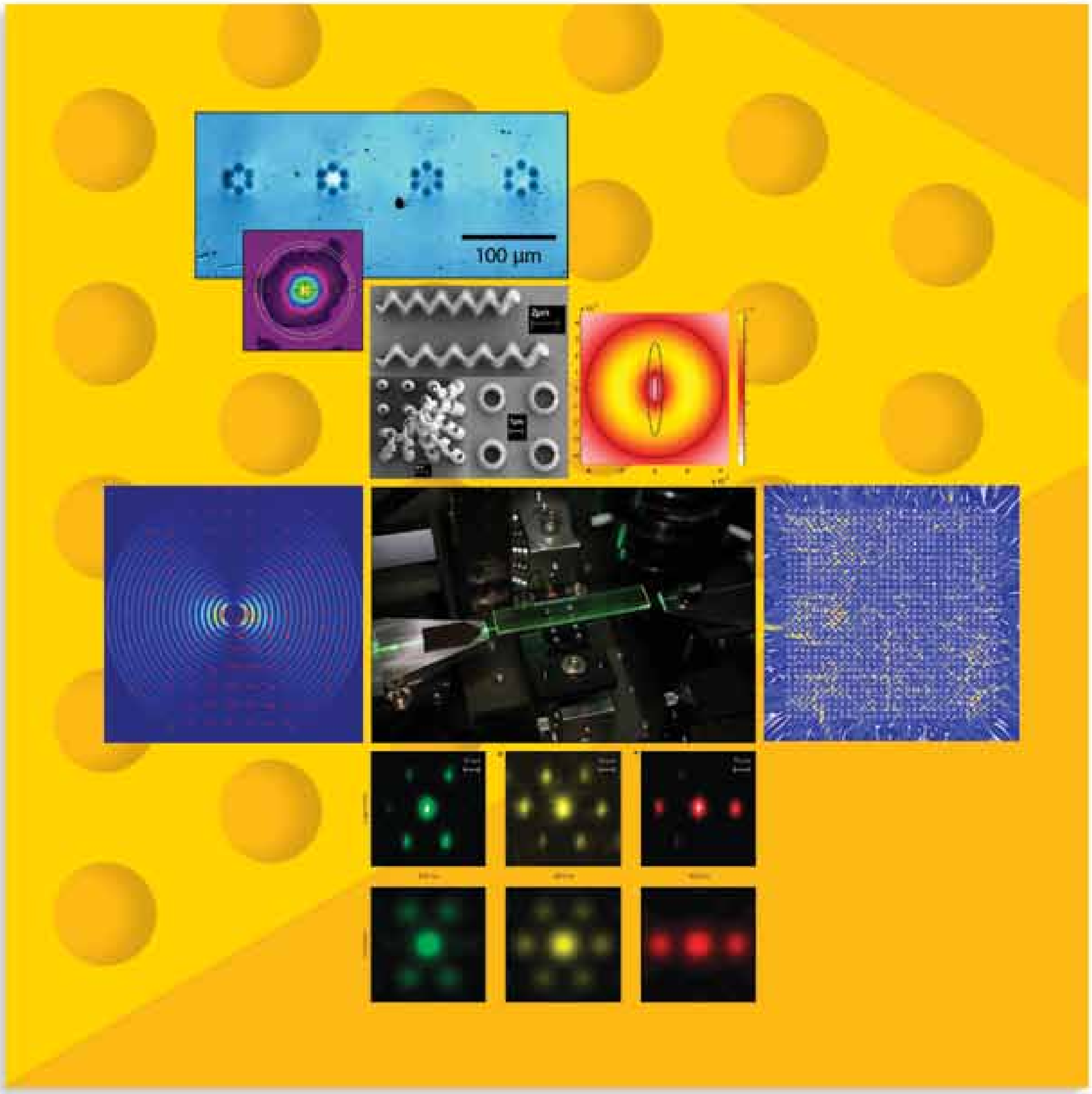
ANNUAL 2009 REPORT



CUDOS

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

THREE DIMENSIONAL PHOTONIC BANDGAPS

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Long term goal and motivation

To develop and characterise three-dimensional (3D) photonic crystals (PCs) possessing complete bandgaps and novel nonlinear properties with the aim to realising miniaturised all-optical devices for a range of innovative photonic applications. We are investigating the control of radiation from optical emitters placed within PC materials, and also fabricating waveguides within the PCs to develop devices based on these materials. The manipulation of light within a PC is a long term goal. This goal matches the entire CUDOS vision on a highly integrated photonic chip with a significantly increased processing capacity by adding an extra dimension in space.

CUDOS approach

To realise a complete bandgap it is essential to construct 3D lattices in materials with high refractive index contrast. The CUDOS team approaches the problem in two steps:

- To demonstrate useful passive and active photonic devices in low refractive-index materials, such as polymer and opals, which possess partial bandgaps, to develop and accumulate expertise in material science, fabrication and device design. In the mean time, investigate a number of ways to construct 3D PCs in high-index materials, including chalcogenide glasses and Lithium Niobate *et. al.*.
- To transplant the knowledge obtained from low-index PCs to high index 3D PCs with complete bandgaps and functionalities to realise the 3D PC photonic chip architectures.

Three dimensional Photonic Bandgaps team.

CUDOS possesses unique expertise in theoretical simulations, material science, photonic design and world-class facilities across its participating universities to conduct the cutting-edge research in this flagship project.

- 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.
- Experimental: the CUDOS team applies the state-of-the-art nanofabrication techniques based on the 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. 1). Chalcogenide glasses have been strategically selected as the building platform for 3D PCs because of their high index enabling a complete bandgap and their high nonlinearity. The application of these novel materials allows the integration of the 3D PC components with diverse chalcogenide-based elements built by other CUDOS nodes to form a functional photonic chip. With our expertise in material science, novel emitters, including quantum dots (QDs) and nano-diamonds have been 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. With our home-made world-class time correlated single photon counting system (TCSPC) operating in both the visible and the telecommunication wavelength regions we have successfully observed inhibition of spontaneous emission from nano-emitter in 3D PCs.

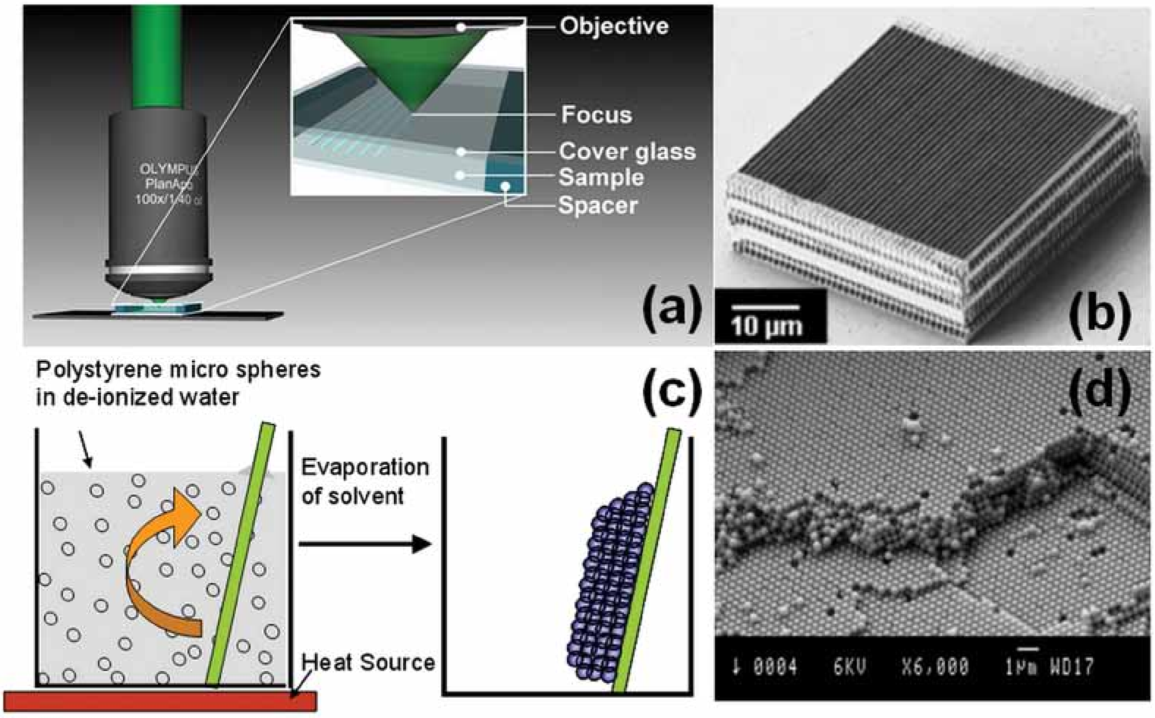


Fig 1. Schematic drawing of (a) the DLW setup and (b) a woodpile 3D PC generated by DLW in high index chalcogenide glasses. (c) Self-assembly setup and (d) opal PC generated by self-assembly.

Collaborative links

Within CUDOS

This flagship project involves researchers from five Universities within the CUDOS.

- Theoreticians in 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 in Australian National University (ANU) provide valuable support and raw materials for experiment.

External to CUDOS

- The long term collaboration with Oxford University, UK, on adaptive fabrication in high index materials was further enhanced in 2009 after Prof. Tony Wilson (CUDOS PI), Dr. Martin Booth and Dr. Edward Boteherby from Oxford University visited Swinburne 2009 and Mr. Ben Cumming visited Oxford in January 2009, respectively (supported by two joint international collaboration grants (Investors: Gu, Wilson, Booth, Zhou) from the *Leverhulme Trust* (UK) and *ARC Linkage International*). Significant progress has been made in the experimental adaptive aberration compensation, as will be detailed in the 'Achievement highlights' section.
- The collaboration link with Prof. Daniel Jaque's group at Universidad Autónoma de Madrid, Spain on PC fabrication in rare-earth ion doped lithium niobate has proven to be fruitful. In the past two years, 4 joint papers have been published in high level journals including Applied Physics Letters and Advanced Materials. In 2009, Prof. Daniel Jaque and his students Airan Rodenas, and Ms. Emma Martin visited Swinburne in June 2009.
- The collaboration with Prof. Xue-Hua Wang's group in Sun Yat-Sen University, China, on radiation control with 3D PCs and nonlinear superprisms was consolidated after Dr. Jia visited Prof. Wang under the support from the Australia-China Young Scientist Scheme in April 2009 and Prof. Wang's visit to Swinburne in June 2009.

- The collaboration link with Prof. Chunlei Du from Institute of Optics and Electronics, Chinese Academic of Sciences, China was initiated in 2009 in the field of plasmonics nanophotonics. One joint publication was achieved from this collaboration.
- Collaboration with the Quantum Information group at Macquarie, Jim Rabeau, his student Carlo Bradac and postdoc YanHua Zhang on radiation control in opal PCs.

Goals for 2009

Based on the long-term strategy of this project, in 2009 the team was aiming to achieve results in the following aspects:

- 3D nanostructure and PC fabrication in chalcogenide glasses
- 3D lifetime mapping of nanoemitters in PCs
- Single photon sources based on nanodiamond emitters in opal
- Nonlinear and active PCs in quantum doped nanocomposites
- Adaptive fabrication in high index nonlinear materials
- Modelling of Defects states and homogenization in woodpile photonic crystals

Achievements and highlights for 2009

3D nanostructure and PC fabrication in chalcogenide glasses

In our previous experiment on fabrication of 3D PCs in chalcogenide glasses, we demonstrated that using a femtosecond laser beam it is possible to induce structural modification in a highly localised area of the glass through a two-photon induced nonlinear process at wavelength 800 nm [1]. It has been also noticed recently that similar phenomena can be induced through thermal effects. Using a high repetition rate laser, heat can be accumulated over a number of pulses, which generates local heating within the glass. As a result much finer features can be generated leading to a bandgap in the shorter wavelength region. To understand the effect of the laser repetition rate on the 3D PC fabrication in As_2S_3 films, two extreme conditions have been considered. For low repetition rate fabrication a Ti:Sapphire laser (wavelength 800 nm, repetition rate 1 KHz, Spitfire) was used [1]. For high repetition rate fabrication the same setup was used except that the repetition was changed to 80 MHz (Spectra Physics, Tsunami, pulse duration 80 fs). Using a laser beam with a higher repetition-rate heat can be locally accumulated over a number of pulses leading to structural modifications within the glass. As a result smoother and smaller rods can be obtained with a faster scanning speed (Fig.1). It is expected that changing the repetition rate between the two extreme conditions of high and low repetition rates should enable optimum fabrication conditions for 3D PCs.

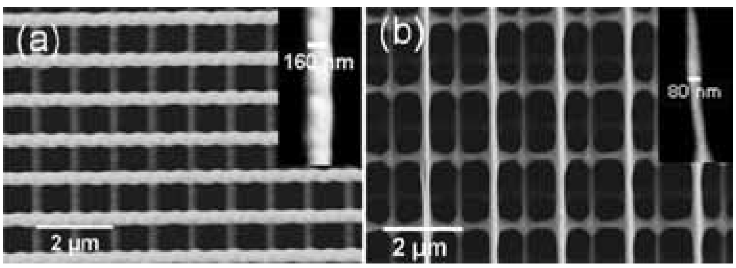


Fig 2. SEM images of chalcogenide PCs fabricated with high (left) and low (right) repetition rate laser beams.

3D lifetime distributions of nanoemitters in PCs

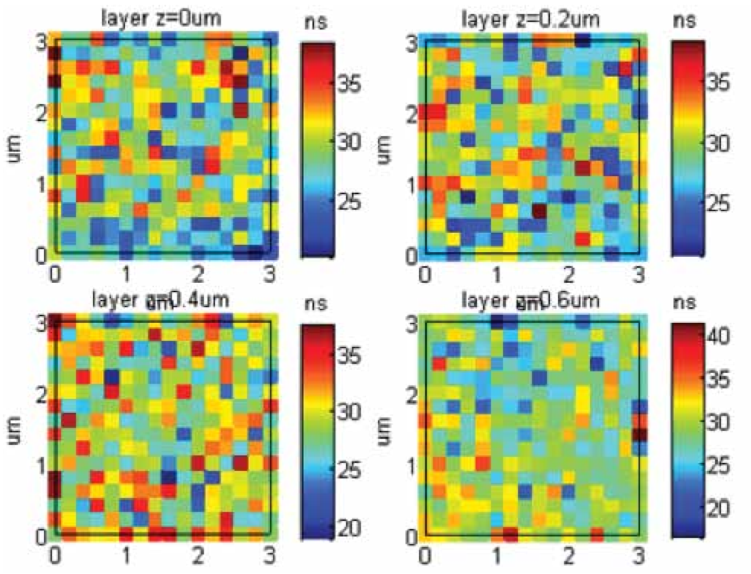


Fig 3. Life time distribution of QDs embedded at different depth into 3D PCs.

Spontaneous emission is the fundamental basis for diverse everyday applications. Realising the control of spontaneous emission is of critical importance. Due to the change of the local density of states (LDOS) of the electromagnetic field compared to that in free space PCs are promising candidate to control spontaneous emission of the embedded emitters since their inception. For emitters inside a PC, LDOS theory pointed out that their decay lifetime is position dependent. By 3D mapping the lifetime of QDs infiltrated into PCs, the 3D LDOS in PCs can be experimentally measured. In experiment, PC fabricated by the two-photon-polymerisation method using Ormocer was infiltrated with near-infrared emitting core/shell QDs. The fluorescence of these QDs was designed to match the pseudo-gap of the PC. The measured lifetime distribution of QDs inside the PC at different depth is shown in Fig. 3. To understand the physical origin of the observed inhibition of spontaneous emission inside a 3D PC, the lifetime distribution of QDs inside the PC has also been theoretically calculated according to the position dependent LDOS theory.

Single photon sources based on nano-diamond emitters in opal

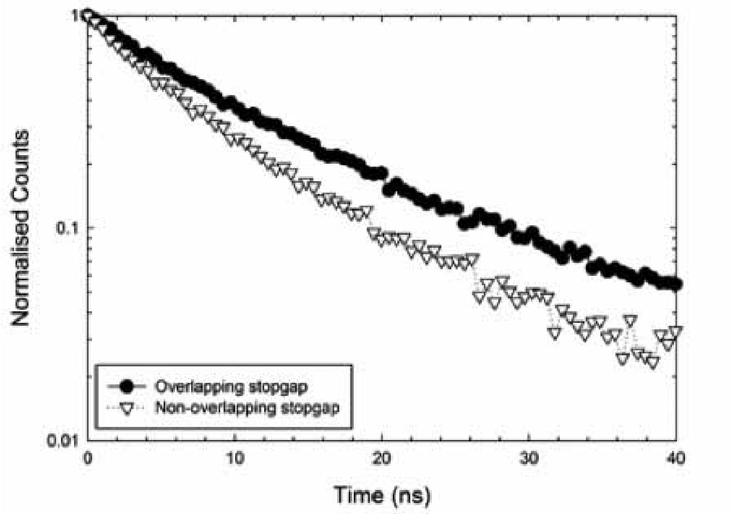
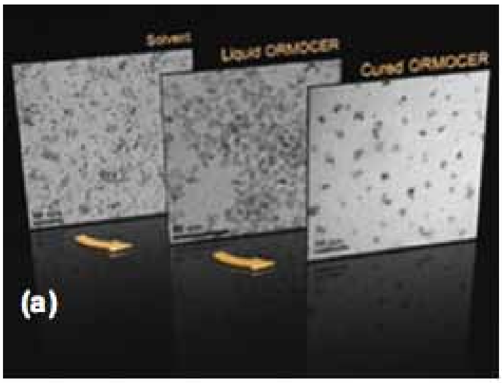


Fig 4. Time-resolved fluorescence measurements of the NV centers inside opals.

Nano-diamond particles were incorporated into the polystyrene opals to explore the radiation control of the N-V centres of the nano-diamond emitters inside the 3D PC structure of the opal. Despite the relatively low refractive index contrast of the polystyrene opal, the spectra of the emitters show a distinct bandgap effect, corresponding to the wavelength of the bandgap seen in reflection from the opals. Furthermore the lifetime of the emitters is increased when the emitters are placed within the opal. The lifetime of the nano-diamond emitters is also affected by their placement on top of the opal surface. The variance of the lifetime of the individual emitters is significantly reduced when the emitters are placed on the opal surface, compared with when they are placed on a polished silica cover slip. This interesting result, which is consistent with our modelling, has potential to increase the utility of these emitters for many applications [2].

Nonlinear and active PCs in quantum doped nanocomposites

Organic-inorganic hybrid polymers are promising materials for multi-photon fabrication of functional miniaturised photonic structures. The incorporation of highly nonlinear nano-crystal QDs can transform the plain polymer into a multi-functional active medium thus opening various possibilities for achieving novel active photonic devices. In 2009, we demonstrated the functionalisation of the organic-inorganic polymer, namely Ormocer, by lead-based QDs. As shown in Fig. 5(a), the nanocomposites have high quality and uniform dispersion of QDs. It has been shown through the Z-Scan measurement (Fig. 5(b)) that the nanocomposites possess ultra-high third-order nonlinearity. The nonlinear nano-composite has been proven to be suitable for the fabrication of three-dimensional micro/nano photonic device using the two-photon polymerisation (2PP) technique. The fabricated photonic crystals show stop gaps with more than 80% suppression in transmission at the telecommunication wavelength region.



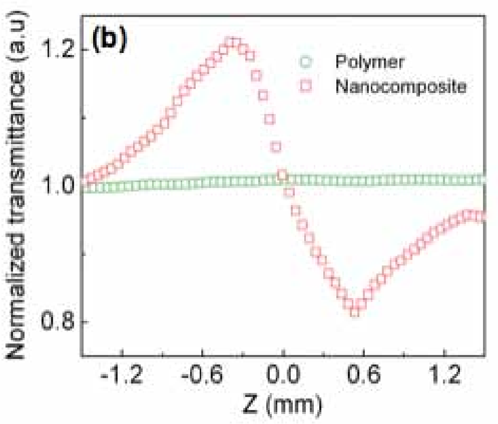


Fig 5. (a) Transmission electron microscopic images showing the process and quality of the QDs and nano-composites. (b) closed-aperture Z-scan results at 800 nm for the nanocomposites.

Aberration compensation in 3D nanofabrication in chalcogenide glasses

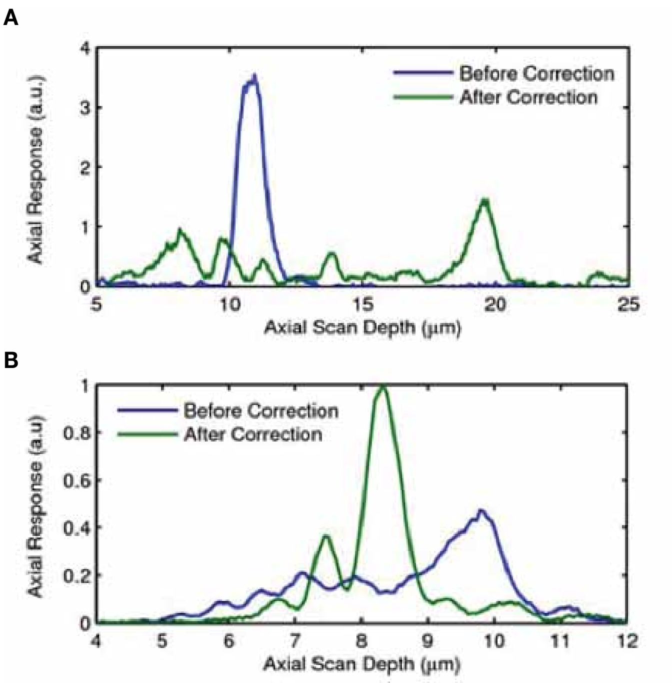


Fig 6. Axial response showing adaptive optics compensation result at (a) low laser power and (b) high laser power.

To address one of the most serious problems involved in DLW in high refractive-index thick chalcogenide glass film, which is the aberration induced by refractive-index mismatch, adaptive optics compensation has been developed at Swinburne theoretically and experimentally. It has been found that the strong aberration in chalcogenide film can be very well compensated by pre-loading designed phase patterns to the writing beam and a nice and clean focal spot can be obtained for fabrication power at low level (Fig. (a). The compensation deviation from the expected results when the intensity is much stronger (Fig. (b).This suggests that the high nonlinearity of the chalcogenide glasses might cause severe impact in the compensation process, which makes the compensation more complicated.

Modelling of Defects states and homogenisation in woodpile photonic crystals

In 2009 substantial progress has been made in theoretical modelling of PCs with defects using the multipole theory. Woodpile PCs have been generalised and is being used to characterize linear defects in such structures. Q factors for embedded waveguides as high as 10^4 can be achieved for a relatively small stack lengths (24 layers) (Fig. 7).

It has been also shown that the woodpiles homogenise to a uniform slab at long wavelengths and have determined the effective dielectric constant.

Some preliminary coding using the finite element method has been undertaken to allow modelling of more general structures, e.g., with non-circular cross-section and or intersecting layers.

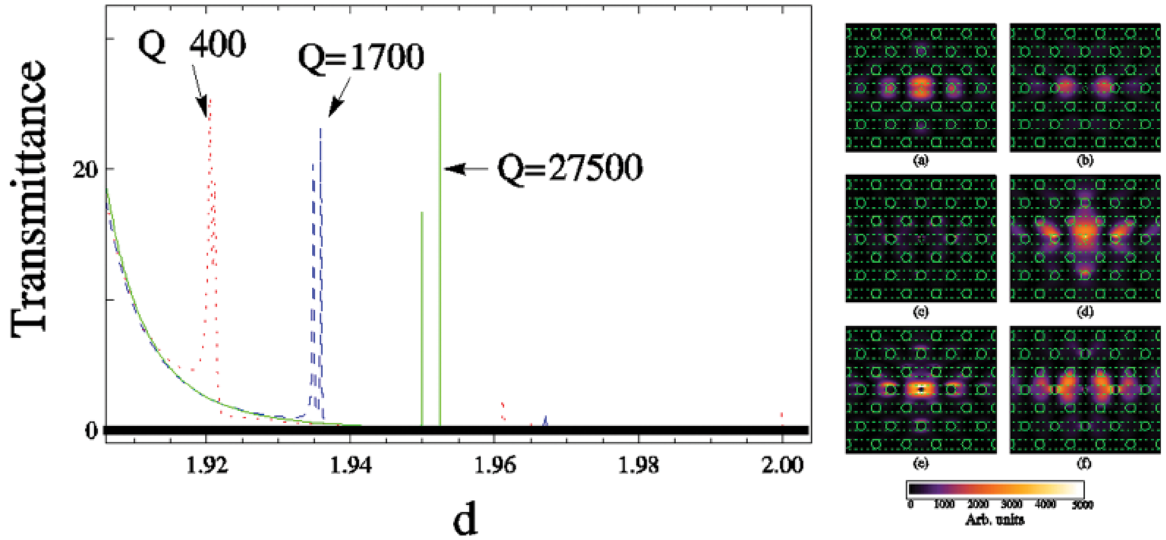


Fig 7. Q factor of the defect states and their field distribution

Targets for 2010

In 2010 we will comply our strategic plan and finalise the following work: 3D mapping of nano-emitter lifetime distributions in PCs; Bandgaps in 3D chalcogenide glass PC fabricated with appropriate repetition rate; adaptive fabrication in high index nonlinear chalcogenide glasses; device design and fabrication in highly nonlinear QD nanocomposites; and further theoretical modelling of defects states and homogenisation in woodpile PCs.

References

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