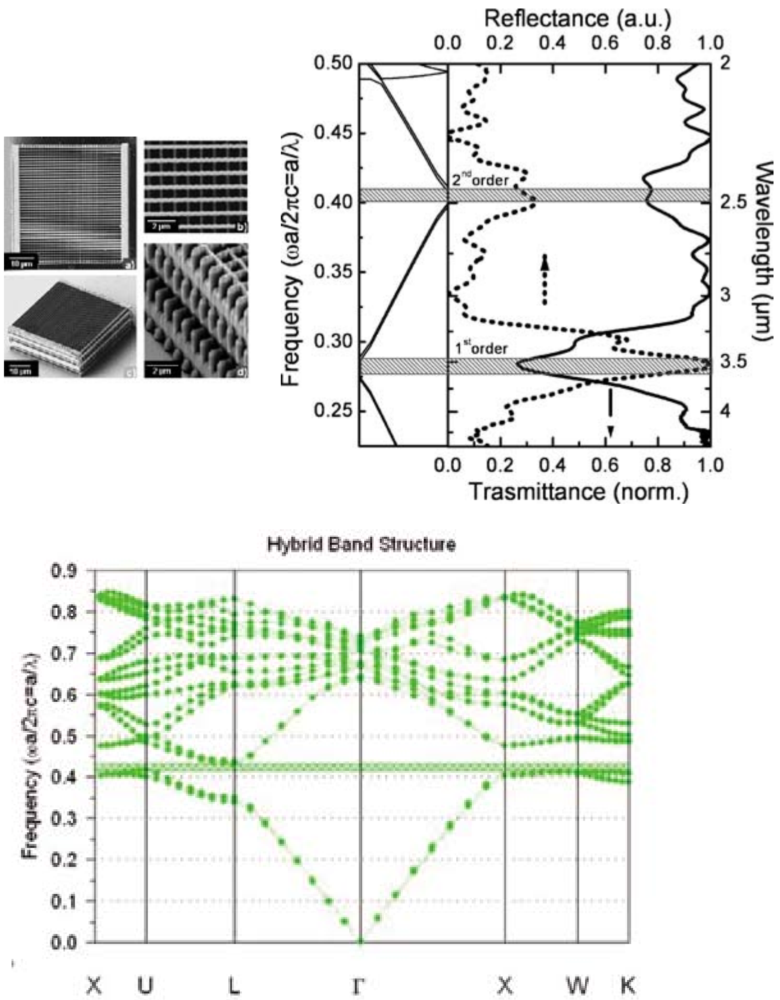

Fig 7. (a): SEM image of 3D chalcogenide PCs with different lattice constant. (b) Left: Calculated band structure of a 3D woodpile PC predicating the presence of both the first and the second order stop gaps. (b) right: Measured transmission and reflection spectra of the 3D woodpile PC matching exactly the calculation. (c) Calculated band structure of a 3D PC showing a complete bandgap.

Aberration compensation in 3D nanofabrication in chalcogenide glasses

One of the most serious problems involved in DLW in high refractive-index thick chalcogenide glass film is the aberration induced by refractive-index mismatch. Adaptive optics compensation has been developed at Swinburne theoretically and experimentally to address this. We found that the strong aberration (Fig. 8(a)) in chalcogenide films can be very well compensated by pre-loading designed phase patterns (Fig. 8(c)) to the writing beam. A nice and clean focal spot can be obtained (Fig. 8(b,d)) for fabrication.

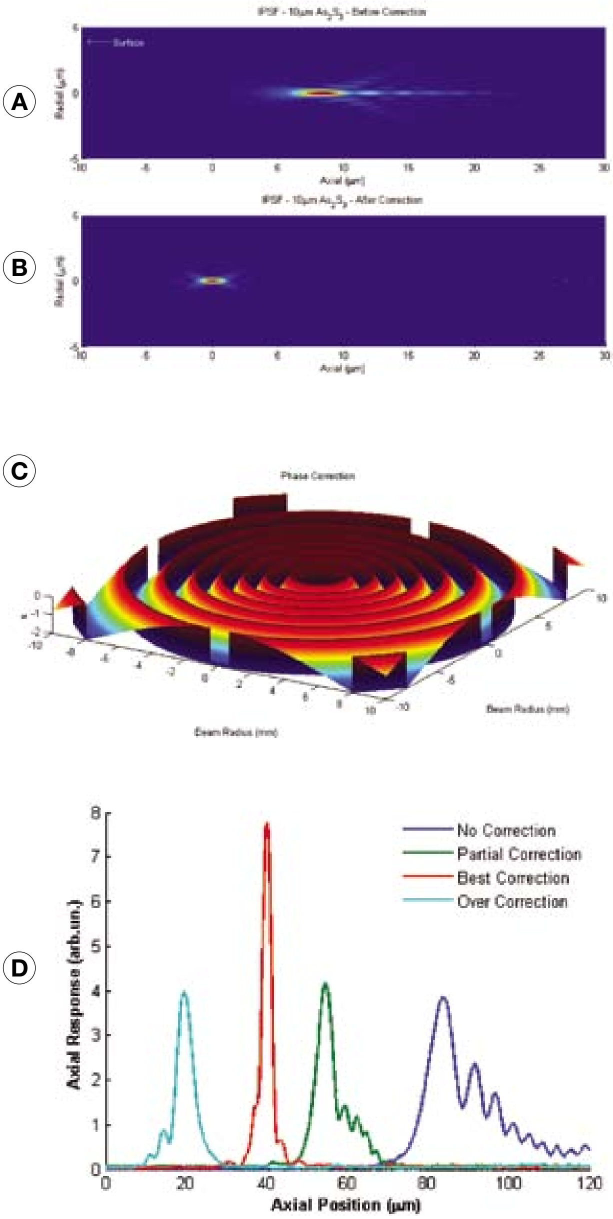

Fig 8. (a) The degraded focal spot caused by strong aberration. (b) The nice and clean focal spot after aberration compensation. (c) A typical pre-designed phase pattern to compensate the aberration in chalcogenide glasses. (d) Axial response showing the effect of aberration compensation.

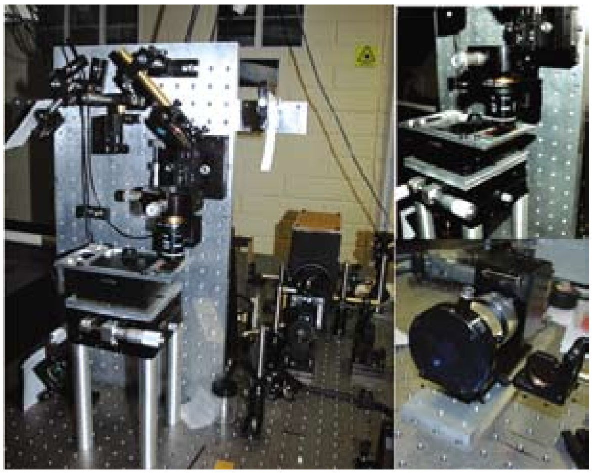

Fig 9. The experimental setup for aberration compensation in DLW in high-index materials.

To experimentally implement the aberration compensation, a new fabrication setup incorporating a 4f system and a liquid crystal phase modulator was constructed at Swinburne, as shown in Fig. 9. The test compensation experiment on ChG films with different thickness demonstrated that the system is functional.

Targets for 2009

In 2009 we will continue to follow our strategic plan to further investigate (theoretically and experimentally) the radiation dynamics of nanometric sources in polymeric and opal 3D PCs with an emphasis on functionality. For example active devices, nonlinear superprism and waveguides will also be reinforced. On the other hand, we will achieve complete bandgap and pursue functionalities in high refractive-index 3D bandgap materials, for example synthesize active chalcogenide based nanocomposites and doped inverse opals, waveguide design and fabrication, nonlinearity investigation, for novel photonic applications.

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