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 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 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.

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 ISL (International Science Linkage) grant awarded in 2007 to collaborate with the "Microphotonic and Photonic Crystals Research group" headed by Professor Thomas Krauss at the University of St Andrews ended in September 2010. This collaboration, which used 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 was a major success for photonic crystal-related activities (slow light and switch projects).

CUDOS hosted Prof. R.W. van der Heijden, from the Department of Applied Physics, Photonics and Semiconductor Nanophysics, Eindhoven University of Technology for three months. Prof. R.W. van der Heijden worked with Alvaro Casas Bedoya, Dr. Snjezana Tomljenovic-Hanic, Dr. Christelle Monat, Dr. Christian Grillet and Dr. Peter Domachuck on mode gap cavities induced by liquid crystal infiltration .

Goals for 2010:

After having successfully demonstrated in 2009 the writing of a high Q cavity, one of our primary goals was to continue exploiting AMTIR1 and its photosensitivity to demonstrate switching using a high Q PhC cavity and also create CROW-based (Coupled Resonators Optical Waveguides) slow light structures.

In parallel we wanted to extend our efforts on developing Ge_{11}-based glass that deposits much closer to the bulk index and develop new writing methods for PhC devices which enable devices of arbitrary length to be fabricated with no stitching errors. This is crucial in our efforts towards the creation of an 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.

Achievements and highlights for 2010:

In 2009 we demonstrated a high-Q (~125000) cavity in chalcogenide created using an optical exposure post-processing technique[2,3]. We used these cavities in 2010 to investigate the photosensitive and thermo-optic nonlinear properties of chalcogenide glass photonic crystal (PhC) cavities at telecommunications wavelengths[4]. We observed a photosensitive refractive index change in the near-infrared in AMTIR-1 ($Ge_{33}As_{12}Se_{55}$) material enhanced by light localization in the PhC cavity and resulting in a permanent blue-shift of the nanocavity resonance. Thermo-optic non-linear properties were thoroughly investigated by first, carrying out thermal bistable switching experiments (figure 1), from which we determined thermal switching times of 63μs and 93μs for switch on and switch off respectively and second, by studying heating of the cavity with a high peak power pulsed laser input, which showed that two-photon absorption was the dominant heating mechanism. Our measurements and analysis highlighted the detrimental impact of near-infrared photosensitivity and two-photon absorption on cavity based nonlinear optical switching schemes. We concluded that glass compositions with lower two-photon absorption, more stable properties (reduced photosensitivity like $Ge_{11.5}As_{24}Se_{64.5}$ glass) and with better heat conduction (by applying a conductive cladding for instance) were therefore required for nonlinear applications in chalcogenide photonic crystal cavities.

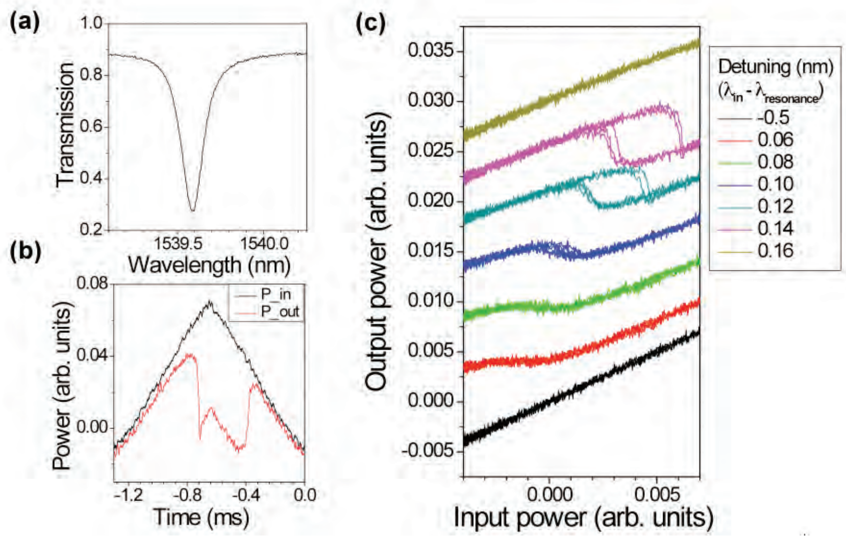

Fig 1: (a). The resonance spectrum for the thermal bistable switching measurement. Resonance linewidth (FWHM) = 0.148nm, λ_0 = 1539.597nm (b): Input and output power plotted as a function of time for a detuning of 0.14nm. Switching times were: t_{rise} ~ 63μs, t_{fall} ~ 93μs (c): Output power against input power for a range of detuning. Thermal hysteresis was observed for sufficiently large detuning.

During the past year ANU (Xin Gai, Tom White and Barry Luther-Davies) designed high-Q resonant cavities in a $Ge_{11.5}As_{24}Se_{64.5}$ chalcogenide glass PhC membrane completely embedded in a silica cladding[5]. We identified that the optimum structure required a narrowed PhC waveguide (Fig.2). Using FDTD simulations we studied the Q-factor and effective mode volume of this mode for different cavity lengths using a simple heterostructure formed by shifting the lattice period. We found that the intrinsic Q-factor increased from 40,000 to 3,500,000 by simply increasing the length of cavity. Even though the cavity is much longer than a traditional heterostructure, the mode volume V, where $V_{eff} = V\cdot(\lambda/n_{core})^3$ can be controlled below 3 when the Q-factor is 1 million. Using a more complex heterostructure design where the lattice shift is graded between the cavity and the mirrors led to Q-factors over 20,000,000 with V being < 4.

These structures are currently being fabricated.

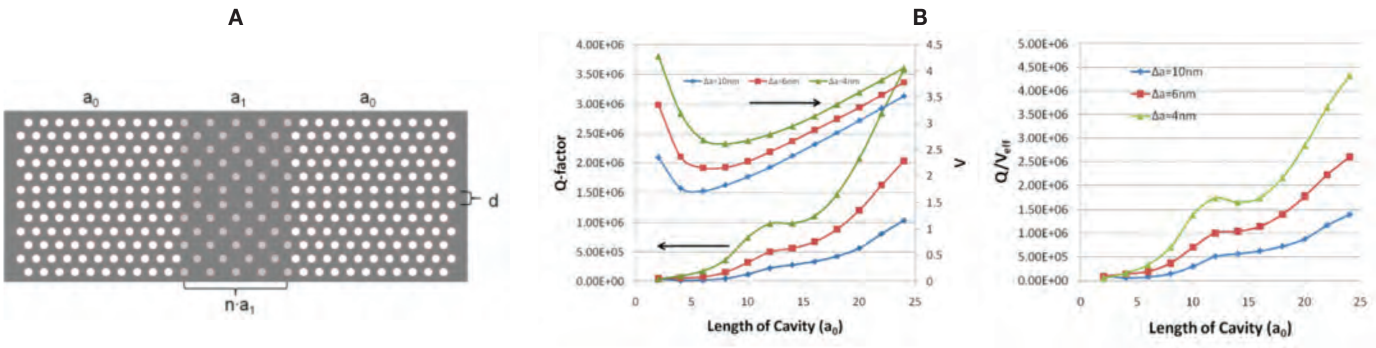

Fig 2: (a) Heterostructure cavity. a_0 is period of PhC. $\Delta a=a_1-a_0$ is the constant shift of cavity, a_1 is the period of cavity parallel to the waveguide direction. (b) The Q-factor and mode volume V. (c) The Q/V_{eff} ratio.

Another highlight of 2010 was the observation of bistable switching in Chalcogenide 1D Photonic Crystal Nanocavities. These 1D waveguide nanocavities[6] offer many benefits over 2D cavities, including ease of design and fabrication, small size, and the ability to confine light in material systems with index contrasts too low to support 2D photonic bandgaps[7,8]. Here we report the first demonstration of high-Q 1D photonic crystal nanocavities in the chalcogenide glass $Ge_{11.5}As_{24}Se_{64.5}$. This material has a high nonlinear figure of merit due to its low two-photon absorption and large Kerr nonlinear coefficient n^2, making it ideal for ultrafast switching applications[9]. The cavity geometry is shown in Fig. 3 (a), consisting of a 1D array of holes in a 580nm wide waveguide on a silica substrate. The cavity is formed by tapering the size and spacing of the holes in the centre of the PhC [4], to support a mode with calculated intrinsic Q-factor $>10^6$, and volume $\sim 0.7(l/n)^3$. To achieve high transmission through the cavity at resonance, we reduce the number of holes in the mirror such that the loaded Q-factor is much lower than the intrinsic one. Fig. 1(c) shows the measured resonance peak of a cavity with $Q=2.2\times10^4$.

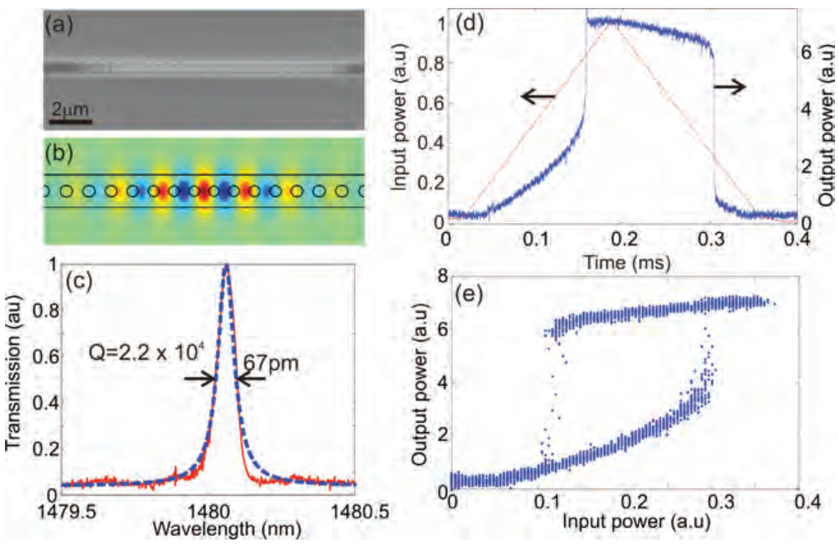

Fig 3: (a) SEM image of a fabricated chalcogenide wire nanocavity. (b) Calculated E_y field profile of the cavity mode. (c) Measured resonance transmission spectrum (solid red curve), and fitted Lorentzian with $Q = 2.2\times10^4$ (dashed blue curve). (d) Transmitted power (blue curve) while sweeping the input power up and down (red curve) with a CW laser detuned just above the resonance wavelength. (e) Bistability curves showing output power as a function of input power.

For CW input light, thermal nonlinearities dominate, and we observe bistable switching as shown in Fig. 1(d-e). The switching time is approximately 0.5ms, which is consistent with thermal switching times in 1D silicon nanocavities[10] and we estimate the switching threshold power to be <40mW. These results demonstrate the high fabrication quality of the cavities and the strong enhancement provided by the high-Q, low-volume mode. Again, reducing thermal effects is the key challenge to observing ultrafast Kerr switching in such nanocavities. This requires new cavity designs optimized for low thermal resistance[8] without damaging the optical properties. For example, a silica cladding would reduce the thermal effects by a factor of ~3, while still providing intrinsic Q-factors $>5\times10^5$, and even greater improvements could be achieved with other cladding or substrate materials. Combining these thermally-optimized, high-Q cavity designs with highly nonlinear chalcogenide glasses will provide new opportunities for low-power, ultrafast switching and optical signal processing.

In a project involving Ph.D. student Irina Kabakova, and Ben Eggleton and Martijn de Sterke, all-optical switching in an optical fibre Bragg grating was investigated both theoretically and experimentally. A number of different types of gratings were proposed and used for all-optical switching. We theoretically compared the properties of uniform gratings and of gratings with a π phase shift, both of which have a strong intensity dependence of the transmission[11]. We found that gratings with a π phase shift perform better both in terms of switching threshold and in terms of their susceptibility to the presence of loss.

We then experimentally studied all-optical switching in a fiber Brag grating with a π phase shift[12]. The phase shift leads to a small, high-Q cavity with a very narrow spectral transmission feature, which can be shifted by a relatively modest nonlinear effect leading to intensity dependent transmission. The switching in these structures exploits the ultrafast nonlinear Kerr effect which has a response time of tens of femtoseconds, which is so fast that it is negligible on the time scale of the experiments. The parameters in these experiments were chosen such that some of the switching dynamics would be revealed. An example of nonlinear shifting is indicated in Fig.4.a. It shows the transmission (normalized to the input) versus time at low intensities (blue) and high intensities (red). While at low intensities the peak transmission is approximately 20%, at high intensities it increases to close to 60%. Figures 4.b&c show measured and calculated normalized transmissions for different power levels. The saw-tooth-shaped response is characteristic of the switching process, while the subtle features on top of the sawtooth, appearing around 1 ns, are associated with the energy rearranging itself in the cavity. A drawback of this switching scheme is that the switching powers in these fibres tend to be quite high (roughly 1 kW), because of the weak nonlinearity of silica glass.

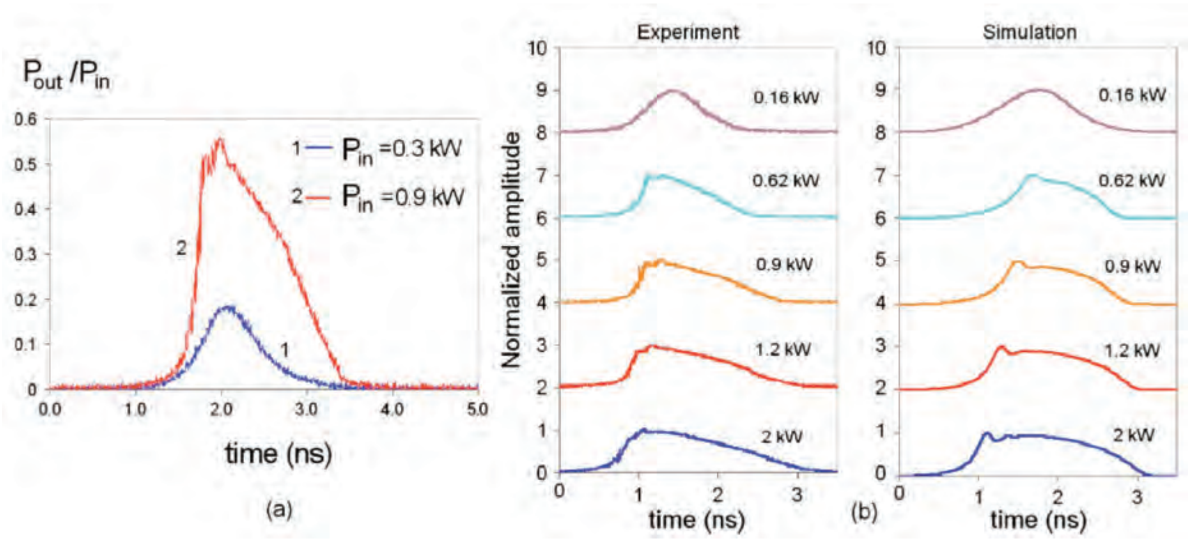

Fig 4: (a) transmission (normalized to the input) versus time at low intensities (blue) and high intensities (red). (b) measured normalized transmissions for different power levels (c) calculated normalized transmissions for different power levels.

More recently we have studied all-optical switching in bismuth oxide glass in collaboration with colleagues at the CRC in Ottawa, Canada. The Kerr nonlinearity in this glass is approximately 30 times larger than in silica glass, and because of the small effective mode area, these fibers are approximately 300 times more nonlinear than conventional fibres. This led to a reduction of the required switching power to tens of Watts for the gratings we studied.

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