CUDOS

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

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CHALCOGENIDE PHOTONIC CRYSTAL ALL-OPTICAL SWITCH

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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 in two-dimensional photonic crystals of 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), 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 to achieve 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 Dr Mike Steel (RSoft) have a strong device design and modeling capability. At ANU we now produce unique chalcogenide-based planar photonic devices using proprietary capabilities for deposition, lithography and ion beam etching. At Sydney we also have a novel evanescent coupling process for getting light in and out of these microphotonic devices and a set of characterization capabilities (micro-alignment rigs, high power lasers, and sophisticated optical measurement and data acquisition systems) to measure their optical performance.

Collaborative links

During 2006 we benefited from a collaboration involving former CUDOS student Dr Yinlan Ruan (now at the Centre of Expertise in Photonics at the University of Adelaide) and the group of Professor Yong-Hee Lee and his student Myung-Ki Kim in KAIST, Korea. Under an Endeavor Australian Cheung Kong award, Yinlan visited KAIST to develop processes for the fabrication of photonic crystals by e-beam lithography and chemically assisted ion beam etching. Several of the samples produced at KAIST have been used for the laboratory demonstrations reported here.

We established a new international collaboration with the Microphotonic and Photonic Crystals Research group headed by Professor Thomas Krauss at the University of St Andrews. This group has been active for over a decade and has made some pioneering demonstrations and is one of the leading European laboratories in the field of photonic crystals. Dr Grillet visited the St Andrews group during 2006 and used their lithography system to write photonic structures in planar chalcogenide substrates fabricated at CUDOS.

Goals for 2006

Our goals for this year focused on two substantial experimental challenges needed to demonstrate all optical switching in a chalcogenide photonic crystal using a resonant cavity:

- Design and manufacture a resonant cavity defect with a high-Q factor.
- Couple light efficiently into the resonant cavity defect

Achievements and highlights for 2006

Sufficient light must be coupled into the high Q PC cavity to induce bistable behavior. We achieved efficient evanescent coupling from a novel low-loss fiber taper (Fig. 1) into L3 photonic crystal nanocavity resonators (so-called because three holes are removed) with different end-hole shift and diameters. Q values predicted from 3D FDTD simulations are greater than 10,000 for the optimal geometry.

Figure 1. Coupling scheme used: schematic showing the coupling from a tapered fibre to PhC nanocavity

Structures have been manufactured using either FIB milling [1-3] or e-beam lithography plus chemically assisted ion beam etching [4]. Figure 2 shows results of experimental measurements performed on a cavity with both a side-hole shift and diameter reduction. A Q value as high as 10,000 was measured for a separation of the fibre from the resonator of 800 nm. As this separation decreases and the loading of the cavity increases, the measured Q factor also decreases (as expected) down to 2000 and the depth of the transmission dip increases up to 1.5 dB.

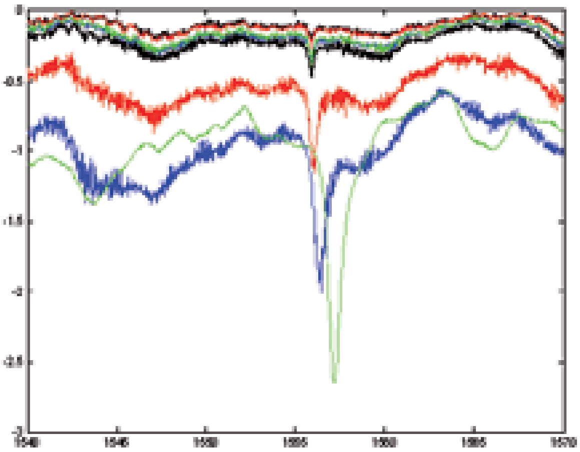


Figure 2. Transmission spectra through the tapered fibre for coupling to a modified L3-type nanocavity as a function of fibre to PhC separation.

These data indicate that simple chalcogenide PC resonators can exhibit sufficiently high Q to make all-optical switching feasible, even though the transmission depth is in this case restricted to a few dB, which limits the contrast ratio of the expected switching device.

We investigated ways in which a high-Q nanocavity in a photonic crystal slab (PCS) could be formed. There are two usual approaches: either as a point cavity or by forming a “heterostructure”. We considered both; our results indicate that nanocavities with the highest Q values that may be realised in a chalcogenide-based PCS are photonic crystal double-heterostructures, where regions of slightly different lattice constant are combined in a single slab to create a cavity. We designed cavities of this type with Q=7×10^5, comparable to the best results reported to date in silicon-based PCS [6].

One of the highlights of 2006 was the development and demonstration of a novel concept for creating high-Q cavities in PCS of photosensitive material. Spatially selective post exposure to light in a photosensitive uniform photonic crystal slab alters the refractive index permanently and was shown to yield high-Q nanocavities [7]. These high-Q cavities (up to Q=1×10^6) can be achieved with photo-induced index changes that are consistent with those seen in chalcogenide glasses.

We successfully demonstrated this photosensitive post tuning of a planar photonic crystal device [5]. We used the photosensitivity of AMTIR-1 chalcogenide glass to modify the optical properties of a photonic crystal waveguide (Figure 3a). A W1 PC waveguide was exposed to 633 nm light at an intensity of 1.3 W/cm². The resulting change in the dispersion of the modes of the waveguide was detected using an evanescent probing technique, which yielded a shift of 5 nm in the wavelength for resonant coupling (Figure 3b).

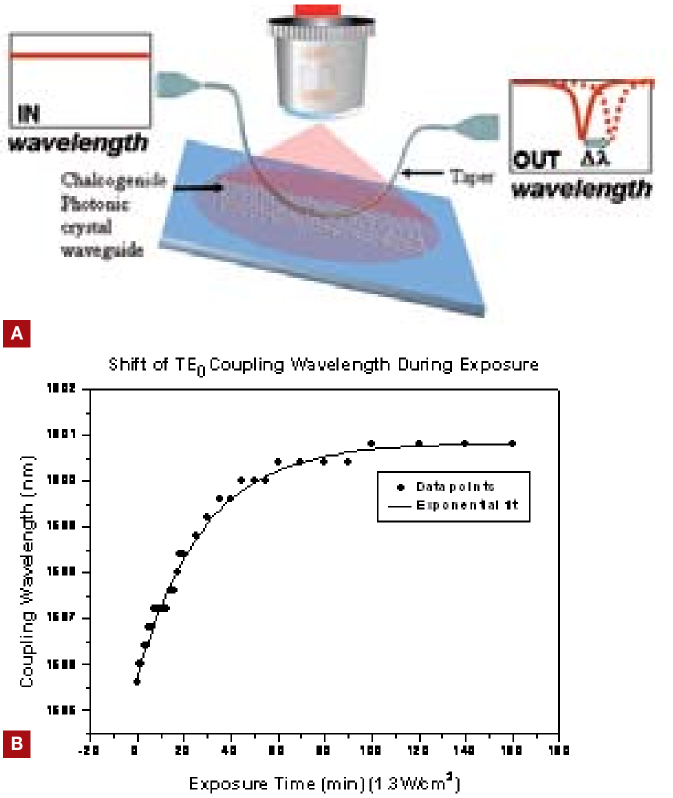


Figure 3. a) Schematic showing the principle of operation of the photosensitive post tuning of a Chalcogenide photonic crystal waveguide. b) Shift in coupling wavelength versus exposure fluence at 633 nm of the PC waveguide

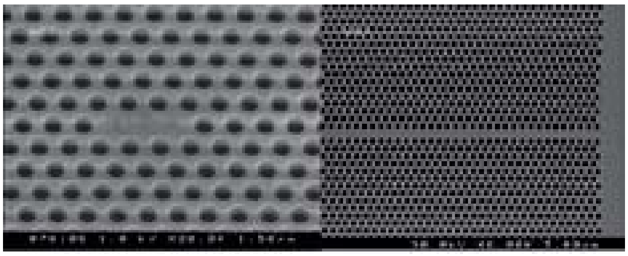
Modelling

We continued to study Fano resonances in PCS [8]. We improved the robustness of the algorithms in a sophisticated new tool based on Bloch mode and multipole techniques which we use for modelling and characterising Fano resonances in photonic crystal slabs. As a result, the capabilities of the method were substantially extended. The method now accommodates both square and hexagonal lattices as well as multiple layer structures (e.g., composite chalcogenide-nitride layers) in both normal and off-normal incidence configurations. This latter extension required the development and implementation of generalised Fresnel matrices that characterise the reflection and transmission of Bloch modes on either side of the interface of two inhomogeneous PC media.

Fabrication

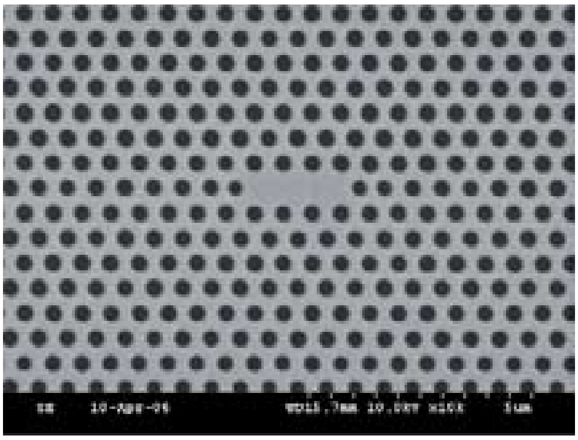
We refined our system for correcting drift in the focused ion beam mill used for producing accurate 2-D photonic crystal patterns (Figure 4) in chalcogenide films. The long milling times (greater than an hour) for the photonic crystal patterns invariably leads to significant mechanical or electronic drift in the ion beam relative to the sample surface and this leads to distortion or defects in the photonic crystal lattice. Improvements in quality of the reference marks used to monitor machine drift has allowed a five-fold increase in the useful "lifetime" of those reference marks and by fine tuning the parameters in the drift tracker, the positioning error is now estimated to be 1 nm (down from 5 nm).

Removal of the gold coating used to control sample charging during milling is crucial, since residual metal contaminants can increase the losses of the resulting optical structures. We successfully trialled a lift off layer below the gold to help gold removal and reduce losses.



▲ **Figure 4. SEM micrograph of a) a photonic crystal L3 cavity b) a photonic crystal waveguide fabricated by FIB milling**

We collaborated with the KAIST group of Professor Yong-Hee Lee and former CUDOS student Yinlan Ruan to show that standard e-beam lithographic process combined with Chemically Assisted Ion Beam Etching (using Cl_2 and Ar etchant) can also be used to create 2-D chalcogenide glass photonic crystals (Figure 5). Free-standing membranes on oxidized silicon substrates have been produced by removing the underlying silica layer with a buffered oxide etch. A series of L3 cavities with shifted end holes of variable size were produced for fibre coupling experiments. The quality of the lattices was limited by that of the e-beam writing system. The acquisition of a new Raith 150 e-beam writer to be installed at ANU in 2007 should allow this process to be further developed within CUDOS.



▲ **Figure 5. SEM micrograph of a photonic crystal L3 cavity with shifted end holes fabricated using ebeam lithography at KAIST, Korea**

Targets for 2007

For effective switching we need to increase the inherent Q of the resonator (i.e. before loading via fibre coupling) so that the taper-cavity coupling system exhibits a high Q resonance with highly efficient coupling. Our first target of 2007 will be to design, model and manufacture cavities that meet those requirements. Once we achieve this, we aim to demonstrate an all-optical switch in a chalcogenide photonic crystal nanocavity operating at least at 10 GHz.

In parallel, we will pursue our efforts on "photosensitive post processing" and plan to demonstrate the first high-Q photonic crystal-based photo-written resonant cavity structure.

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