3D BANDGAP CONFINEMENT

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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 practical devices. We placed nanometre-sized quantum dots (QDs) and nano-diamonds inside 3D PCs and investigated their radiation dynamics.

CUDOS approach

The key to realise a complete bandgap is to construct 3D lattices in materials with high refractive index contrast. We approach the problem in two steps: first, demonstrate useful passive and active photonic devices in low refractive-index materials, such as polymer and opals, which possess partial bandgaps; and second, develop and accumulate expertise in material science, fabrication and device design. We also investigate construction of 3D PCs in high-index materials, including chalcogenide glasses and lithium niobate. 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.

The expertise available in CUDOS on theoretical modelling and simulations, material science, photonic design and device fabrication

Three dimensional Photonic Bandgaps team.

and world-class facilities across its participating universities provide CUDOS with unique capabilities to conduct the cutting-edge research in this flagship project.

Collaborative links

- The long term collaboration with Oxford University, UK, on adaptive fabrication in high index materials continued with Dr. Michael Ventura visiting Oxford in November 2010.The trip developed a collaborative research effort towards adaptive optics-enabled single shot laser writing.
- During September Mark Tuner visited Dr. Gerd Schroder at the Institut für Theoretische Physik in Erlangen, Germany. This visit involved the development of novel 3D network designs, with geometrical chirality and cubic symmetry to be fabricated using direct laser writing in the near future.
- Dr. Baohua Jia as part of the Australian Academy of Science travel support visited University of Southampton and Oxford University over September and October. Discussions with Nikolay Zheludev and Tony Wilson on nonlinear metamaterials strengthened collaborative efforts towards plasmonic metamaterial devices.
- The collaboration with Prof. Daniel Jaque's group at Universidad Autónoma de Madrid, Spain on PC fabrication in rare-earth ion doped lithium niobate has resulted in5 joint papers over three years in high level journals including Applied Physics Letters and Advanced Materials.

Goals for 2010

Based on the long-term strategy of this project, in 2010 the team aimed to achieve results in:

- 3D mapping of nano-emitter lifetime distributions in PCs.
- Bandgaps in 3D chalcogenide glass PC fabricated with appropriate repetition rate.
- Adaptive optics-assisted fabrication in high index material.
- Nonlinear chalcogenide glasses.
- Device design and fabrication in highly nonlinear QD nanocomposites.
- Theoretical modelling of defects states and homogenisation in woodpile PCs.

We have made substantial advances to the successful fabrication of high quality 3D PCs deep within high index materials including chalcogenide glasses using adaptive optics. We have also extended our program to capture dynamic parallel writing achievable using similar theoretical and experimental techniques.

Achievements and highlights for 2010

Spontaneous emission of quantum dots controlling with photonic crystals

PCs fabricated by the two-photon-polymerisation in Ormocer were infiltrated with PbSe/CdSe core/shell quantum dots (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 shows approximately 15% increase compared with that of QDs outside the PC (Fig. 1). To understand the physical origin of the observed inhibition of SE inside 3D PC, the lifetime distribution of QDs inside the PC used in experiments (d=1000 nm, c=√2×1000 nm, h=375 nm, w=150 nm, refractive index n=1.552, air refractive index n_0=1) has been theoretically calculated according to the above position dependent LDOS theory. But it shows emission enhancement results different from our experiment, and further study is needed to understand this difference. These results help us to understand the manipulation of light generation in PCs. Theoretical study shows the possibility of accurate manipulation of SE inside PCs with the property of position dependent LDOS. Our experiment results show SE change inside PC compared with free space reference. [1]

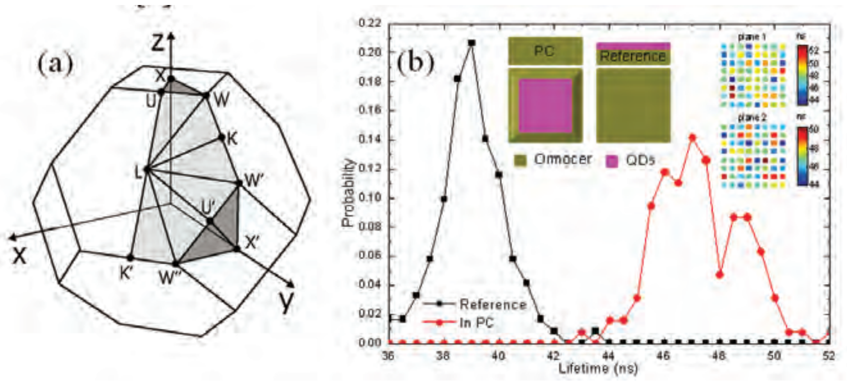

Fig 1: (a) Brillouin zone for the woodpile PCs used in experiment. (b) Lifetime distributions measured in PCs and reference samples showing obvious inhibition of QD emission in PCs.

Three-dimensional nanofabrication in chalcogenide glasses

We have designed and fabricated 3D PCs with high refractive index in chalcogenide glasses (ChGs) and have been able to successfully produce Fabry-Perot type devices (Fig. 2). The devices have been fabricated in the middle of a PC and consist of a slab about 1.6 µm of ChGs polymerised by femtosecond-laser direct writing of multiple lines with an offset of 50 nm between each other. Infrared transmission measurements revealed pronounced cavity mode peaks within the photonic stop band.

Besides the defect fabrication, we have also been working on the nanofabrication in ChG using a high repetition rate laser. Under such a circumstance, 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.

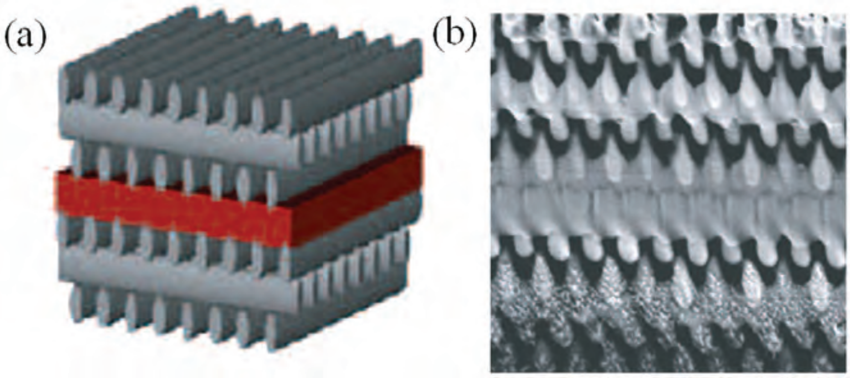

Fig 2: (a) Sketch of 3D woodpile PC in ChGs with a planar defect in the middle. (b) SEM image of fabricated PC with the planar defect in the middle.

Aberration compensation for 3D nanofabrication

We have compensated the strong spherical aberration that impairs direct laser writing within high refractive index materials (Fig. 3). The ongoing collaboration with Oxford University's Alexander Jesacher and Martin Booth has led to the successful un-aberrated fabrication of three dimensional (3D) photonic crystals in lithium niobate (LiNbO3) for the first time [2].

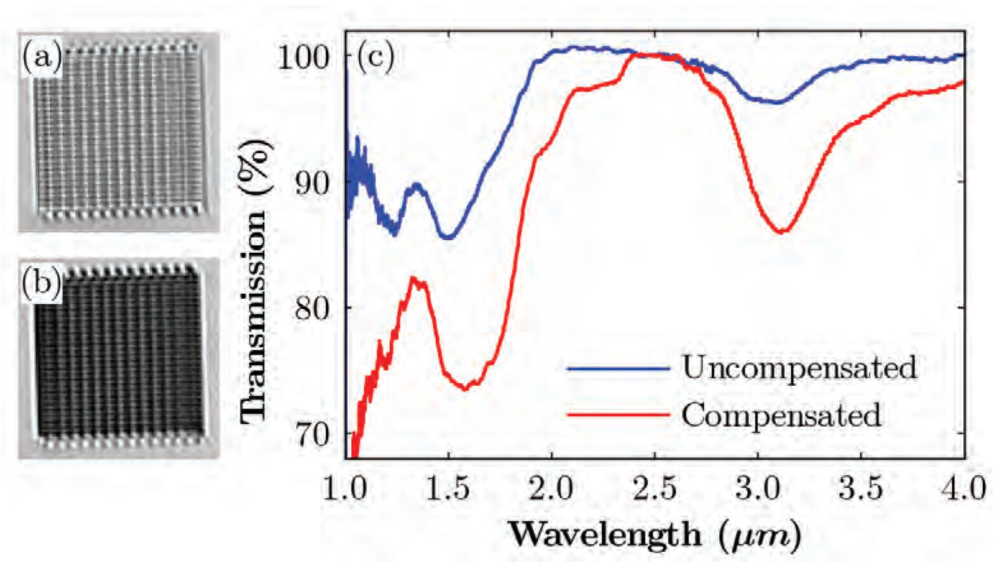

Fig 3: (a, b) Optical images of 32 layer, 4.5 um lattice constant photonic crystals fabricated in lithium niobate, with and without compensation of the index mismatch aberration respectively. Fig. (c) Transmission spectrum of the two crystals, showing improvement in bandgap strength when compensation is applied.

Nonlinear quantum dot nanocomposites for three-dimensional photonic crystals using two-photon polymerisation

Organic-inorganic hybrid polymers are promising materials for multi-photon fabrication of functional miniaturised photonic structures. The incorporation of highly nonlinear nanocrystal quantum dots (QDs) can transform the plain polymer into a multi-functional active medium, thus opening possibilities for achieving novel active photonic devices. Dr. Baohua Jia, Dr. Dario Buso, Dr. Joel van Embden, Dr. Jiafang Li and Prof. Min Gu at Swinburne functionalised the organic-inorganic polymer Ormocer by lead-based QDs (Fig. 4). It has been shown through the Z-Scan measurement that the nanocomposites possess ultra-high third-order nonlinearity. The nonlinear nanocomposite has been proven to be suitable for the fabrication of three-dimensional micro/nano photonic device using the two-photon polymerisation (2PP) technique [3]. The paper was published in Advanced Materials and selected as the cover story (Fig. 4).

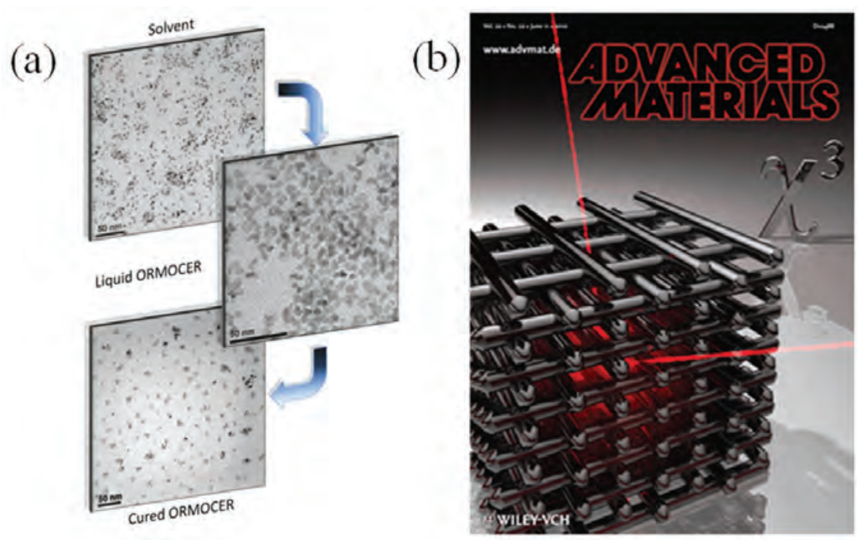

Fig 4: (a) A sequence of TEM images showing the QDs at each stage of the dispersion process. (b) The paper has been published on Advanced Materials and being selected as the cover story.

Dynamic parallel direct laser writing of three-dimensional photonic crystals by a spatial light modulator

A novel holographic femtosecond laser processing system with parallel, arbitrary, and variable patterning features was developed using a spatial light modulator (SLM) displaying a computer generated hologram (CGH). This technique is able to produce large-scale two-dimensional (2D) and three-dimensional (3D) arrays with single exposure, thus increasing the fabrication speed remarkably [4].

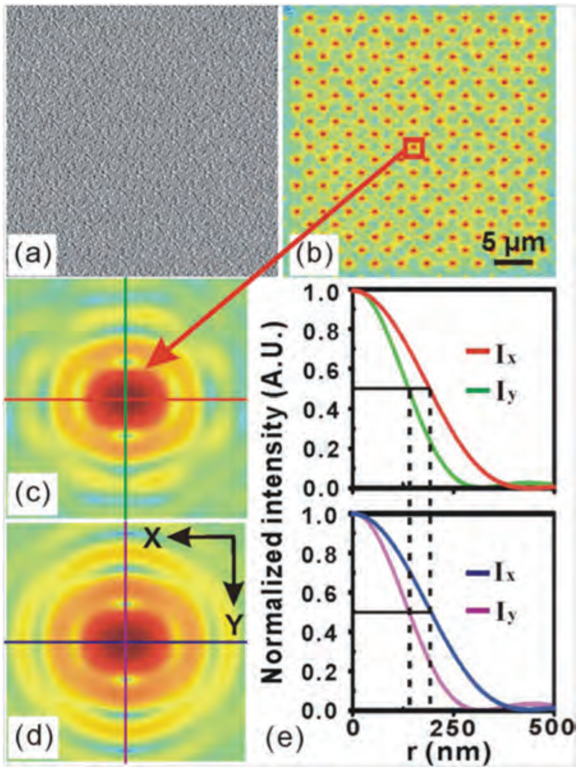

Fig 5: (a) Phase pattern consisting of 1080 × 1080 (256 gray levels) pixels for a 200-spot array; (b) calculated intensity distribution from the phase pattern using the Debye integral; (c) density plot for one focal spot in the array; (d) density plot for a single focal spot; (e) intensity cross sections along the marked color lines of the spots. The scale bar is 5 µm.

References

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