

# CUDOS

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



## Annual Report 2005



## Optical Buffers using slow light

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Students: Neil Baker, Joe Mok

The photonic integrated circuits (PICs) that are under development to replace electronics in the next generation of optical communications networks will use light to replace functions presently carried out by microelectronic circuits. One of the most important of these is buffering: the delay or even temporary storage of data signals for re-timing and synchronization operations. This is a major challenge because, unlike electrons, photons never stay still. However, they can be slowed appreciably, and research is underway at CUDOS to control this effect to achieve controllable delays within a PIC.

Although the speed of light in vacuum is fixed at  $c=2.997 \times 10^8$  m/s, the speed at which light pulses travels through a medium can differ substantially from this. The aim of all "slow light" projects is to reduce the speed at which short light pulses travel to create the basis of an optical buffer.

The importance of buffering in an optical communications system is illustrated in the schematic. The packets of information traveling through optical systems can come along a variety of paths. Two or more packets from different network paths can arrive at the same node at nearly the same time, as shown in the top part of the figure. Two packets, each consisting of three pulses, coloured red and blue, both need to go through to channel A. If nothing is done the two packets collide, and their information scrambles and is thus lost. In order to avoid a collision, the bottom buffer is used to delay the blue packet for a time slight over the duration of a packet (middle part of the figure). As a consequence, a collision is avoided and

no information is lost (bottom part of the figure). The aim of CUDOS' research is to devise the physical principles that might eventually lead to practical optical buffers.

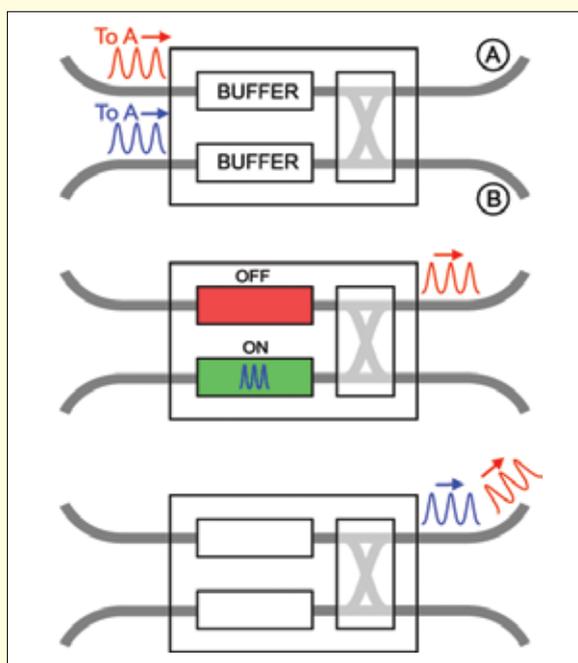
Spectacular slow light experiments by researchers at Harvard University in the USA in 1999 reported light pulses slowed down to the speed of riding a bicycle. Though very exciting, this work is neither cheap nor very practical: the experiment was done using an atomic vapour that was cooled down to temperatures within micro-Kelvins of absolute zero ( $-273^\circ$  C). In other slow light experiments to date in optical fibres, pulses have been delayed by only a fraction of their duration meaning that buffering as shown in the figure would not be possible.

A limiting factor in these experiments is the effect of dispersion, which causes pulses to broaden in time. If the dispersion is too strong, adjacent pulses in a packet start to overlap, again causing loss of information, defeating the purpose of the whole exercise. The occurrence of dispersion in these systems is not simply a matter of bad luck: there is a fundamental limitation that makes it very difficult to delay a pulse by times that are much longer than its duration.

There are a number of approaches to avoid this fundamental limit. Ours relies on the observation that the refractive index of materials is actually not constant, but depends on intensity. The nonlinearity can compensate for the effects of dispersion, allowing light to be delayed without any changes in the shape of the pulse. However in silica glass the nonlinear effect is so weak that it is only seen at the high intensities found in focused, high power lasers. In our experiments, therefore, we focus and tightly confine roughly 2000 W of optical energy into a silica optical fibre. The combination of high power and tight confinement enables the ensuing intensity (power per unit area) to be large enough for the nonlinear effect to play a role.

We use a one dimensional photonic crystal that we write in the core of an optical fibre to delay the light pulse. In such a grating, the refractive index jumps up and down with position in a periodic fashion. This causes the light to zig-zag through the fibre grating, sometimes going forwards, sometimes going backwards, so that it takes longer to make it to the far end. In other words, the light slows down. Without the nonlinear effect, this slow light suffers from dispersion like any other type of slow light and the light pulses broaden, whereby the information is lost. However the nonlinearity of the glass neutralises the effects of dispersion and allows the pulse to maintain its shape as it travels through the grating. In principle these pulses, gap solitons, can travel indefinitely. Their delay is limited only by the length of the grating.

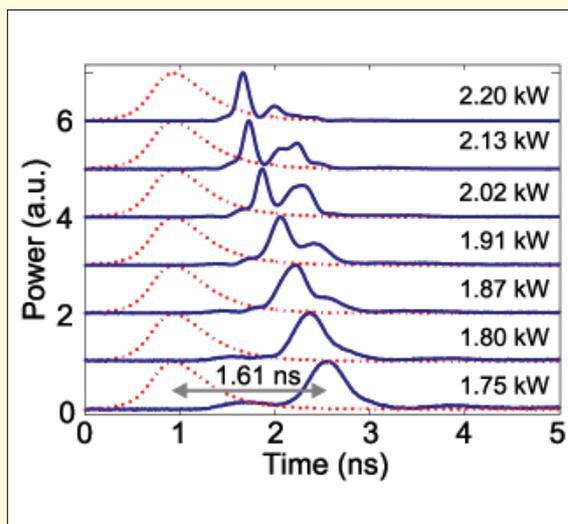
CUDOS is the leading group in the world pursuing slow light using gap solitons. During 2005 we made excellent progress: our gratings are 10 cm long and have roughly 400,000 refractive index jumps. Our latest results summarized in the second



▲ Schematic showing deployment of an optical buffer to avoid a "collision" between two packets switched onto the one channel.

figure show the pulse that is transmitted through the grating versus time for a number of different input intensities (blue curves). The red, dotted curves shows the transmission if the grating were not there. At 1.75 kW input power, the pulse delayed by 1.61 ns, which is almost 2.5 times the pulse width of 0.68 ns. The measured maximum pulse delay corresponds to a speed of roughly  $c/6.5$ . The figure also shows that the delay, and thus the velocity at which the pulses propagate, can be changed by varying the input power. These results are amongst world's best, and are a promising starting point for future research.

One of the main drawbacks of our approach to achieving slow light is that high pulse intensities are required. These high intensities are needed to achieve the required nonlinear response in the silica optical fibre. The required pulse intensity could be reduced if a glass with a higher nonlinearity were used. We are starting to use chalcogenide glass, whose nonlinearity that can be 100-1000 times larger than that of silica. Using these glasses the required pulse intensity could be reduced by a similar factor, so that the generation of slow light by gap solitons can be considered to be truly practical.



▲ Delays measured in the transit time of an optical pulse through a fibre Bragg grating, shown for different input powers.

## Integrated Chalcogenide Glass All-Optical Regenerator

**Project Leader:** David Moss

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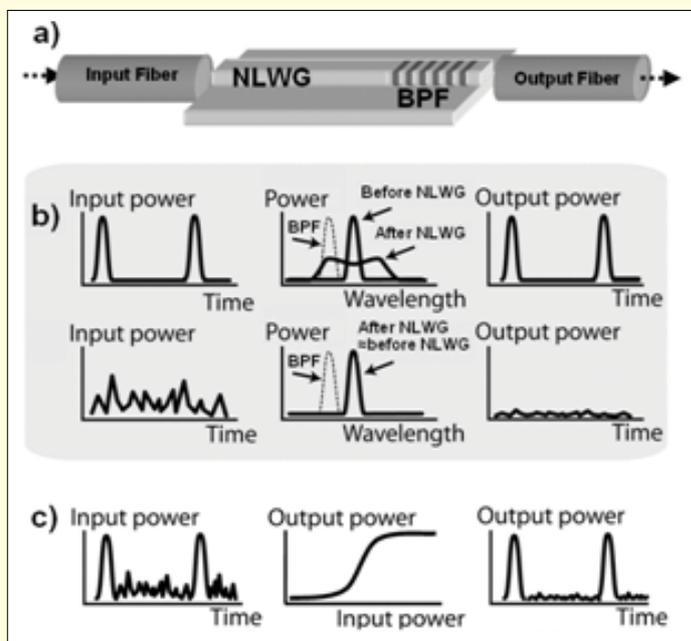
**Students:** Vahid Ta'eed, Michael Lamont, Mehrdad Shokooh-Saremi, Amrita Prasad, Neil Baker, Yinlan Ruan

FLAGSHIP PROJECT

As signals are transmitted through a telecommunications network they suffer distortion and attenuation. Regeneration is the process of recovering the signal quality and involves re-shaping the signal, re-amplifying it and possibly also re-timing it. In present-day systems, which operate at bit rates up to 10Gb/s or even 40Gb/s, regeneration is generally done electronically. The optical signal is converted into an electronic signal, regenerated and then re-transmitted as an optical signal. Not only is this approach extremely expensive, but it is now reaching the stage where it cannot cope with data bit rates higher than current state of the art systems. Laboratory demonstrations of optical data transmission have now reached speeds of 640 Gb/s. At these bit rates, optical-electronic-optical conversion procedures will be impossible due to speed limitations of the detectors, laser sources and processing electronics. Replacement of the O-E-O stage with an all-optical regenerator has become an increasingly important challenge in photonics research. The challenge must be viewed in the context of developing photonic integrated circuits that enable multiple network functions to be integrated onto one planar optical substrate: clearly, optical regeneration must also be developed on a PIC.

Regeneration requires a nonlinear relationship between the input and output optical signals (see figure). This nonlinearity must have a response time of less than 100 fs. Chalcogenide glasses have high coefficients of Kerr nonlinearity with response times less than 20 fs and so are potential material systems in which to develop a compact optical regenerator.

Our approach, named the Mamyshev regenerator after its inventor, utilises a short length of waveguide etched in a planar chalcogenide glass film followed by an in-waveguide Bragg grating filter. The filter pass band is offset from the



▲ Principle of device operation. NLWG – nonlinear waveguide, BPF – bandpass filter.

a) The optical regenerator consists of a 5 cm long nonlinear  $As_2S_3$  rib waveguide where spectral broadening occurs due to intensity-dependent phase modulation, followed by an integrated Bragg grating band pass filter, offset from the signal frequency, near the exit facet.

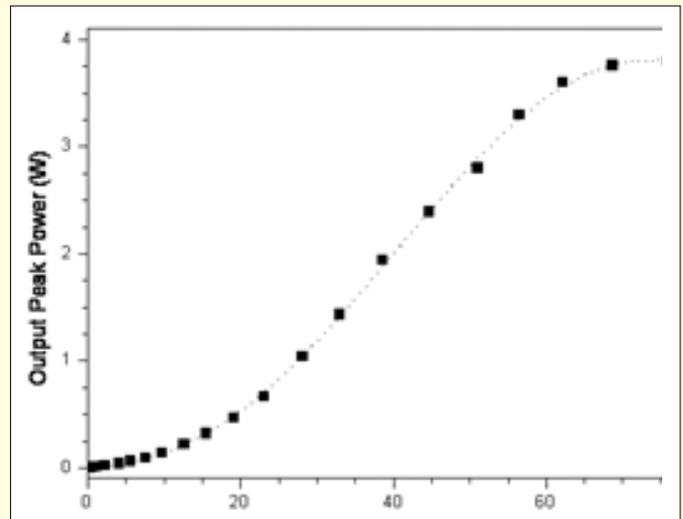
b) Input noise experiences less spectral broadening than the signal does, and hence is attenuated more than the signal after filtering.

c) This nonlinear power transfer curve results in both signal to noise and bit error rate improvement.

signal wavelength so that at low intensities the optical signal is blocked by the filter. On the other hand, higher intensity pulses, representing logical “1’s”, undergo spectral broadening due to a nonlinear effect. As the spectrum broadens with increasing input power, a portion of it overlaps with the transmission band pass filter and consequently is transmitted. The result is the “S-shaped” nonlinear power transfer curve, shown in part (c) of the figure, reducing noise on both the signal “0’s” and “1’s”, improving both the optical signal to noise ratio (OSNR) and, for bits that contain information, the Bit Error Rate (BER). This device is potentially much faster (>1 Tb/s) than devices based on real carrier dynamics such as semiconductor optical amplifiers, since it is based on the pure Kerr nonlinearity.

In the past year CUDOS has demonstrated all-optical signal regeneration with 1.5 ps pulses. The device is based on  $As_2S_3$  chalcogenide glass which has attracted significant interest in the past few years as one of the most promising nonlinear optical materials. The glass we use was developed in CUDOS, and deposited as a thin film for subsequent lithography and etching to produce the waveguide. Waveguide gratings were written near the exit facet of the waveguide with green light using a Sagnac interferometer. This yielded extremely high quality gratings in terms of both width and strength depth, with very sharp edges - critical for the successful performance of this device.

We demonstrated the device performance by measuring the transmitted power versus input power with 1.5 ps optical pulses from a tunable modelocked laser at peak powers up to hundreds of Watts. The result in the figure shows that the device exhibits a clear nonlinear “S-shaped” power transfer curve, as required for optical regeneration.



▲ Resulting ‘S’ shaped power transfer curve enabling suppression of noise and BER improvement. The dotted curve is a guide to the eye.

Looking forward towards future practical applications, a key consideration for these devices is the optical power required for operation. Whilst this first demonstration device operates at peak powers from tens to hundreds of Watts, practical devices would need to operate at sub-watt power levels. By increasing the device length (to 50 cm or even longer) through the use of spiral structures, increasing the material nonlinearity (by optimizing material composition) and by decreasing the waveguide area by a factor of 10, a reduction in operating power by two orders of magnitude will be achieved, resulting in sub-watt power level operation.

## Compact Optical Switch in a 2-D Photonic Crystal

**Project Leader:** Barry Luther-Davies

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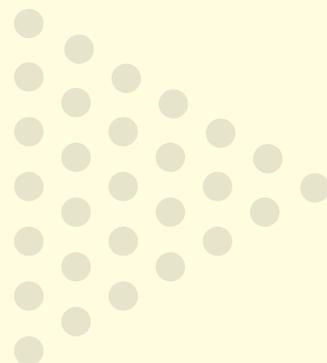
**Students:** Darren Freeman, Amrita Prasad, Michael Byrne

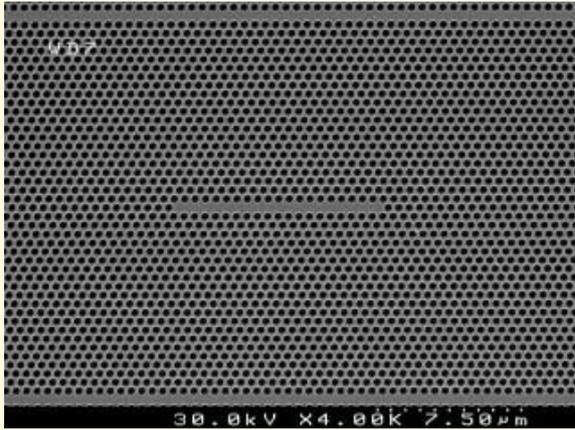
FLAGSHIP PROJECT

A “holy grail” in photonics has been the development of optical devices with similar functionality to that which the transistor provides in electronics. A “photonic transistor” would, for example, allow control of high-speed optical signals by light itself which, in principle, should simplify and lower the cost of future optical communications networks. However, it has proven to be very challenging to make devices that operate at sufficiently low optical powers (ultimately a few mW) and at speeds above those achievable with electronics (several tens of GHz).

In this project we aim to demonstrate all-optical switching in chalcogenide photonic crystals and explore the properties of these materials for fast all-optical processing. We are investigating switching due to optical bistability in a high-Q resonator fabricated in two-dimensional photonic crystals in thin membranes of chalcogenide glass. If the volume of the resonator is small, the power needed to observe bistability can be very low.

Whilst silicon has become the material of choice for much photonic crystal research, its nonlinear optical properties based on thermal effects or the generation of free carriers are unsuitable for fast all-optical switching. Our interest in chalcogenide glasses as alternative materials stems from their generally excellent ultra-fast nonlinear optical response combined with a sufficiently high refractive index (between 2 and 3) to be useful for photonic crystal fabrication.





▲ A resonant cavity formed by a line defect in a photonic crystal. A waveguide can be seen at the top of the image.

Fabricating 2-D photonic crystals in chalcogenide glass membranes raises several challenges not faced by the community working on silicon. Silicon is a very stable and predictable material whose properties have been the subject of intense study due to its importance in electronics. While chalcogenides on the other hand are relatively poorly understood, they display a myriad of tantalizing properties that can be tuned via composition. The challenge is to optimize those required for optical devices (such as third order nonlinearity) while minimizing others (absorption).

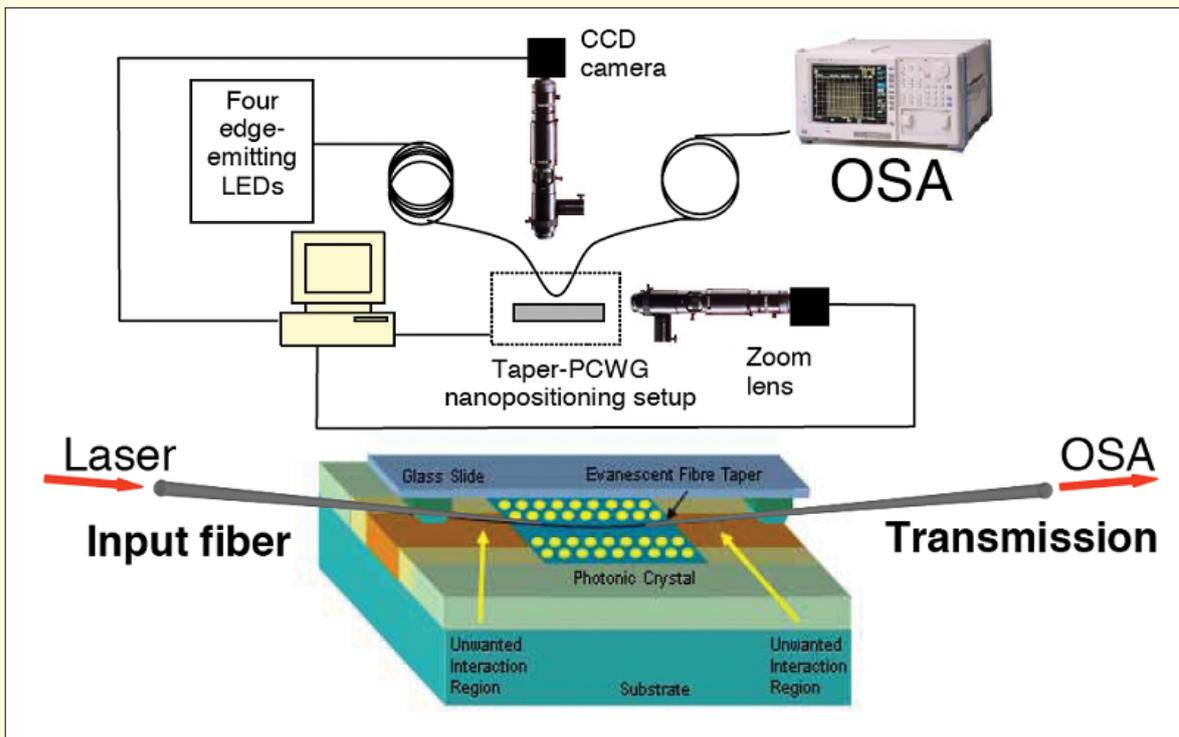
Photonic crystals composed of high and low refractive index materials must be fabricated with a combination of exceptional dimensional accuracy (at the few nm level) and contain optically smooth interfaces. We have developed a single step process based on the use of a customised focused ion beam (FIB) mill to directly pattern chalcogenide membranes to create photonic crystals. This novel approach is now providing structures with a quality rivalling those produced in silicon with far more complex and mature procedures.

Overall our project envisages two paths to all-optical switching: firstly we fabricate uniform lattices that display high-Q Fano resonances when probed optically at normal incidence. All-optical switching at wavelengths close to a resonance should be possible albeit using relatively high power probe pulses. Secondly, to obtain switching at low optical powers, photonic crystal lattices containing defect waveguides and resonators will be fabricated. By coupling light into these structures all-optical switching at low power should be observable.

This project draws on resources from three CUDOS partners: ANU, UTS and Sydney University. The complementary role of these groups is as follows:

- The ANU group fabricates air-clad photonic crystal membranes up to  $100 \times 100 \mu\text{m}$  in size using a focused ion beam mill. These membranes are characterized by measuring the Fano resonance spectra at near normal incidence for comparison with simulations.
- Modeling of the optical response of these membranes is carried out both at UTS and the University of Sydney. New and efficient approaches to modeling Fano resonances of the slab membranes are being developed at UTS to assist in the interpretation of experiments. More numerically intensive FDTD simulations performed at Sydney University provide information used to design defect waveguides and resonators for low-power switching experiments.
- The Sydney experimental team has assembled facilities for evanescent coupling from tapered optical fibres into defect mode waveguides created in the photonic crystal membranes. They will also lead the effort to observe low power all-optical switching in these structures.

During 2005, we made significant improvements in the quality of the photonic crystal lattices produced by focused ion beam milling of chalcogenide membranes to fabricate structures suitable for hosting micro-resonators. We developed a new experimental system for characterizing the optical response



▲ Top: Experimental setup for evanescent coupling from silica nanowire to photonic crystal waveguide. Bottom: Close up of the geometry used for alignment of the taper to the photonic crystal waveguide (PCWG).



▲ PhD student Darren Freeman and researcher Sally Stowe at the FIB facility at the ANU.

of photonic crystal lattices by probing near normal incidence, observing very strong inhibition of the optical transmission (below -40dB) near to Fano resonances. We successfully implemented a three-dimensional finite-difference time-domain numerical tool (RSOFT Fullwave) that simulates the Fano resonances of photonic crystal slabs, and we demonstrated efficient (>98%) coupling from a tapered optical fibre into defect waveguides within a chalcogenide photonic crystal lattice.

On the theory side, we developed a new semi-analytic method for characterising the properties of photonic crystal slabs that confine light via two mechanisms – a 2D band gap confinement in the transverse direction, and total internal reflection vertically. The software is being used to assist in fine-tuning the structures to produce high-Q resonances.

These achievements put in place all the basic building blocks needed to demonstrate all-optical switching in chalcogenide photonic crystals.

## Three-dimensional photonic crystals for emission control

Project Leader: Min Gu

Researchers: Yuri Kivshar, Lindsay Botten, Judith Dawes, Martijn de Sterke, Ross McPhedran, Mick Withford, Jesper Serbin, Martin Straub, Guangyong Zhou, Craig Bullen, Mike Steel.

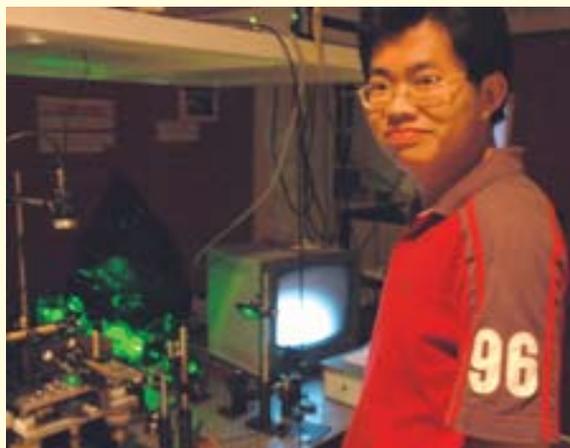
Students: Michael Ventura, Jiafang Li, Aaron Matthews

FLAGSHIP PROJECT

Three of our Flagship projects are built around studies in one and two dimensional photonic crystals. This Flagship focuses on the design, synthesis and photonic applications of three dimensional photonic crystals. These “meta materials” are notoriously difficult to fabricate, but the effort is worth the reward since their optical properties differ quite remarkably from those of ordinary materials. The differences are due to the role that diffraction from the periodic refractive index structure in the crystal plays in guidance and spectral transmission. Since the basic physical phenomenon is based on diffraction, the periodicity of the photonic crystal structure has to be in the same length-scale as the wavelength of the light i.e. approximately 1  $\mu\text{m}$  for photonic crystals operating in the near infrared part of the spectrum. This makes the synthesis cumbersome and complex.

The imposition of a 3D periodic variation in refractive index into a high refractive index material results in a profound change to the emission properties of the material. Emission can be inhibited, or constrained so that it occurs only in certain directions over certain wavelength bands. This effect leads to the potential for realizing ultra-compact, low threshold lasers and opens up new areas of physics in which the emission behaviour of atoms inside a “unit cell” of the crystal is determined by their specific location and may be calculated through a local density of states approach. CUDOS has a strong theoretical activity in this area, which is discussed in the Radiation Dynamics project.

During 2005 we consolidated our earlier work in which two elegant approaches to fabricating 3D structures in polymer



▲ Jiafang Li in the lab fabricating photonic crystal structures by means of two-photon polymerisation.

were demonstrated. Each relies on highly localized nonlinear interactions between a material and a femtosecond laser. In one approach a micro-explosion technique is used to modify, point by point, the refractive index of solid polymer. In the other, a two photon polymerisation technique with 3D scanning is used to create woodpile-structured crystals.

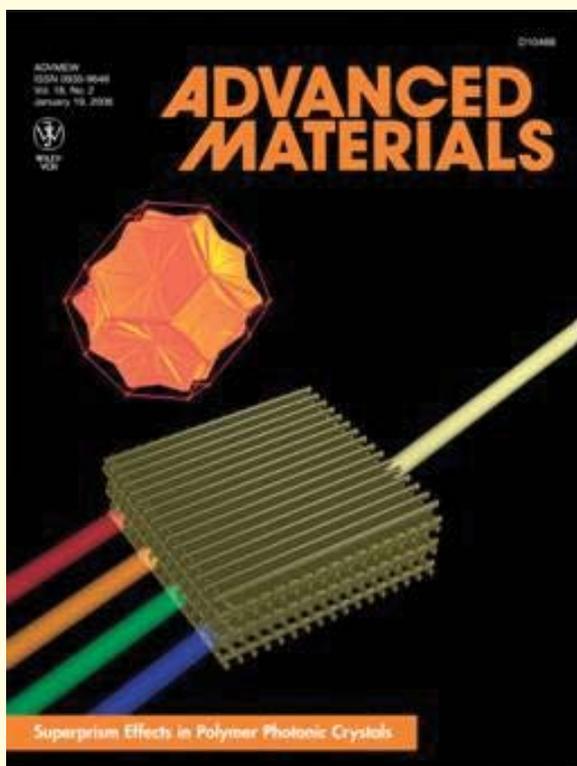
Some examples of applications of 3D photonic crystals were investigated as part of this Flagship project. Reported here are results that illustrate the potential of photonic crystals as compact multiplexers in wavelength division multiplexed systems, as compact Fabry Perot etalons, and as “omni-directional mirrors”.

## Polymer photonic crystals as compact multiplexers

The effect of light being split into its spectral components when entering a prism can be experienced in everyday life. Light entering a PC can experience super-refraction which is up to two orders of magnitude larger than the dispersive properties of conventional prisms (the so called superprism-effect). This effect might form the basis of an extremely compact optical add-drop multiplexer, suitable for integration into a PIC with other optical functions. We have shown that light propagating inside 3D polymer PC's based on the woodpile structure (see figure) changes its direction of propagation by more than 60° when the wavelength of the light is changed by only 150 nm. Within that wavelength range, the dispersive properties of the crystal even change from positive to negative refraction. We fabricated the photonic crystal structures by means of the two-photon polymerisation (2PP) technique, which is a direct laser writing method that allows for the fabrication of any arbitrary 3D microstructure with a resolution of ~150 nm. The photonic crystals fabricated by means of 2PP have their lowest band gap at 1.2 μm and possess super-refractive properties at ~1 μm.

## Polymer photonic crystals as etalons

Photonic crystals are often called "semiconductors for light", since the periodic dielectric function in a PC leads to a photonic band structure in analogy to the electronic bands in a semiconducting crystal. In order to realise a functional, electronic semiconductor device, one has to incorporate defects into the material. In the same way, defect structures play a very important role in photonic crystals. Depending on the dimensionality of the defect structure, one distinguishes between point defects, linear defects and planar defects.



▲ Superprism: White light is coupled into a 3D photonic crystal (woodpile structure) and is split into its spectral components after only a very short distance (cover taken from Adv. Mater. 18 (2), 2006).

We demonstrated the introduction of a planar defect to the centre of a 3D PC structure and showed how such a device is analogous to a simple Fabry-Perot etalon. The wavelength of the cavity resonance depends on the size of the planar cavity as well as the incident angle of light in the cavity. Such a PC planar cavity is on the order of 30 μm cubed and would be ideal in the integration of ultra compact photonic circuits in which precise wavelength selectivity is important. This development allows greater design flexibility when developing a microlaser within a photonic crystal.



▲ Michael Ventura synthesizing quantum dots for photonic crystal doping.

## 3D photonic crystals – complete band gaps

Since the first publications of Yablonovitch and John on the optical properties of periodic, dielectric structures in 1987 there have been intensive research efforts related to the design and new methods for the fabrication of functional photonic crystal devices. Since then, the realisation of complete photonic band gap structures using simple and flexible fabrication techniques has been central aim in the field of photonic crystals research. It remains a very challenging task for experimentalists, since it requires the fabrication of 3D micro-structures in high refractive index materials. Our approach to solve this problem is to synthesize new composite materials that have a higher refractive index than polymer but still can be processed like a standard polymer material using micro-fabrication techniques such as two-photon polymerisation and the laser-induced microexplosion method.

A sol-gel approach has been used to prepare the composite materials. Titanium dioxide (TiO<sub>2</sub>), which has a high refractive index of 2.5 ~ 2.8 and a large transparent range of 0.4 μm ~ 4.5 μm in its crystalline state, is used as a doping material. A precursor is used to infuse this material into an organic polymer matrix. The resulting transparent composite material contains approx. 50 wt% of TiO<sub>2</sub> and has a refractive index of n=1.7. To increase this further, we are developing a new method based on the infiltration of high refractive index material into the 3D polymerised structures.