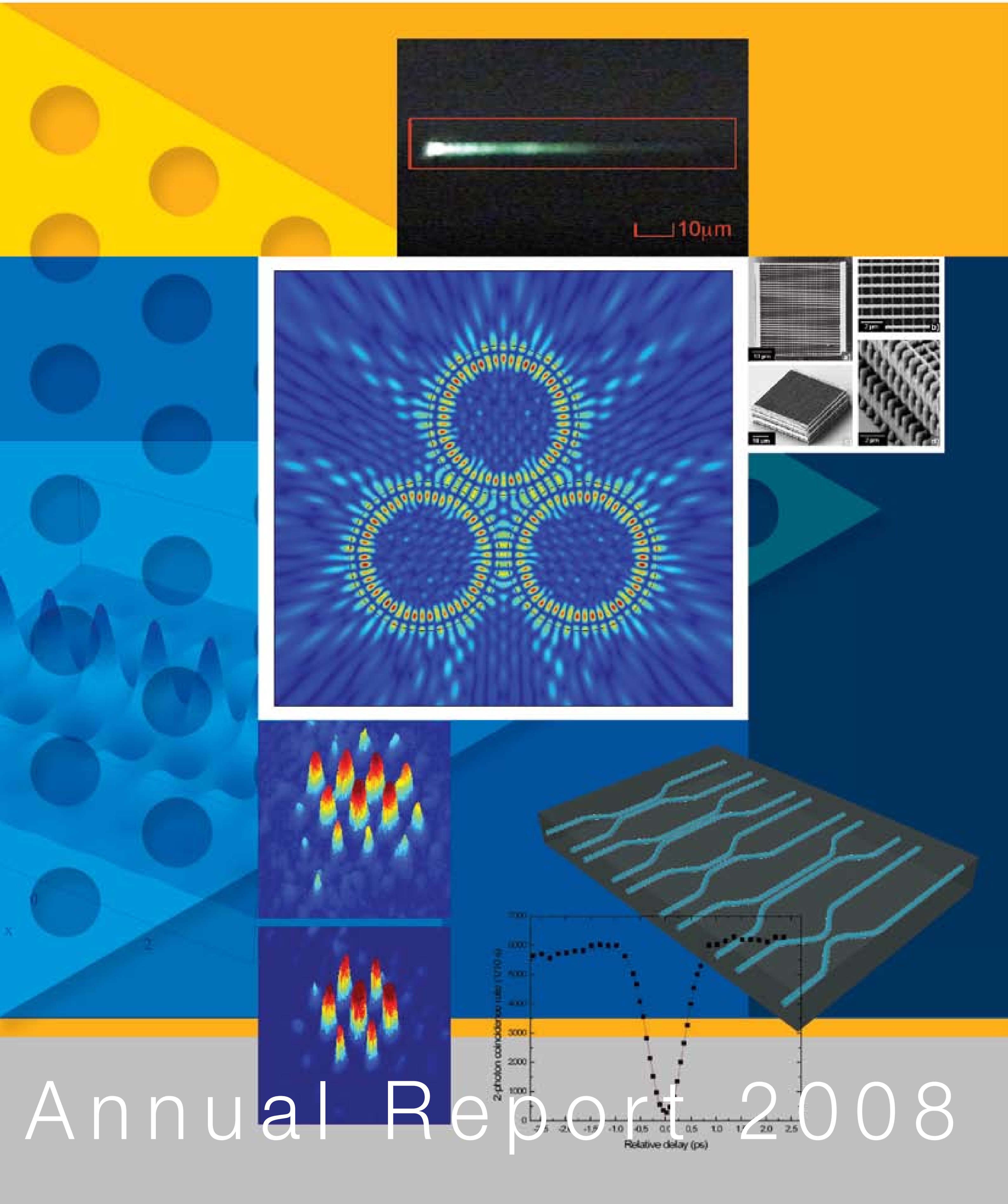
CUDOS

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



Annual Report 2008

CHALCOGENIDE PHOTONIC CRYSTAL ALL-OPTICAL SWITCH

Project Manager: Christian Grillet

Science Leader: Barry Luther-Davies

Contributing staff: Snjezana Tomljenovic-Hanic, Eric C Magi, Cameron Smith, Christian Kartnush, Benjamin J. Eggleton (Sydney), Steve Madden, Duk Choi, Andrei Rode (ANU), C. Poulton (UTS)

Students: Xin Gai (ANU), Michael Lee (Sydney)

Partner Investigators: Thomas Krauss (St Andrews), Kobus Kuipers (AMOLF Amsterdam)

Four year vision/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 high-speed 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 strategy/competitive advantage

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 with A/Prof. Mike Steel (Macquarie University) have a strong device

Chalcogenide Photonic Crystal team.

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

In 2008, our international collaboration, initiated in 2006 with Professor Thomas Krauss' group at the University of St Andrews and strengthened by the award of an ISL (International Science Linkage) grant in 2007, ran at full steam. This funding helped the establishment of a formal collaboration between CUDOS (Sydney and the Australian National University) with international partners from the European consortium SPLASH (Slow Photon Light Activated SwitcH) under the Future and Emerging Technologies Programme of FP6, in particular with researchers from St Andrews, Scotland and the FOM Institute for Atomic and Molecular Physics (AMOLF), Amsterdam. Our goal is to use advanced electron-beam fabrication facilities at the University of St Andrews to lithographically write PhC structures in chalcogenide membrane produced at ANU, then post- process and characterize these structures at Sydney and probe the optical dynamics inside these micro-optical structures at FOM.

Preliminary talks with other SPLASH partners, in particular the Glasgow University group headed by Prof. Richard Delarue and Dr. Marc Sorel in 2007 are now leading to a collaborative effort to develop processes for the fabrication of nanowires and ring resonators in chalcogenide. A first batch of samples containing AMTIR nanowires produced at Glasgow University and the James Watt nanofabrication centre with an advanced ebeam lithography system (VB6 UHR EWF lithography tool) was sent to ANU for a series of nonlinear measurements.

The concept of "heterogeneous integration" has the potential to create a new generation of integrated devices in area as diverse as nonlinear photonic signal processing, QED devices and bio-sensing. In 2008 several collaborations aiming at implementing this concept were initiated.

A collaboration between CUDOS and Prof. Mortensen's group at DTU Denmark has been initiated by Dr. C. Karnutsch. The work will investigate the possibility of exploiting our fluid insertion technique into PhC platform for thermo-optical compensation.

A collaboration with Prof. Jelena Vuckovic's group at Ginzton Laboratory, Stanford University yielded positive outcomes during 2008. Andrei Faraon a PhD student at Stanford University developed a process, in collaboration with ANU, to locally change the refractive index in planar optical devices by photo-darkening of a thin chalcogenide glass layer deposited on top of the device. In this particular case the method was used to tune the resonance of GaAs-based photonic crystal cavities. This paper led to a published article in APL [1].

Goals for 2008

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 preexisting PhC platform.

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 2008

In 2007 we initiated a series of investigations of alternative ways to re-configure *'a-posteriori'* high Q cavity in a chalcogenide PhC platform. This work has continued through 2008, focussing on novel alternative ways of achieving this. We employ the 'mode gap' mechanism with which we create double-heterostructure type cavities. This provides confinement along the waveguide axis of the W1 and that can be created by any means which locally increases the effective index of the waveguide. Our approach, described below, uses spatially-selective liquid filling of the photonic crystal holes to change the refractive index.

Our approach is considerably more straightforward than the lithographic elongation of the PhC lattice in a short section of a 'W1' waveguide to form a double-heterostructure cavity. While some of the highest experimentally-demonstrated Q-factors have been achieved with this approach, it requires extreme control over the fabrication process. The geometry of the structure must be finalized at the design stage of fabrication and there is very limited scope for post-processing or tuning the cavity. The enormous precision required to realize these sophisticated nanostructures eventually becomes a limiting factor.

Investigation of cavity writing of high-*Q* cavities in AMTIR1-based photonic crystal slab using the photosensitivity of this material is underway. To achieve this phase masks have been produced at ANU and sent at Sydney University.

Our numerical studies show that high-Q cavities with values potentially reaching 10^6 can be achieved via selective fluid infiltration [2] of a W1 PhC waveguide. Following those numerical predictions, using an evanescent probing technique, we offered [3] the first proof of principle demonstration of optofluidic double-heterostructure type cavities, formed using a glass microtip (Figure 1 (a)) to selectively infiltrate 1.5 index liquids into the central section of PhC W1 waveguides made in chalcogenide via focused ion beam (FIB) milling.

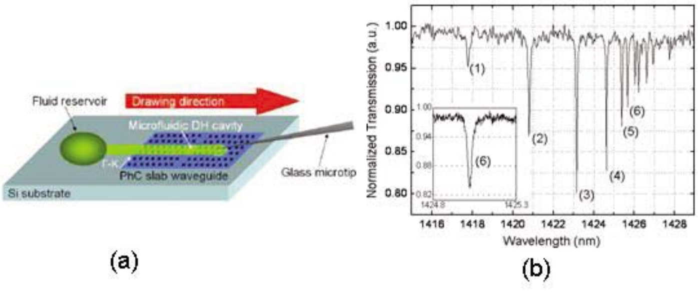


Fig 1. (a) Infiltration schematic: a glass micro-tip is used to draw the infiltration fluid across the PhC section, forming the DH stripe. (b) Transmission spectrum of a microfluidic double heterostructure cavity in Si. Inset, close-up view of resonance (6). The intrinsic Q is around 60000.

The modest Qs obtained (<5000) were attributed to high material absorption losses resulting from incomplete removal of the carbon layer used to prevent charge build up during FIB milling, or alternatively undesired Ga implantation resulting from FIB milling [4]. To measure those losses, M. Lee et al developed "an expanded *k*-space evanescent coupling technique" to retrieve the waveguide dispersion and its associated losses [4].

Notwithstanding the lower than expected Q values, this approach offers a versatile way to write microcavities by choosing the width of the infiltrated PhC area and the refractive index of the infused liquid. The reversible nature of these double-heterostructures enabled by fluid mobility offers a "rewrite" potential, which was demonstrated in 2008 in silicon PhC structures [5]. The double heterostructure cavities yielded higher Q resonances, up to Q = 3.5×10[4] (limited by the resolution of the optical spectrum analyser), using this more easily processed and higher index silicon material as compared to chalcogenide. The cavity length could be accurately adjusted using the microtip infiltration technique; the cavities were then erased by complete removal of the penetrated fluid, and then rewritten, paving the way for complete reconfigurable, rewritable photonic circuits (see figure 2). More recent experiments have shown intrinsic Q-factors approaching 6×104 [6] (figure 1 (b)), demonstrating the potential of this approach for realizing microresonators that can be useful for efficient devices in standard chip technology.

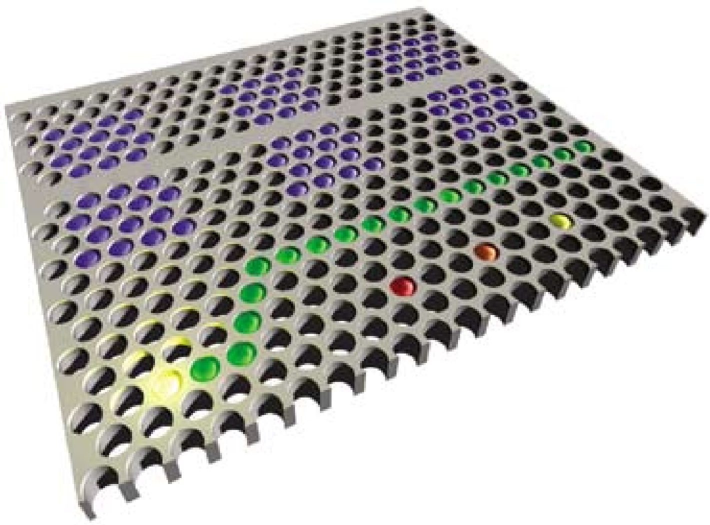


Fig 2. Schematic vision of the "reconfigurable optofluidics photonic chip"

Following the visit of A. Faraon from Stanford University one of the highlights of 2008 was the publication of the APL paper "Local tuning of photonic crystal cavities using chalcogenide glasses" [1]. In this article, we reported experimental tuning of (i) GaAs-based photonic crystal cavities by up to 3 nm at 940 nm and (ii) the embedded InAs QDs by using the photosensitivity of a thin chalcogenide layer deposited on top of the GaAs cavities. This tuning method is not only suitable for GaAs devices, but can possibly be implemented with any other materials, including silicon nanophotonic circuits [1]. This work was a collaborative effort between Stanford University, ANU and Sydney University.

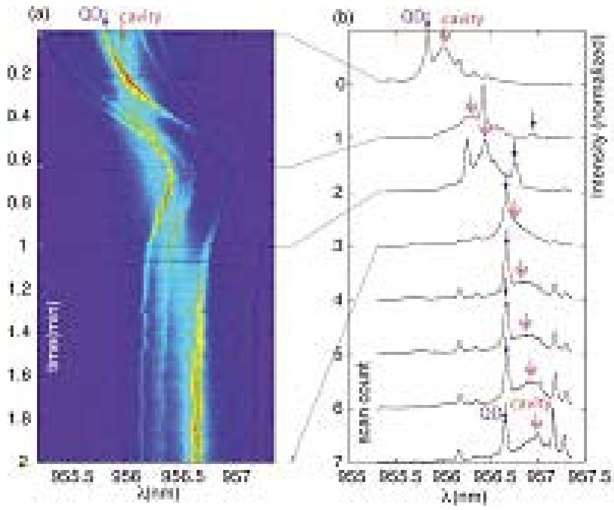
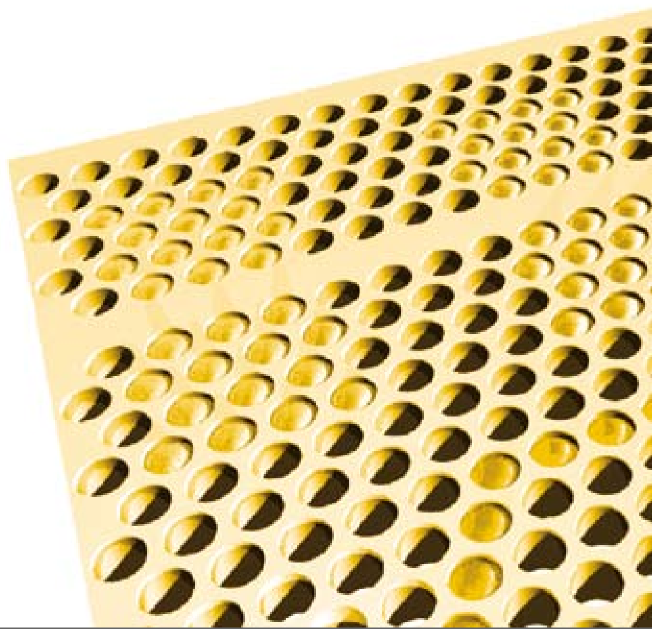


Fig 3. (a) Spectra showing cavity and QD shifting, as a function of exposure time. The QD lines first shift rapidly, presumably through changing material strain induced by the chalcogenide layer. Soon after, the QD lines become stationary, while the cavity continues to redshift. This data set was taken on a sample with 50 nm of As_2S_3. (b) Individual scans of QD/cavity tuning show that after strain relaxation, the cavity can beshifted independently of the QDs. Scans 4–7 were taken for *t*_2 min when the pump power was temporarily increased to speed up the chalcogenide exposure.

One of our goals for 2008 was to start investigating a new range of alternative resonators in chalcogenide. We demonstrated this year the possibility of producing chalcogenide microspheres (As_2S_3) based on an optical fuse in a chalcogenide fiber [7] (see figure 4a). We also developed an evanescent coupling approach based on a silica nanowire to couple light into and probe these microspheres (Figure 4b). We measured loaded Q values approaching 20,000.

The ability to couple to high *Q* chalcogenide microsphere modes opens up the prospect of a wealth of science in both telecommunication and mid infrared windows. It is expected that applications of chalcogenide microsphere can be as versatile as silica microsphere with the added advantage of the higher nonlinearity provided by the chalcogenide and the possibility of accessing the mid infrared window.



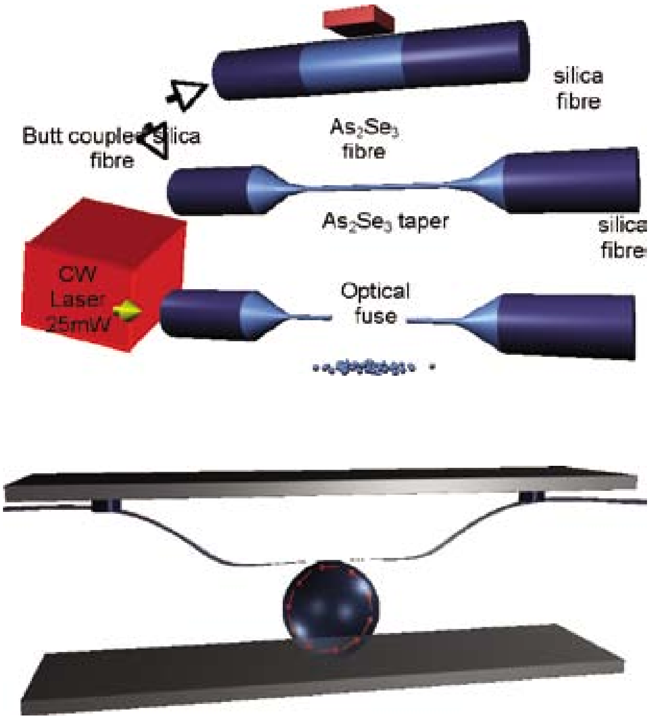


Fig 4. (a) Fabrication process, (b) coupling setup between a silica taper and a microsphere

Fabrication

In 2007 a collaborative effort with St Andrews was established to systemise and optimise the fabrication process for both AMTIR-1 and As_2S_3 chalcogenide membranes. This process is now being further developed within CUDOS with the installation at ANU in 2007 of a new Raith 150 e-beam writer.

Prior to 2008 all our 2D chalcogenide PhC structures were realized in a single PhC membrane configuration. In 2008 we began the transition from single device in a single membrane towards an actual integrated photonic circuit in chalcogenide with cascaded photonic crystal elements (PhC cavities and waveguides) coupled to a conventional TIR circuit (integrated nanowires) to communicate with the outside world (Figure 5).

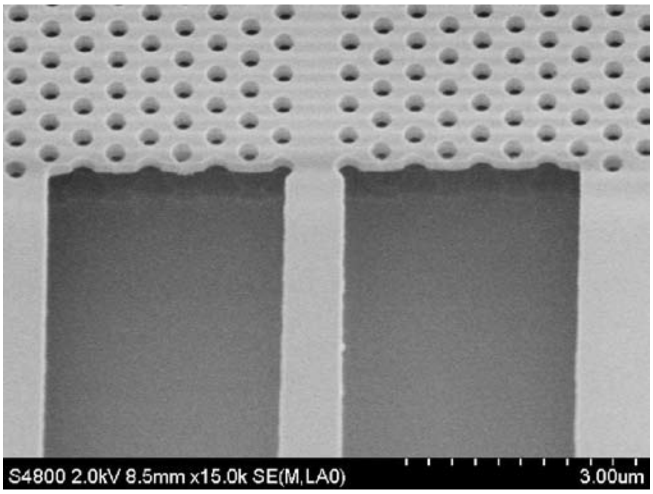


Fig 5. SEM picture of a photonic crystal waveguide connected to a nanowire in AMTIR1 recently produced at St Andrews

Targets for 2009

In 2008 we successfully commenced the transition from a single photonic device in a single membrane to interconnected photonic crystal structures. We will pursue 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. In parallel, strong efforts will be devoted to the optimization of the process to meet state of the art quality PhC structures (in terms of side wall angle, roughness, homogeneity, deviation to the nominal parameters…).

We will exploit 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 preexisting PhC platform. Our objective will be to demonstrate the potential of this photosensitive technique to relax the constraint on the fabrication accuracy normally required to achieve a high degree of functionalities in a photonic integrated circuit.

In parallel, we will pursue our investigation of alternative resonators in chalcogenide. Specifically, we will start nonlinear measurements on chalcogenide microspheres, and develop a fabrication process for “toroid-like” resonators based on fused chalcogenide disks.

References

[1] A. Faraon et al, *“Local tuning of photonic crystal cavities using chalcogenide glasses,”* Appl. Phys. Lett. **92**, 043123 (2008).

[2] S. Tomljenovic-Hanic et al *“Design of high-Q cavities in photonic crystal slab heterostructures by air-holes infiltration,”* Opt. Express **14**, 12451-12456 (2006)

[3] C. L. C. Smith et al *“Microfluidic photonic crystal double heterostructures,”* Applied Physics Letters, **91**, 121103 (2007).

[4] M. W. Lee, et al *“Characterizing photonic crystal waveguides with an expanded k-space evanescent coupling technique,”* Opt. Express **16**, 13800 (2008).

[5] C. L. Smith et al, *“Reconfigurable microfluidic photonic crystal slab cavities,”* Opt. Express **16**, 15887-15896 (2008)

[6] U. Bog, et al, *“High-Q microfluidic cavities in silicon-based two-dimensional photonic crystal structures,”* Opt. Lett. **33**, 2206 (2008).

[7] Christian Grillet, et al, *“Fiber taper coupling to chalcogenide microsphere modes,”* Appl. Phys. Lett. **92**, 171109 (2008)