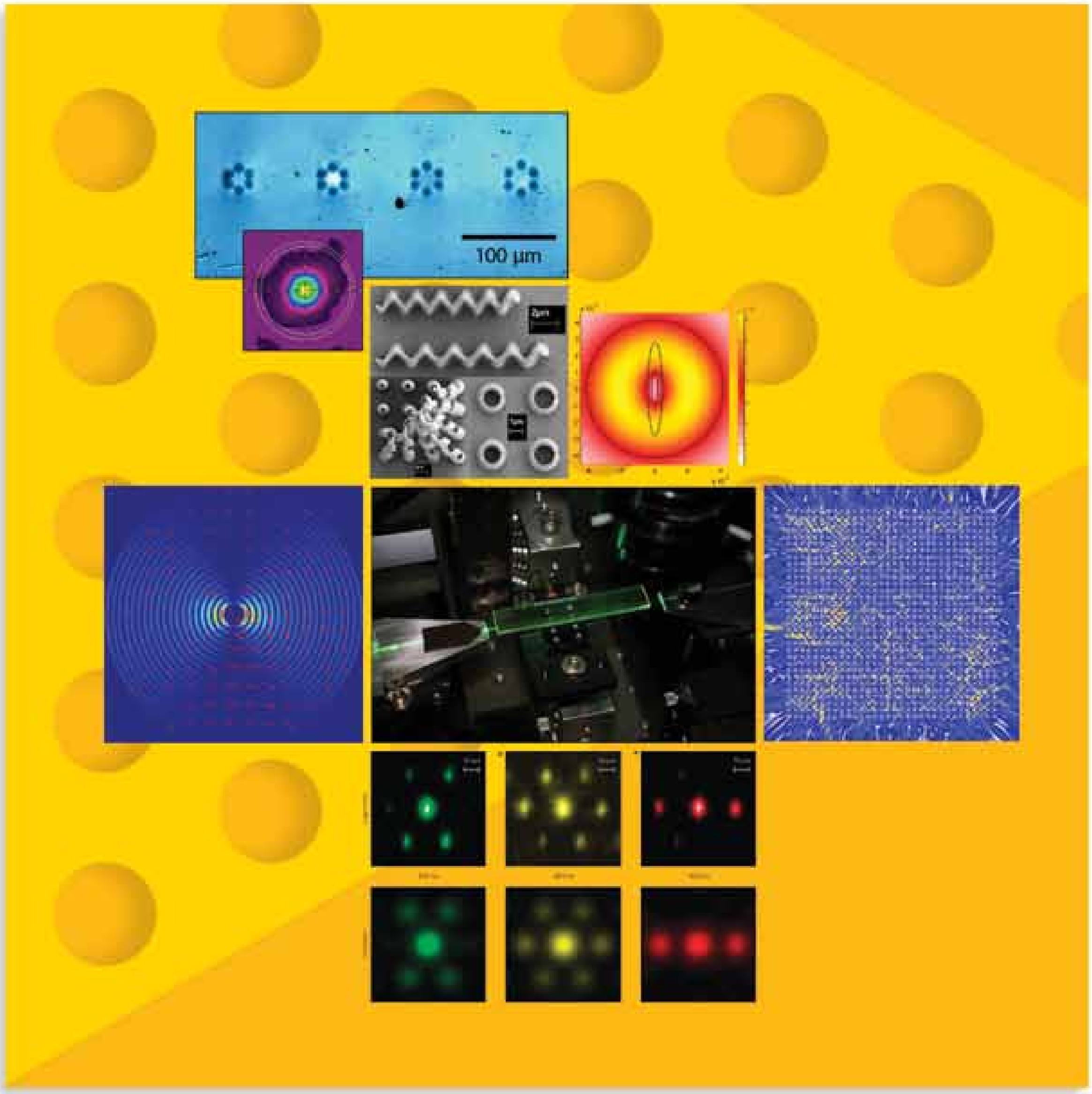
ANNUAL 2009 REPORT



CUDOS

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

PHOTONIC CRYSTAL ALL-OPTICAL SWITCH

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Long term goal and motivation: The development of optical devices with similar functionality to that which the transistor provides in electronics is a "holy grail" in photonics. A "photonic transistor" would allow control of highspeed optical signals by light. This would simplify and lower the cost of future optical communications networks. The challenge is 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 investigate switching due to optical bistability in a high-Q resonator fabricated from two-dimensional photonic crystals (PhC) in nonlinear chalcogenide glass. If the volume of the resonator is small and the glass nonlinearity is high, the power needed to observe bistability can be very low. We use chalcogenide because of its ultra-fast nonlinear optical response. The nonlinear optical properties of silicon are based on thermal effects or the generation of free carriers, both relatively slow effects, while those in chalcogenide are based on the Kerr effect, whose response time is far more rapid. Chalcogenide glasses have sufficiently high refractive indices (between 2 and 3) to be useful for photonic crystal fabrication.

CUDOS approach

The key to all-optical processing lies in the ability to enhance the nonlinear optical response of a device. Two approaches can be used to achieve this. First, the device should be fabricated from materials with the highest possible ultra-fast third order optical nonlinearity. Second, the optical structure should be chosen to enhance the nonlinear response by reducing the mode size and/or by trapping the beam inside a resonator thus increasing the intensity of the light wave in the nonlinear material. Our strategy is to apply both approaches in our research.

We use nonlinear chalcogenide glasses that have a high index of refraction (allowing light to be trapped in small waveguides or resonators), relatively large ultra-fast third order nonlinearity and low linear and nonlinear optical losses. We use these materials to fabricate 2-D photonic crystals in which light is tightly confined in a high-Q optical resonator, lowering the threshold for a nonlinear optical response. This will lead to switching at speeds limited only by the Q of the resonator, at exceptionally low power and without interference from thermal or free-carrier induced effects.

The research skills and facilities in CUDOS provide a world-leading platform to carry out this project. UTS and Sydney in collaboration

Photonic crystal all-optical switch team.

with A/Prof. Mike Steel (Macquarie University) have a strong device design and modeling capability. At ANU we now produce the world's best chalcogenide-based planar photonic devices using unique deposition, lithography and ion beam etching capabilities.

At Sydney we use an evanescent coupling process for getting light in and out of these microphotonic devices and a suite of characterization capabilities (micro-alignment rigs, high power lasers, and sophisticated optical measurement and data acquisition systems) to measure their optical performance.

Collaborative links

The international collaboration initiated in 2007 with the award of an ISL (International Science Linkage) grant to collaborate with the "Microphotonic and Photonic Crystals Research group" headed by Professor Thomas Krauss at the University of St Andrews was running at full steam in 2009. This collaboration destined at 1) using advanced electron-beam fabrication facilities at the University of St Andrews to e-beam write PhC structures in silicon and chalcogenide membrane produced at ANU and 2) sharing the microfabrication know-how, was key in the realisation of several 2009 major successful outcomes in photonic crystal-related activities (slow light and switch projects).

In 2009 a collaborative effort with Prof. R.W. van der Heijden, from the Department of Applied Physics, Photonics and Semiconductor Nanophysics, Eindhoven University of Technology has been initiated on the topic of "Air-hole filling of Quantum Dot incorporated InGaAsP Photonic Crystal Nanocavities" and will lead to a formal collaboration and exchange staff between CUDOS and Eindhoven.

Preliminary talks with Prof Rojo-Romeo from INL laboratory in Lyon and CEA LETI in Grenoble are now leading to a collaborative effort to develop processes for the fabrication of micro-pillars type photonic crystal. A first batch of samples containing photonic crystal micro pillar in silicon and III-V SC produced at CEA LETI has now been sent to Sydney for a series of measurements.

Goals for 2009

One of our primary goals was to extend the development of a single device in a single membrane towards an actual integrated photonic circuit in chalcogenide with cascaded photonic crystal elements (cavities and waveguides) coupled to a conventional total internal reflection circuit (integrated nanowires) which communicates with the outside world. Achievement of this goal relied on development of a fabrication process for realising chalcogenide photonic crystal using e-beam lithography technique both at ANU and St Andrews. In a related effort, we aimed to develop approaches allowing the relaxation of constraints on the fabrication accuracy normally required to achieve a high degree of functionalities in a photonic integrated circuit. These were based on exploiting the photosensitive properties of chalcogenide as a flexible and powerful post processing tool to trim properties of individual components and/or create new defects in a pre-existing PhC platform and more specifically a high Q cavity with intrinsic Q factor at least greater than 50000.

In parallel, a new range of alternative resonators in chalcogenide were to be investigated including microspheres, rings and toroidal rings, with the aim of assessing their potential impact in areas as diverse as sensing, mid infrared sensing and all optical switching.

Achievements and highlights for 2009

Having a baseline electron beam lithography process for PhC fabrication led to great expectations for 2009 and these hopes have largely been fulfilled. The first major achievement was working low loss AMTIR-1 W1 membrane waveguides. Testing in Sydney suggested that losses were in the few 10s of dB/cm, not bad for a first cut process. Using post-processing of the waveguides via the red light photosensitivity of AMTIR-1, double heterostructure cavities were demonstrated in Sydney with high Q factors for the first time [1] (see below).

More complex structures (e.g. coupled resonator waveguides, etc) require coupling into and out of the PhC waveguide using integrated planar waveguide structures. The major challenge involved is the under etching process to free the membrane from the silica substrate, where the tiny dimensions of the suspended waveguide leave it vulnerable to breakage or lift off. After much effort, a process has been developed both at ANU and St Andrews that has successfully integrated the connecting waveguides as shown in Figure 1, and a mask set and architecture devised to enable the fabrication of a wide range of devices with the connecting waveguides.

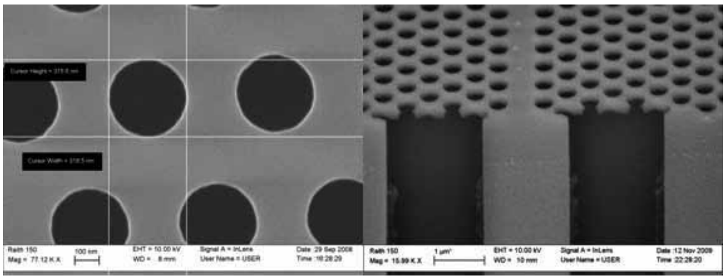

Fig 1. SEM images of ANU-made photonic crystal. (a) The photonic crystal before under-cut process. (b) Test PhC Waveguide with connecting waveguide post under etch

One issue identified was the swelling of the AMTIR-1 membrane due to relaxation of the glass from its deposited state back towards the bulk state. This causes buckling of the membrane of up to ~2mm given sufficient time or light exposure. This effect is very difficult to eliminate and so work has started on replacing the AMTIR-1 with a Ge11 based glass that deposits much closer to the bulk index [2]. Work has also begun on a new writing method for PhC devices which enables devices of arbitrary length to be fabricated with no stitching errors. A further advantage of this method is that it may reduce the hole placement errors seen with standard methods leading to lower losses and improved cavity Q factors.

One of the highlights of 2009 was the demonstration of a high-Q (~125000) cavity in chalcogenide created using an optical exposure post-processing technique as shown in Figure 2 [1,3]. Cavity defects in two-dimensional planar photonic crystals (PhCs) are of interest because they can provide a high degree of both spatial and temporal light confinement. Typically, PhC cavities are created by making a geometric modification of the periodic lattice of the PhC at the time of fabrication; however a number of post processing techniques have also been demonstrated [4]. One such technique is to selectively modify the refractive index of a photosensitive material [1,3]. The advantages of this method include the possibility for smooth apodization of the induced index profile and that it allows for some post-fabrication control of the cavity properties. The photosensitive refractive index change of chalcogenide glass was used to locally modify a PhC and create a double-heterostructure type PhC cavity. A tapered fiber evanescent coupling technique was used to measure the cavity in situ during its formation and using this method which gives some in situ control over the final cavity properties.

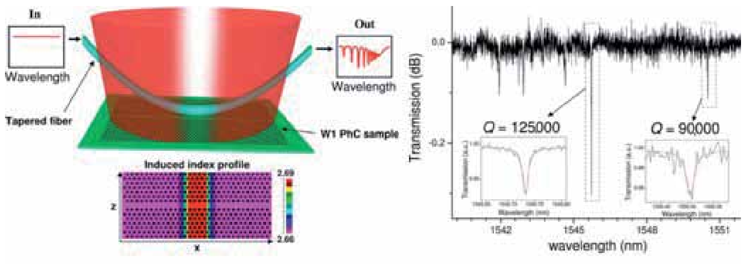

Fig 2. (left) Schematic view of the experiment showing a chalcogenide PhC waveguide undergoing a selective exposure to locally modify the refractive index of the material. The tapered fiber measurement system is also shown along with a sample index profile for a photoinduced double-heterostructure cavity. (Right) Measurement of the cavity resonances, postexposure, using a swept-wavelength system with 3 pm resolution. Q factors of up to 125,000 can be inferred.

Designing a photonic crystal heterostructure cavity is a computationally expensive task, taking many hours on state-of-the-art supercomputers. On the other hand, computation of bulk PC properties such as band diagrams is now routine, and this task can most often be accomplished on a desktop. In 2009, we have developed a new semi-analytical method by which the properties of PC cavity modes can be deduced purely from the PhC band-structure [5]. The method is an extension of perturbation approaches developed in the solid-state literature, and results in easily-calculable expressions for the envelope function of the cavity mode. This method works best for the shallow perturbation regions where conventional numerical methods experience difficulties, and can be applied to 1, 2 and 3- dimensional structures. We have applied this method to shallow PhC waveguides and are currently in the process of testing the limits of the method's accuracy for fully-3D photonic crystal heterostructure cavities.

Targets for 2010

In 2010 we will pursue our efforts on replacing the AMTIR-1 with a Ge11 based glass that deposits much closer to the bulk index. We will also develop a new writing method for PhC devices which enables devices of arbitrary length to be fabricated with no stitching errors. This will be crucial in our efforts towards the creation of an actual integrated photonic circuit in chalcogenide with cascaded photonic crystal elements (PhC cavities and waveguides) coupled to a conventional total internal reflection circuit (integrated nanowires) to communicate with the outside world.

After having successfully demonstrated in 2009 the writing of a high Q cavity, we will continue exploiting AMTIR1 and its photosensitivity to create CROW-based (Coupled Resonators Optical Waveguides) slow light structures.

In parallel, we will pursue our investigation of alternative resonators in chalcogenide. Specifically, we will develop a fabrication process for disk and ring resonators in Ge11 and we will characterise both their linear and nonlinear properties.

References

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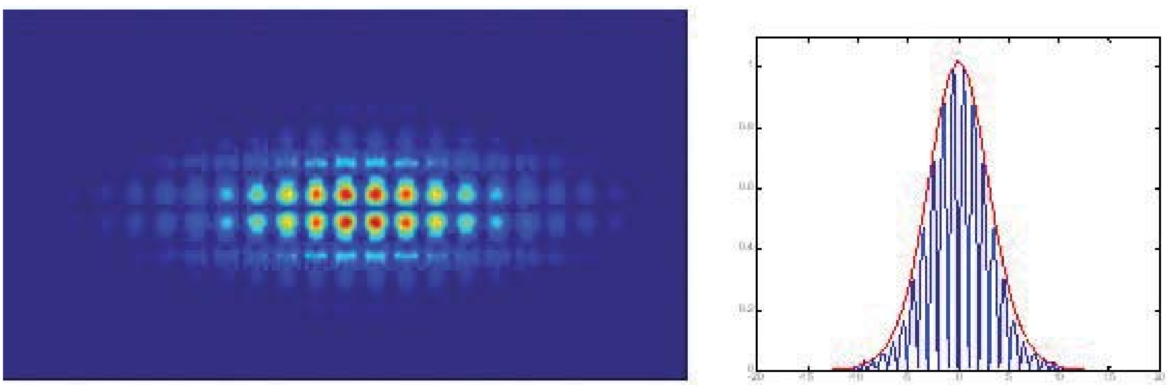

Fig 3. (left) 3D PC heterostructure cavity computed using the new semi-analytical method. (right) A direct comparison between the predicted envelope function (red) and the fields computed using FDTD. The envelope contains no fitting parameters and is computed using only the properties of the PC band-edge.