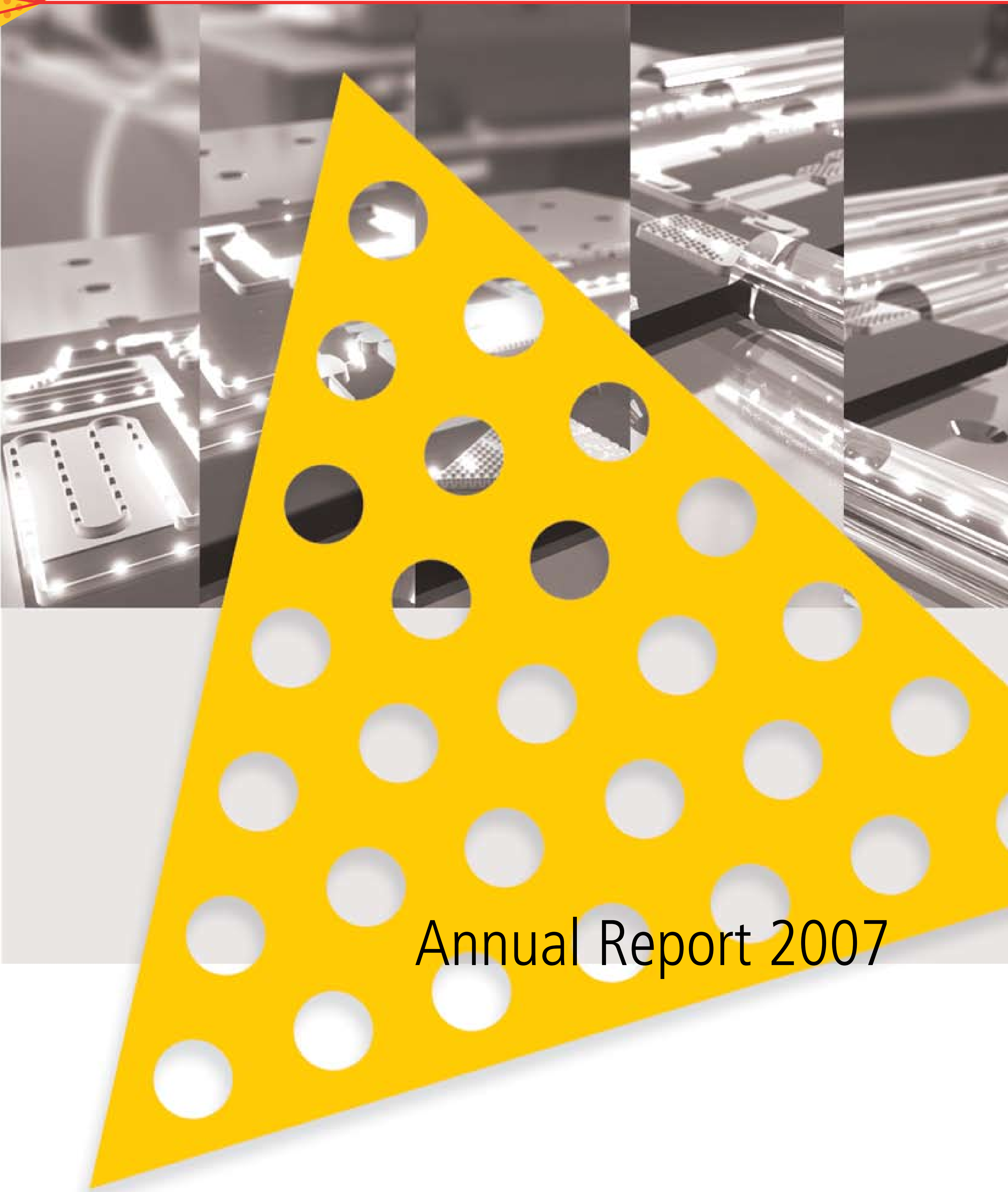
CUDOS

The Centre for Ultrahigh bandwidth Devices for Optical Systems (CUDOS)
An Australian Research Council Centre of Excellence



Annual Report 2007

3D BANDGAP CONFINEMENT

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Four year vision/long term goal and motivation

The goal of this project is to develop and characterise three-dimensional (3D) photonic crystals (PCs) possessing a complete bandgap and novel nonlinear properties leading to miniaturised all-optical devices for a range of innovative photonic applications. This aim matches the CUDOS vision of a highly integrated photonic chip with a significantly increased processing capacity by adding an extra spatial dimension. Passive components such as PC waveguides and superprisms and active elements including low threshold and directional emitters are key components to enabling an integrated photonic chip. During 2007 the CUDOS team innovatively combined nanometric emitters-quantum dots (QDs) and nanodiamonds-with 3D PCs and investigated the radiation dynamics of these nano-emitters.

CUDOS strategy/competitive advantage

Materials with high refractive index contrast are required to a complete bandgap in a 3D lattice. To address this challenging problem, the CUDOS team first studied passive and active photonic devices in 3D PCs made of low refractive index materials, such as polymer and opals, which possess only partial bandgaps. This provides expertise in material science, fabrication and device design. We then develop ways to construct 3D PCs in high index materials and transplant the knowledge obtained from low index PCs to realise high index 3D PCs with complete bandgaps. The detailed milestones in this second phase of this project are shown in Fig. 1.

CUDOS possesses unique expertise in theoretical simulation, material science, photonic design and world-class facilities across its participating universities to conduct the cutting-edge research in this flagship project. With regard to computational modelling, CUDOS has significant expertise in FDTD and semi-analytic modelling, as well as good access to supercomputing facilities at the APAC National Facility. Experimentally, the CUDOS team has elegant and world-leading nanofabrication techniques based on direct laser writing and self-assembly methods, allowing the fabrication of 3D PCs with bandgaps in the visible and near infrared (NIR) wavelength regime (Fig. 2).

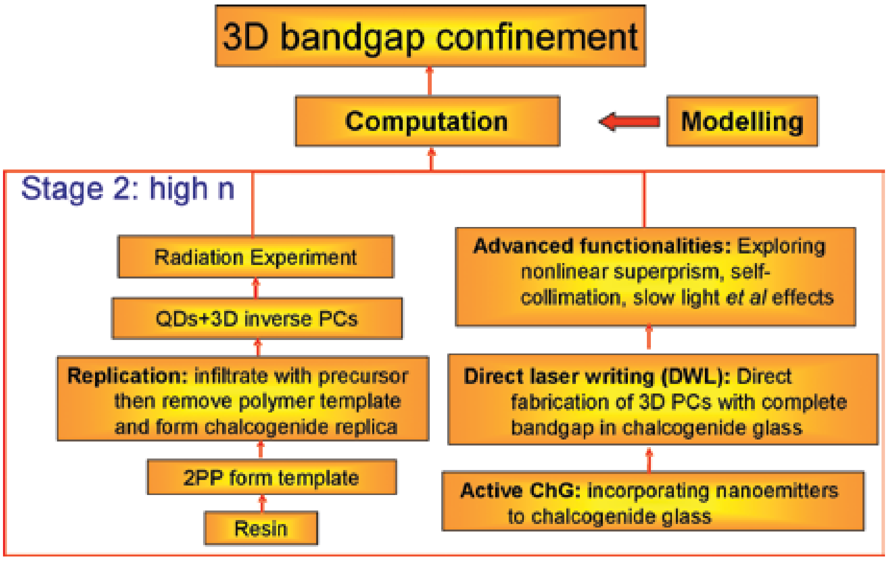

Fig 1: A schematic diagram illustrates the CUDOS approach to the 3D bandgap confinement project, the second phase: high refractive index 3D PCs

Chalcogenide glasses were selected as the building platform for the 3D PCs. Not only do they have the high refractive index required for a complete bandgap but their large nonlinearity provides the opportunity to investigate some novel device concepts. The Centre's capability in this area is strong, with an internationally-acknowledged program in chalcogenide materials and device fabrication. With our expertise in material science, novel QDs and nanodiamonds were successfully incorporated into 3D PCs providing a unique way to manipulate the spontaneous emission by the versatile bandgap materials and to redistribute the energy to a desirable format.

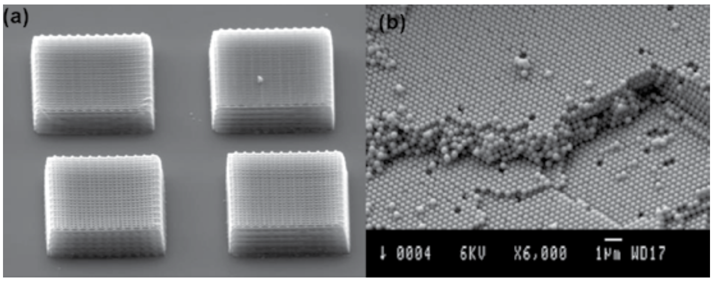

Fig 2: 3D PC formed by (a) two photon polymerization (2PP) technique and (b) self-assembling of polystyrene beads

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 in University of Technology, Sydney (UTS) and the University of Sydney developed a model for the temporal and spatial features of the radiation dynamics of nanometric emitters embedded in the 3D photonic bandgap materials. Experiments were carried out in both Macquarie University (MQ) and Swinburne University of Technology (Swinburne). The Australian National University (ANU) provided the chalcogenide films for experiment and valuable advice on the material.

External collaborations

The linkage with Xuehua Wang, a former CUDOS member at ANU who now holds a professorial chair as a Cheung Kong scholar at Sun Yat-Sen University, China was enhanced after his visit to Swinburne in 2007. Prof. Wang is an active researcher in the photonics area and has made a key contribution to the new theoretical model of describing novel quantum optics phenomena in nano-structures, such as PCs and nanometal structures. This collaboration will improve our understanding of the bandgap effect from the 3D PCs when infiltrated with QDs.

The fabrication of opals containing rare earth ions as emitters was supported by a DEST International Science Linkages grant and an EU Phoremost-funded collaboration with the Tyndall Institute in Ireland, where Prof Martyn Pemble fabricated "2+1 dimensional" PCs from Langmuir-Blodgett films of silica and polystyrene microspheres. CUDOS PhD student Mr. Luke Stewart visited Ireland for 2 weeks in 2007 to learn the microsphere fabrication technique. A further visit by Dr Frank Dillon from the Tyndall Institute is planned for March 2008, during which Eu-doped opals and Langmuir Blodgett films will be characterised.

Our long-term collaboration with Prof. Tony Wilson's group in University of Oxford has been consolidated with visits by Prof. Wilson to the 6th CUDOS workshop as a PI and Dr. Martin Booth to Swinburne for collaborative research. Prof. Wilson is a pioneer in confocal microscopy and aberration compensation. The aim of the collaboration is to solve the strong aberration problem occurring during the direct laser writing in high refractive index materials.

Two joint international collaboration grants, one from Leverhulme Trust (UK), the other one from ARC Linkage International, have been awarded to support this project.

A new collaborative link with Prof. Daniel Jaque's group at Universidad Autónoma de Madrid, Spain was initiated in 2007 with support from the Australian Academy of Science. Prof. Jaque is a well-known expert in solid-state lasers, optical spectroscopy, crystal engineering and microstructure fabrication. This collaboration aims to study the radiation properties of rare-earth ion doped PCs. A PhD student, Mr. Airán Ródenas Seguí from Prof. Jaque's group, visited Swinburne for 3 months in 2007 to work on the PC fabrication in rare-earth ion doped lithium niobate.

We have initiated a collaboration with Prof. Alessandro Martucci's group in Padova University, Italy to develop chalcogenide glass nanocomposites,. This international linkage is a key step towards the achievement of complete control of radiation emission.

Goals for 2007

We had two broad goals for 2007. First, we aimed to experimentally demonstrate the inhibition and redistribution of spontaneous emission for wavelengths within the photonic band gap of a 3D low refractive index PC and compare the results to theory based on the calculation of the local density of states. The second goal was to demonstrate 3D bandgaps in high refractive index chalcogenide glasses.

Achievements and highlights for 2007

Successful measurement of inhibition and enhancement of spontaneous emission of QDs in polymeric 3D PCs at telecommunication wavelengths

During 2006 we succeeded in measuring the spectral redistribution of lead based QDs embedded in 3D PCs. To gain insight of the influence of photonic bandgaps on the radiation dynamics of QDs, in 2007, we assembled a time correlated single photon counting system (TCSPC) operating in the telecommunication wavelength region combined with a purpose-built confocal microscope (Figure 3). This system, unique internationally, can significantly suppress the background of the QD emission and allow us to investigate radiation dynamics with pico-second resolution.

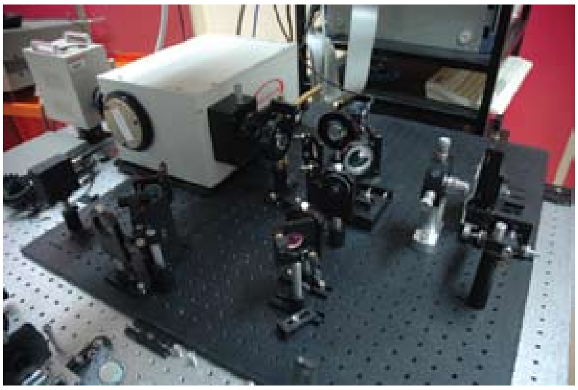

Fig 3: A photo of the confocal based NIR TCSPC setup

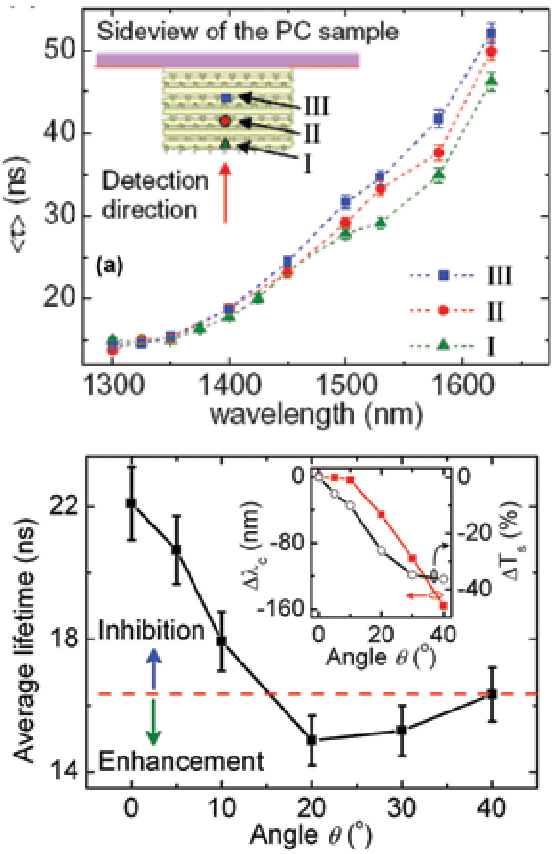

Fig 4: (a) Average lifetime as a function of the wavelength for QDs at three different detection positions (Inset). Position I: close to the top surface of the PC; Position II: 5 ± 1 μm inside; Position III: 10 ± 1 μm inside. (b) Dependence of the average lifetime on detection angle θ for PbSe QDs in the PC. Inset: the shift of the mid-gap ($\Delta\lambda_c$, left) and the change in transmission suppression (ΔT, right) as a function of θ.

Near infrared lead-based QDs with superior size-dependent tunability have been both doped and infiltrated into 3D polymeric woodpile PCs as nanoemitters. In the infiltration approach, the PbSe QDs emitting at 1.58 μm are incorporated into the 3D PCs fabricated with the two photon polymerisation method by drop casting. This results in a thin layer of QDs on the outside of each rod. The 3D PC has a stopgap at exactly 1.58 μm. To examine the bandgap effects on the QD radiation, time-resolved experiments were performed by measuring photoluminescence decays at three different depths (I, II to III in Figure 4(a)) inside the same PC to eliminate the influence from the surrounding dielectric environments. At the bandgap position (1580 nm), where the radiation is inhibited, a pronounced increase of 20% in the decay time was observed at position III indicating that the inhibition of the QD emission physically contributes to the spectral redistribution. This experiment was the first demonstration of lifetime measurement of PbSe QDs infiltrated in 3D woodpile PCs at a telecommunications wavelength. This world first result was published in the prestigious journal Advanced Materials [1].

To further explore the functionality of the active devices, tunability of the spontaneous emission is crucial. We were able to tune the spontaneous emission from a QD-infiltrated 3D PC by adjusting its angle-dependent stop gaps. Angle-resolved photoluminescence decays were obtained. As shown in Figure 4(b), with the change of the detection angle an inhibition of the spontaneous emission of up to 35% was observed in the mid-gap and an enhancement of up to 8.5% was seen at the centre of the band edge [2].

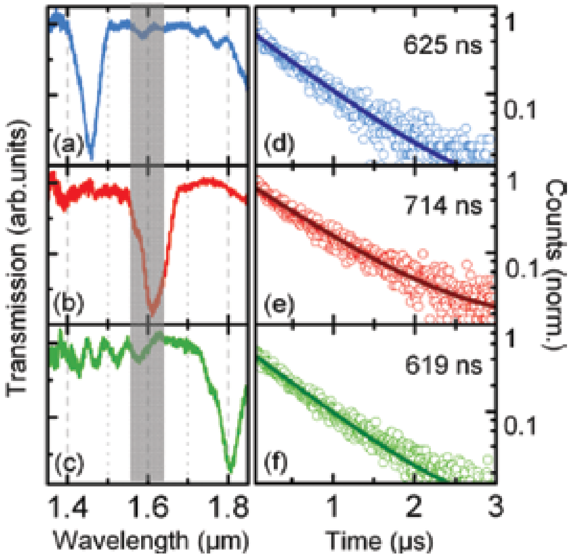

Fig 5: Transmission spectra of the 3D PC with second-order stop-gaps at different wavelengths. (d)-(f) Fluorescence lifetime curves of the PbSe QDs in 3D PCs in (a), (b) and (c), respectively. The shadowed area indicates the emission range of PbSe QDs centred at 1.59 μm with a bandwidth of 120 nm.

In the doping approach, lead based (PbS and PbSe) QDs were mixed with a liquid photosensitive resin to form a nanocomposite, which is then polymerised by UV exposure. 3D PCs composed of void channels were then generated by the micro-explosion method. To produce the 3D PC it is a prerequisite to generate thick nanocomposite layers, a big materials science challenge. We successfully synthesised homogenous PbS quantum-dot-doped polymer material with thickness up to 100 micrometres [3].

The fabricated 3D PC in this bulk nanocomposite has a pronounced infrared transmission suppression of up to 70% in the second-order stop-gap along the stacking direction. This can be tuned through the emission spectral band of the PbSe QDs (centred at 1.6 μm, as indicated by the shadowed area in Figure 5) by increasing the lattice. When the emission is outside the stop-gap the measured lifetime shows almost no change. When the QD emission band overlaps the stop-gap, the lifetime (Figure 5(e)) increases by 14%. This observation is consistent with inhibition of the spontaneous emission by the second-order stop-gap.

This experiment, for the first time, gave measurements of the lifetime of NIR PbSe QDs in doped 3D polymer PCs and has been accepted for publication in *Advanced Materials* [4] and reported in the major photonic conference: Frontier in Optics (FiO) in USA 2007 [5].

As one of the most significant outcomes in 2007, the successful experiment on lifetime measurement have consolidated our knowledge to the radiation dynamics of QDs embedded in 3D PCs and provided an important step towards controlling spontaneous emission with 3D PCs for advanced functional active devices in telecommunications. Further investigations on the radiation dynamics will be performed by adding functional defects to the 3D PC and varying the band gaps by changing the lattice constant.

Radiation dynamics in opal and inverse opal

Opal structures were successfully grown on the surface of optical fibres (Fig 6) to create an “inverse PC fibre”, offering a wavelength-specific increase in the fibre transmission corresponding with the opal bandgap, as presented at CLEO Europe in Munich (2007). We have found that the substrate curvature affects the quality and uniformity of the opal produced (Figure 6(a-c)), as presented at SPIE in Canberra, December 2007.

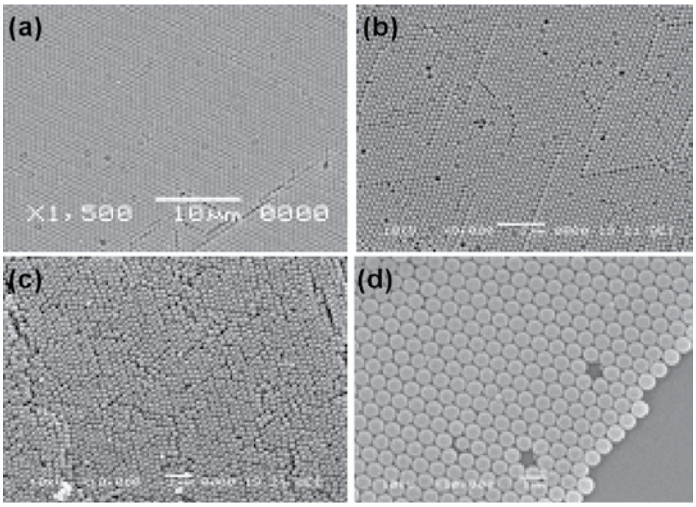

Fig 6: SEM images of opals grown on various surfaces: (a) flat surface, (b) capillary and (c) optical fibre. It is obvious that as the substrate curvature increases, the periodicity of the top layer of spheres gets worse. (d) PC fabricated by spin-coating the spheres onto the wafer.

We collaborated with the Tyndall Institute to develop techniques in fabricating silica and poymethylmethacrylate (PMMA) microspheres and opaline structures formed by self assembly from these microspheres. An improved system for controlling the temperature during self assembly, and employment of spin-coating of microspheres have effectively increased the speed and reproducibility of fabrication of opals (Figure 6(d)). High quality inverse opals were successfully developed with sol gels and in thin SU-8 layers. We also incorporated rare earth ions and nano-diamond emitters into opal and inverse opal PC structures for emission control.

Theoretical modelling of radiation dynamics

Theoreticians in UTS have developed a comprehensive range of computational tools for modelling the radiation dynamics, field profiles and transmittance of woodpile PCs.

The time-based tools implement pulsed point dipole source(s) and computationally integrate the fields until they have escaped the structure and died away internally. The frequency dependence of the field is obtained from a Fourier transform of the time signal, and the local density of states is acquired after normalising the data and calculating the work done by the dipole source. Tools for modelling single source in arbitrary orientations have been developed and generate results which are ready to be compared directly with experimental results for the woodpile structure (with quantum dots distributed either uniformly throughout the structure or confined within a 2D layer). A variation of these tools has been used to model the transmittance and near field of a woodpile (Figure 7). Excellent agreement has been obtained with experimental results and a paper has been submitted for publication.

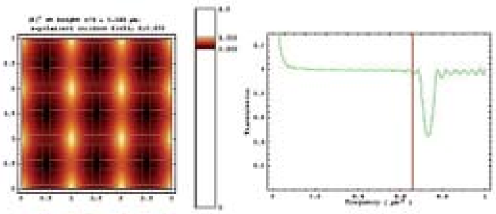

Figure 7. A frame from the (frequency dependent) animation of the near field variation (left panel) over a 3x3 unit cell at the exit face of a 32 layer woodpile, at a frequency, shown by the red line on the transmittance graph (right panel). The field is concentrated in the rods (shown by the lines in the left panel) prior to the band gap.

We also extended our multipole tools to model defect structures (e.g. waveguides, cavities) in woodpile geometries with a semi-analytic approach. A prototype code which can calculate the transmission and reflection of a woodpile has been completed and implementation of the Bloch mode scattering matrix method is underway.

3D photonic crystals in Chalcogenide glass with higher order bandgap

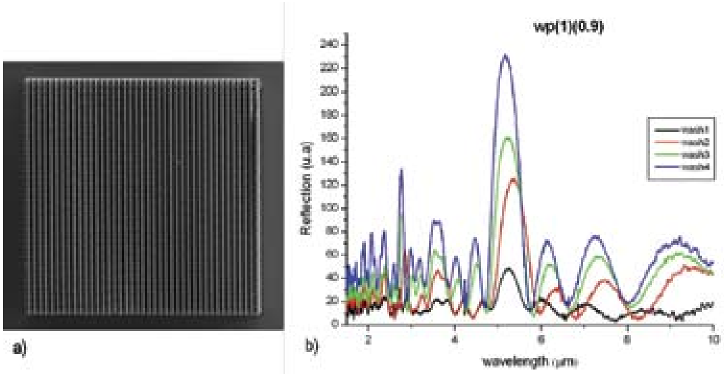

Fig 8: a) SEM image of a 30×30×10 μm3 woodpile structure with a layer spacing of 1.44 μm and an in-plane spacing of 1 μm. b) Reflection spectra of the 3D PCs etched with different times.

During the year we achieved a significant milestone in fabricating a 3D PC from a high refractive index chalcogenide material. In an excellent example of strong Centre collaboration, thin films of arsenic trisulphide (As_2S_3) prepared by the laser group at ANU were processed at Swinburne using a femtosecond laser to fabricate 3D PCs with near infrared higher order bandgaps [8]. This project involved substantial process development - investigating the reaction principle, controlling the fabrication conditions and the washing out process. An example of a 3D PC possessing both fundamental and second order bandgap in the NIR wavelength region is shown in Figure 8. Future experiments will focus on aberration compensation to improve the quality of the 3D PCs, and investigation of nonlinear properties to add functionalities to the PC based devices.

Targets for 2008

In 2008 we will further investigate (theoretically and experimentally) the radiation dynamics of nano-sources in polymeric and opal 3D PCs with an emphasis on near-field measurement and new emitting species. Photonic elements including nonlinear superprisms and waveguides will also be investigated.

We will also aim to fabricate 3D PCs with complete bandgaps using high refractive index materials, for example active chalcogenide based nanocomposites and doped inverse opal, and investigate novel photonic applications.

References

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TUNABLE MICROPHOTONICS

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Students: Bill Corcoran

Four year vision/long term goal and motivation

We aim to demonstrate control of light propagation in nanoscale two- and three-dimensional periodic photonic structures using innovative approaches for electrical and thermal tunability and optical actuation. This is crucial for the operation of all-optical photonic devices in future telecommunication, defence and sensing systems. Highly resolved wavelength selectivity and precisely defined dispersion features will be demonstrated with active tuning and stabilization.

We will achieve highly variable refractive indices in planar, fibre and 3D photonic crystal resonant structures by infiltrating them with liquid crystal and other nonlinear optical liquids and polymers. These can be controlled by applied voltage or internally by self-action. Tunable refraction, self-collimation, nonlinear propagation and switching will be explored. In a second approach we will use the electro-optic and nonlinear properties of $LiNbO_3$ to produce highly resonant and rapidly reconfigurable optical structures.

CUDOS strategy/competitive advantage

The Centre has strong programs of fundamental research in photonic crystal structures and nonlinear approaches to achieve tunability, combined with experimental capabilities in lithium niobate platforms, Bragg grating production and techniques for infiltration of photonic crystals with nonlinear materials including liquid crystal.

We also benefit from strong alliances with end users with well-articulated requirements for specific applications.

Collaborative links

The Centre collaborates with DSTO on this project.

Goals for 2007

This Flagship commenced in 2007 with a goal for the year to build expertise in a number of areas: Bragg gratings in lithium niobate, fluid infiltrated structures and periodically poled lithium niobate, each of which offers a path towards optical actuation and tunability.

1. Bragg Gratings on $LiNbO_3$

The aims for 2007 were to realise Bragg gratings on $LiNbO_3$, primarily using photorefraction due to iron (Fe) dopants. This project is a collaboration between RMIT and The University of Sydney with input from ANU.

The project steps were:

a. Demonstrate Photofractive Fabry-Perot on $LiNbO_3$

b. Demonstrate Bragg grating on $LiNbO_3$

c. Demonstrate Sampled Bragg grating on $LiNbO_3$

d. Demonstrate Tunable, sampled $LiNbO_3$