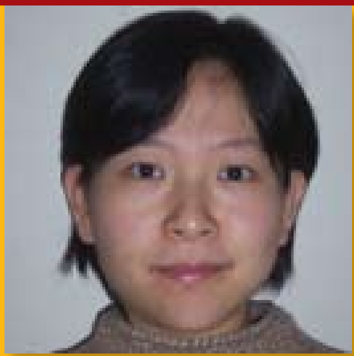
CUDOS

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

ANNUAL REPORT

2006

THREE DIMENSIONAL PHOTONIC BANDGAP MATERIALS FOR EMISSION CONTROL



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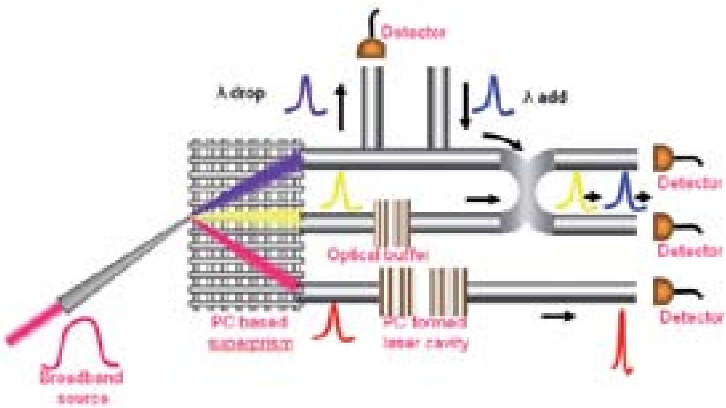
Four year vision/long term goal and motivation

The aim of this project is to design, fabricate and characterise three dimensional photonic crystals (PCs) and related all-optical devices in a range of materials. The CUDOS team applies several direct laser writing methods for the fabrication of three-dimensional PCs with bandgaps in the near infrared wavelength regime. In particular, we have focused on three key developments: (1) Developing 3D photonic bandgap material with full or partial gaps; (2) Incorporating quantum dots (QDs) into the PCs; (3) Demonstrating a significant change in radiation dynamics and/or non-linear effects.

Photonic bandgap materials are believed to be the basic materials in the next generation optical signal processing and communication systems because they can control and manipulate the behavior of light. By replacing electrons with photons as the carriers of information, the speed and bandwidth of the advanced communication systems will be dramatically increased. Such all-optics chips consist of various devices such as photonic crystal waveguides, superprisms, low threshold and directional emitters, as schematically shown in Figure 1.



▲ **Figure 1. A schematic diagram for an all-optical chip consisting of photonic devices that may be fabricated by direct laser writing methods.**

CUDOS strategy/competitive advantage

CUDOS possesses unique expertise across its participating universities to conduct the cutting-edge research toward the arm of this flagship project. At Swinburne University two elegant and internationally unique experimental approaches, two-photon polymerisation and micro-explosion, have been developed to fabricate high quality 3D PCs in polymer and lithium niobate with bandgaps in the near infrared region. With the two-photon polymerisation method, a superprism based on the 3D photonic crystal has been achieved [1], showing a negative refraction effect [2].

Collaborative links

The collaboration in this flagship project extends across four Universities and has been facilitated through tele-meetings and a number of focused discussion symposia. Through those activities, a theoretical model for the temporal and spatial features of emitters embedded in the photonic bandgap materials has been developed and implemented in the experimental work on three- and two-dimensional PCs. The group at Swinburne University has also collaborated with Professor Byoungho Lee's group from Seoul National University to understand the bandgap effect from the three-dimensional PCs.

Goals for 2006

The goals for 2006 related to capability demonstrations as well as fundamental investigations of radiation properties of emitters embedded in PCs. On the capability side, we aimed to fabricate and demonstrate waveguide-coupled superprism devices. For our radiation dynamics studies, we aimed to produce 3D photonic crystal structures doped with quantum dots emitting in the near infrared region for studying the temporal and spectral properties of light emitted from such structures. In particular, we aimed to demonstrate experimentally the inhibition and redistribution of spontaneous emission for wavelengths within the photonic band gap and compare to theoretical results derived from the calculation of the density of states.

Achievements and highlights for 2006

We have chosen PbS and PbSe quantum dots as the infrared radiation source because they can be conveniently introduced into the crystal matrix, and because they have strong emission which can be spectrally tuned by changing the dot size. Two different methods, doping and infiltration, have been used to incorporate the dots into the crystal matrix. In the doping approach, dots are combined with resin in its liquid phase to form a composite.

3D PCs are formed later by the two-photon polymerisation technique. In the infiltration process 3D PCs are developed first using the same approach, but the QDs are incorporated into the structures afterwards leading to a thin layer of QDs on the outside of each rod. In both methods the emission spectrum of the QDs matches the band gaps of the 3D PCs.

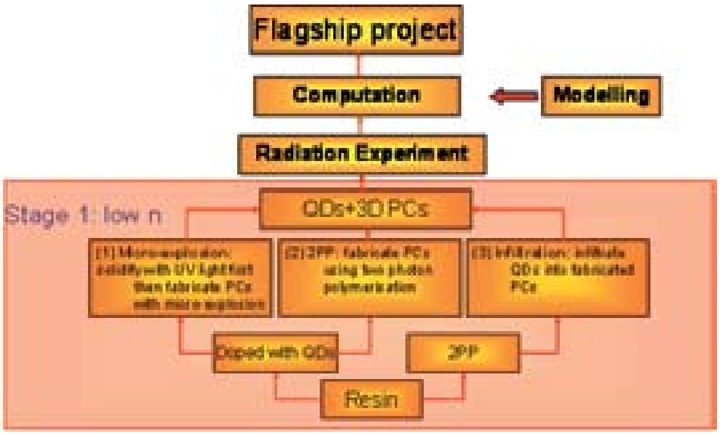


Figure 2. Illustration of the approach to the investigation into the radiation property from 3D PCs in 2006.

Another approach to incorporate radiation sources into two-dimensional photonic structures such as photonic crystal fibres was explored at Macquarie University, in which tapered photonic crystal fibres were filled with dye solution, excited and probed transversely to examine the angular, polarisation and spectral dependence of the emission [3].

Experimental efforts at both universities are closely linked to the theory groups at the University of Technology Sydney, University of Sydney and RSoft Pty Ltd, an international leading software developer for photonics research. The modeling approach involves calculation of the local density of states in the woodpile using a combination of the commercially available RSoft FullWave for finite difference time-domain (FDTD) calculations, and a number of Mathematica packages developed by the UTS group which address the both time resolved and spatially resolved emission problems.

Uniform lead-salt quantum dots as the near infrared emission source

Lead-based QDs have strong emission in the near infrared region and the emission can be readily controlled by changing their sizes, but they are not commercially available. PbSe and PbS quantum dots were synthesised by Craig Bullen, Michael Ventura [4,5] and Jiafang Li [6-8] with emission in a narrow band in the near infrared, indicating a narrow distribution of dot size (see Fig. 3). Polymer doping or infiltration is straightforward after surface modification. The high brightness and controllable emission spectroscopic property make these quantum dots an ideal emission source to study the radiation dynamics in PCs.

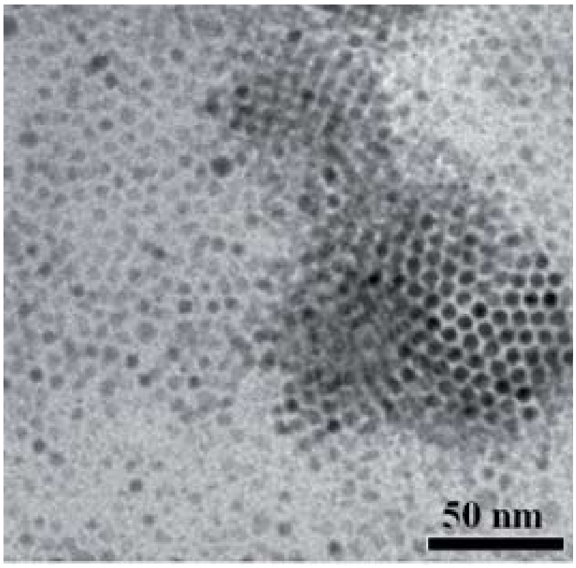


Figure 3. TEM image of PbS QDs synthesised by Michael Ventura as the near infrared emission source

Radiation properties of PbSe QDs within the fundamental bandgap

The fundamental bandgap is normally wider than the higher order ones (if present) and should have a pronounced influence on the emission of QDs in that spectral range. Using the two-photon polymerization method, we fabricated 3D woodpile PCs of polymer with a fundamental bandgap covering the communication region of 1.3 to 1.6 µm. Jiafang Li successfully incorporated PbSe dots into these PCs through infiltration and doping. For the infiltration method, the dots can be added and removed flexibly, leading to a controllable shift in the band gap.

A change in the spectrum of the spontaneous emission from the dots was observed when they were infiltrated within the 3D PC (see the left column in Figure 4) [6, 7]. Evidence for partial bandgaps was found in the transmission spectrum, with up to 50% suppression ratio observed in structure fabricated in QD-doped resin (see the right column in Figure 4) [8]. Angular-resolved and time-resolved measurements are currently being performed.

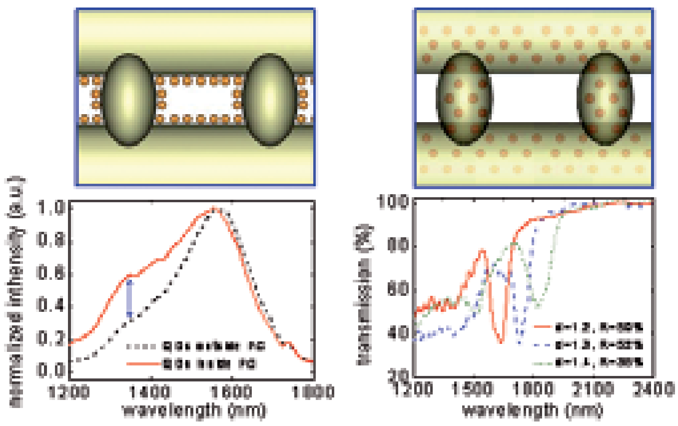


Figure 4. Left column: Normalised photoluminescence spectra from quantum dots inside PC and outside PC at the same excitation condition. The arrow indicates the spectral redistribution in the shorter wavelength range. Right column: Transmission spectra of 3D PCs with different lattice constants d. R is the suppression ratio.

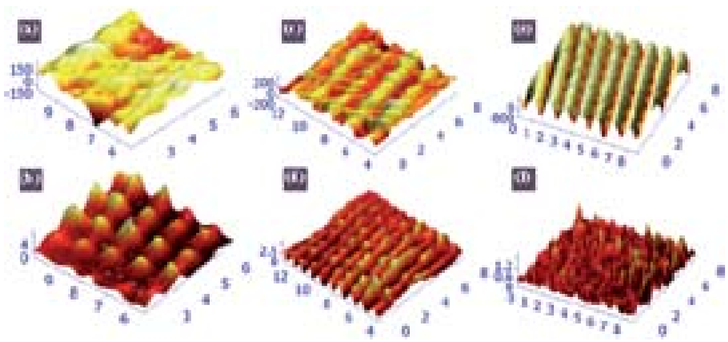
Control of PbS QDs emission by using higher order photonic bandgaps

Higher order gaps are normally much narrower that the fundamental one and more sensitive to the crystal directions. By adjusting the lattice spacing, higher order gaps can be enhanced and controlled. Michael Ventura successfully developed a photopolymerisable PbS quantum dot-doped nanocomposite without losing emission efficiency. Homogeneous materials with a film thickness of up to a few hundreds of micrometres were formed, sufficient to fabricate 3D PCs [4, 5]. Woodpile PCs were fabricated within these nano-composites with higher order gaps overlapping the emission range of the dots. A highly sensitive infrared measurement system was set up to measure fluorescence lifetimes of the woodpile structures (Figure 5).

▲ **Figure 5. Michael Ventura measuring the lifetime of PbS QDs inside a 3D photonic crystal.**

Characterisation of emission from 3D PCs with scanning near field optical microscopy

Dr. Baohua Jia has characterised 3D woodpile PCs using a scanning near-field optical microscope (SNOM) to detect the evanescent signals in the near-field region (~10 nm from the sample). She examined different photonic crystal structures and optimised the fabrication process using both the topographic and optical signals from the SNOM, as shown in Figure 6 [8]. Her next step is to combine this technique with lifetime measurement systems to characterise the radiation dynamics of QDs in the near field region.



▲ **Figure 6. Topography signals (a, c, e) and optical signals (b, d, f) recorded simultaneously with a SNOM from 3D woodpile structures fabricated with different conditions. (a, b): The voids between the rods were totally filled with resin. (c, d): The voids between the rods were partially filled with resin. (e, f): A well-developed woodpile PC with a high quality PBG.**

Theoretical modeling of radiation dynamics

During 2006 the CUDOS group at UTS developed tools to support the experimental radiation dynamics studies of 3D PCs fabricated at the Swinburne node. This work involved Andrew Norton, Ara Asatryan and Lindsay Botten of UTS, and Michael Steel of RSoft Design. The team used the SGI Altix AC supercomputer at the APAC National Facility (http://nf.apac.edu.au/facilities/ac/hardware.php) to run the electromagnetic simulations of 3D woodpiles.

The effect of photonic crystals and other nano-structures on spontaneous emission rates can be inferred from calculations of the Local Density of States (LDOS), a classical quantity measuring the number of available electromagnetic modes into which the created photon can be emitted. As photonic structures become more complicated the numerical calculations become more lengthy and so efficient algorithms and procedures with generally available tools are required. In collaboration with Marc Dignam of Queen's University, we developed new techniques for the calculation of LDOS by finite-difference time-domain (FDTD) simulation.

This work [9], published in Physical Review Letters, contains two strands. In the first, we formalized existing techniques for LDOS calculation by FDTD into a more rigorous theory. This provided a basis for studying the effect that the initial conditions have on the calculated LDOS. The second strand examined LDOS in coupled cavities and showed that by introduction of a "reduced-LDOS", the system can be projected onto a basis of small number of modes, massively improving the efficiency of calculations. These techniques will be important in calculating radiation effects in 3D crystals where the computational load of the complete problem is extreme.

We model both time resolved and spatially resolved emission by employing commercially available software (R-Soft) and in-house codes. In the case of time resolved emission, we solve the field problem for a single source (or multiple sources) with an FDTD simulation, monitoring the field at the source point and post processing the fields obtained from the FDTD simulation with Fourier analysis to compute the work done by the source as a function of frequency, thus computing the local density of states at the source point. This process is then repeated in order to map the LDOS over the region in which sources are located by varying the location of the source.

In the case of the spatially resolved emission experiments, in which we are interested in the directional properties of the emission, we monitor fields at the top of the woodpile due to an embedded source, calculating their Fourier transforms within the FDTD routine in real time, and then post processing these with a generalised, vector (electromagnetic) form of Fraunhofer diffraction theory that enables us to compute the Poynting vector of the emitted radiation. This near field to far field transformation is required to predict the electromagnetic fields that will be observed at distances far from the woodpile where a light-detector would normally be placed. This allows direct comparison of the results of our simulations with the experimental measurements.

The full structure we model is quite large, so access to the APAC National Facility is vital for this work. During the course of the year we have acquired considerable expertise in the use of the FDTD software, built up our knowledge of the "tricks of the trade" needed to yield stable and accurate results, as well as completing the development of a substantial toolkit of post-processing codes that will be used in 2007 to model actual experiments.

Radiation dynamics from two-dimensional photonic crystal fibres

Emission from 2D photonic crystals was also studied. In the 2D case, tapered photonic crystal fibres were filled with dye solution, excited and probed transversely to examine the angular, polarisation and spectral dependence of the emission. Researchers at University of Sydney and Macquarie University collaborated to create tapered hollow-core photonic crystal fibres. Theorists from the University of Sydney and Queens University, Canada modeled the local density of states to explain both enhancements and suppression of emission in various directions and for various wavelengths. This work was published in Optics Express [3].

Self assembled three dimensional photonic crystals

A novel approach to 3D PC fabrication has been investigated at Macquarie in which microspheres "self-assemble" to produce opals. Inverse opals are then produced by infilling the opal structure with another material. These have been grown onto the surface of optical fibres, to demonstrate photonic bandgap effects. This work was presented in a talk at the recent AIP congress December 2006 in Brisbane, and an International Science Linkages grant has been obtained to fund collaboration in this area with Professor Martyn Pemble of the Tyndall Institute, Ireland.

Targets for 2007

In 2007, we will continue our long term goal of fabricating PCs with 3D complete bandgaps in high refractive index materials. A novel approach using As_2S_3 and As_2Se_3 chalcogenide glasses will be investigated.

We will measure the fluorescence lifetime of quantum dots in photonic crystal by using both the near-field as well as far-field techniques. Near-field investigations will give more detailed and accurate information because the results do not depend on scattering. The radiation properties of QDs in the defects of PCs will be studied for evidence of lasing.

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