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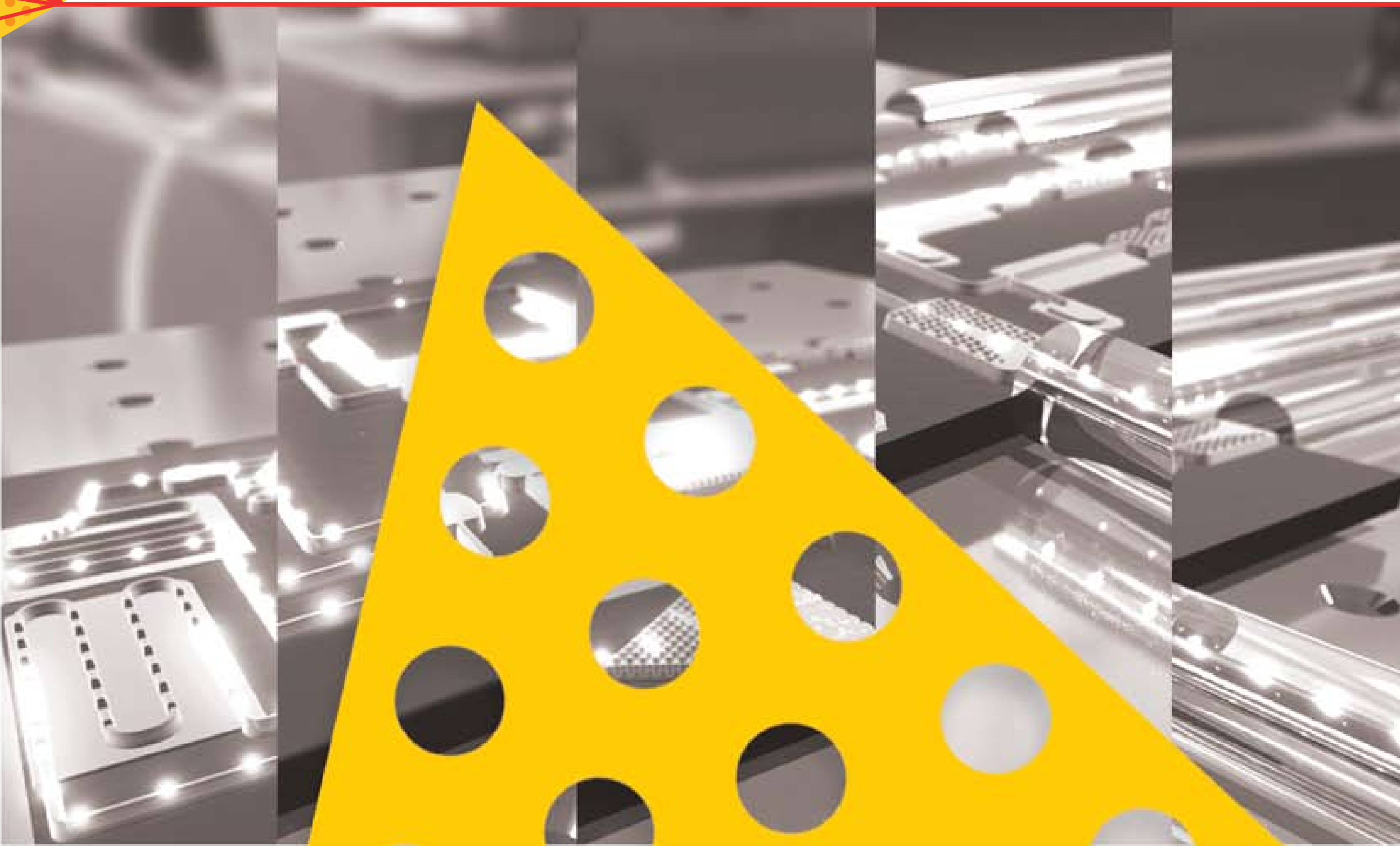

Annual Report 2007

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 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 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 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, now Macquarie) 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 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

In 2007, our international collaboration iwith the "Microphotonic and Photonic Crystals Research group" headed by Professor Thomas Krauss at the University of St Andrews was strengthened by the award of an International Science Linkages grant. This funding will allow the establishment of a formal collaboration 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; and with Australian partners at (CUDOS), Sydney and the Australian National University (ANU). Our goal is to use advanced electron-beam fabrication facilities at the University of St Andrews (St Andrews) to write PC 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 (Glasgow University group headed by Prof. Richard Delarue and Dr. Marc Sorel and the Politecnico di Milano group headed by Dr. Andrea Melloni) have been initiated and should lead to a collaborative effort to develop processes for the fabrication of nanowires and ring resonators in chalcogenide.

We initiated several collaborations aiming at developing new approaches to integrated devices based on the heterogeneous integration of different materials with specific optical properties, based on our capability for deposition and processing of low loss chalcogenide material on different substrates. Opportunities for devices built on these novel platforms are in areas as diverse as nonlinear photonic signal processing, QED devices and bio-sensing. As an example, samples of silicon nanowires produced at Ghent and Karlsruhe have been sent to ANU to validate the possibility of depositing a chalcogenide glass layer over prefabricated Si devices.

We also benefited from a collaboration involving Dr. Sjnezana Tomlenovic-Hanic and the group of Professor Noda at Kyoto University. This group is a leading international laboratory and pioneered the race towards very high Q cavities in photonic crystal. Dr Tomlenovic-Hanic visited Noda's group and numerically demonstrated that a heterogeneous multilayer design that relies on depositing a strip of material on a silicon-based PC slab could lead to post-processed high Q cavities.

In the same vein, we established a collaboration with Prof. Jelena Vuckovic' group at Ginzton Laboratory, Stanford University. Andrei Faraon, a PhD student at Stanford University, visited Sydney University in 2007. In collaboration with ANU, he developed a process to locally change the refractive index in planar optical devices by photodarkening 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.

Goals for 2007

For effective switching we need to increase the inherent resonator Q (i.e. before loading via fibre coupling) and improve the coupling between the "outside world" and the resonator (via the tapered fibre). Our aim is to obtain a taper-cavity coupling system exhibiting a reasonable high Q factor with highly efficient coupling.

Our goal for 2007 focused mainly on establishing "recipes" (in terms of design, modelling and fabrication) to manufacture cavities that meet requirements, eventually aiming at demonstrating an all-optical switch in a chalcogenide photonic crystal nanocavity operating at least at 10 GHz.

Achievements and highlights for 2007

Our 2006 achievements paved the way for our 2007 goals: we achieved, efficient coupling into photonic crystal nanocavity resonators in chalcogenide [1,2] manufactured either by FIB milling [3] or by e-beam lithography plus chemically assisted ion beam etching [4]. Our approach to efficient coupling of light into the high-Q PC cavity is evanescently via a low-loss fiber taper (Fig. 1) [5,6]. Q values as high as 10,000 were measured for L3 type cavities.

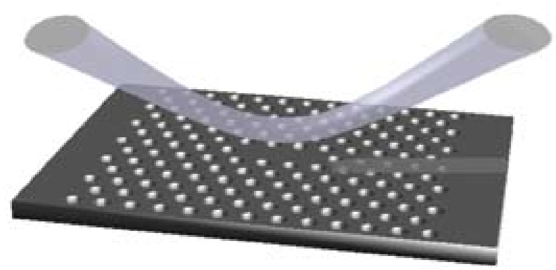

Fig 1: Coupling scheme used: schematic showing the coupling from a tapered fibre to PhC nanocavity

To date, some of the highest experimentally demonstrated Q-factors in a PC cavity have been obtained in double-heterostructure type cavities [7]. These cavities have typically been formed by elongating the PC lattice in a short section of a 'W1' waveguide. At present, the geometry of such structure is finalized at the stage of fabrication, requires extreme control over the fabrication to achieve high-Q cavities (see manufacturing paragraph) and there is very limited scope for post-processing or tuning the properties of the cavity. The enormous precision required to realize these sophisticated nanostructures eventually becomes a limiting factor in achieving high-Q cavities.

In addition to pursuing our efforts on the manufacturing side, we thus investigated alternative ways to create *a posteriori* reconfigurable high Q cavities in a chalcogenide PhC platform. We took advantage of the 'mode gap' mechanism which provides confinement along the waveguide axis of the W1 created by any means which locally increases the effective index of the waveguide to induce a cavity.

We numerically demonstrated that ultrahigh-Q cavities, Q~10^6, can be designed in a chalcogenide-based PC slab using the photosensitivity of this material [8]. Spatially selective post-exposure to light in a photosensitive uniform photonic crystal slab alters the refractive index permanently and can yield high-Q nanocavities [9]. 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. The results are comparable with the best results reported to date in silicon, despite the modest refractive index of chalcogenide glass, n=2.7, when compared with silicon $n\approx3.4$.

We also showed that high Q cavities could be achieved from fluid infiltration [10]. Using evanescent probing we validated this idea and experimentally demonstrated that we could create double heterostructure type cavities via selectively filling holes [11]. This approach offers a versatile way to write microcavities by choosing (a) the width of the infiltrated PC area (figure 2), and (b) the refractive index of the infused liquid. In addition, the reversible nature of these double-heterostructures enabled by fluid mobility offers a "rewrite" potential, paving the way for reconfigurable microphotonic devices and integrated optical sensing architectures.

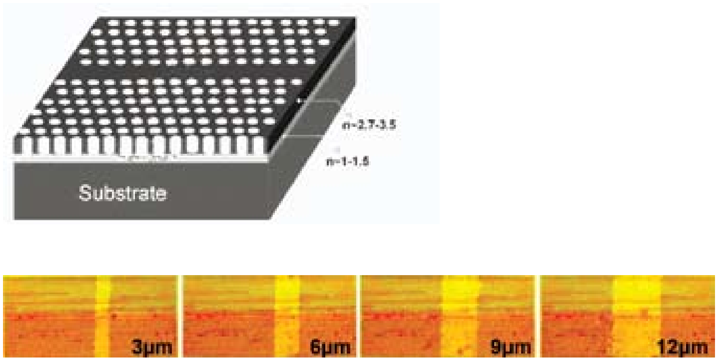

Fig 2: Top: Schematic of a DH cavity created from the infiltration of liquid into a defined area of a photonic crystal lattice. Bottom: A W1 PCS structure exhibiting increasingly wider microfluidic DH cavities.

Recently, in collaboration with Professor's Noda Group at Kyoto University, we introduced a multilayer design that relies on depositing a strip of material on a silicon-based PC slab, see Fig. 3 (a) and (b) [12]. Though a variety of materials can in principle be used, polymers are particularly convenient because of the easy integration with other optical and electronic components. Quality factors of order Q~10^6 can be obtained by depositing a polymer strip on the top surface of the silicon slab. A high-Q cavity is even achievable if the holes of the slab are filled with polymer as shown in Fig. 3 (c). This novel design can be implemented at any time after fabrication, and, depending on the kind of polymer used, can be additionally tuned using either photosensitivity or the electro-optic effect.

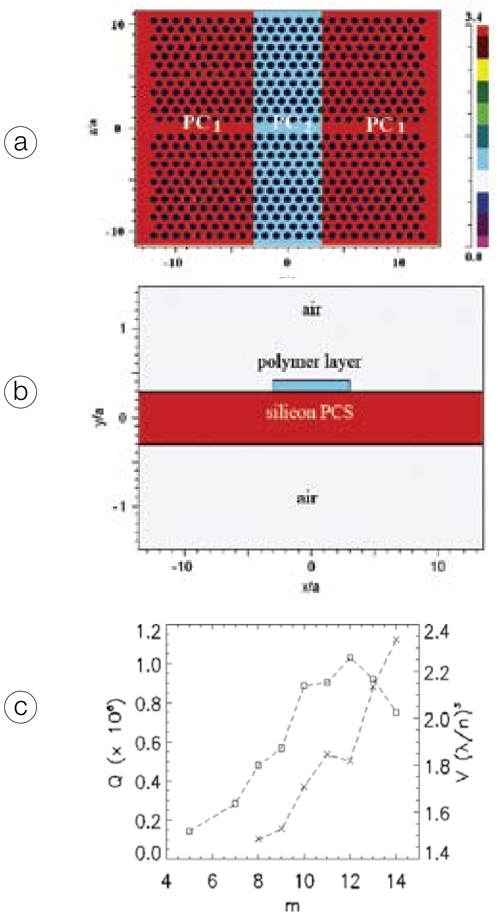

Fig 3: (a) Top view of a double heterostructure cavity; PC2 has slightly higher average refractive index than PC1. The black holes are air holes. (b) Silicon slab with polymer strip on the top; (c) total Q (rectangles) and modal volume V (crosses) versus the cavity width m, the inset shows the PCS cross-section.

One of the highlight of 2007 was a collaborative effort between Stanford University and ANU in which the experimental tuning of GaAs-based photonic crystal cavities by up to 3 nm at 940 nm was achieved by using the photosensitivity of a thin chalcogenide layer deposited on top of the GaAs cavities [13]. The linear three-hole defect PC cavities were first fabricated in a 150 nm thick GaAs membrane containing a central layer of InAs quantum dots. Arsenic trisulphide films with thickness between 30 nm and 100 nm were deposited onto the photonic crystals using thermal evaporation at ANU. After deposition, the resonance wavelength of the cavities was 940 nm. The experiment was performed at cryogenic temperature (T < 60K) to obtain luminescence from the embedded InAs quantum dots, as needed for quantum information processing applications. A 543 nm HeNe laser (1 µW) focused to ~1µm^2 was used to photodarken the As_2S_3 layer. We observed cavity wavelength shifts of 1nm, 3 nm and 4 nm for samples where the As_2S_3 thickness was 30 nm, 60 nm and 100 nm. After tuning, the quality factor Q of the cavities was ~4500 for samples with 30 nm and 60 nm As_2S_3. The smallest area that can be locally tuned is limited by the focus size of the laser beam. The locality of the technique allows for independent tuning of interconnected optical components on PC chips. The method is not only suitable for GaAs devices, but can possibly be implemented with other materials including silicon nanophotonic circuits.

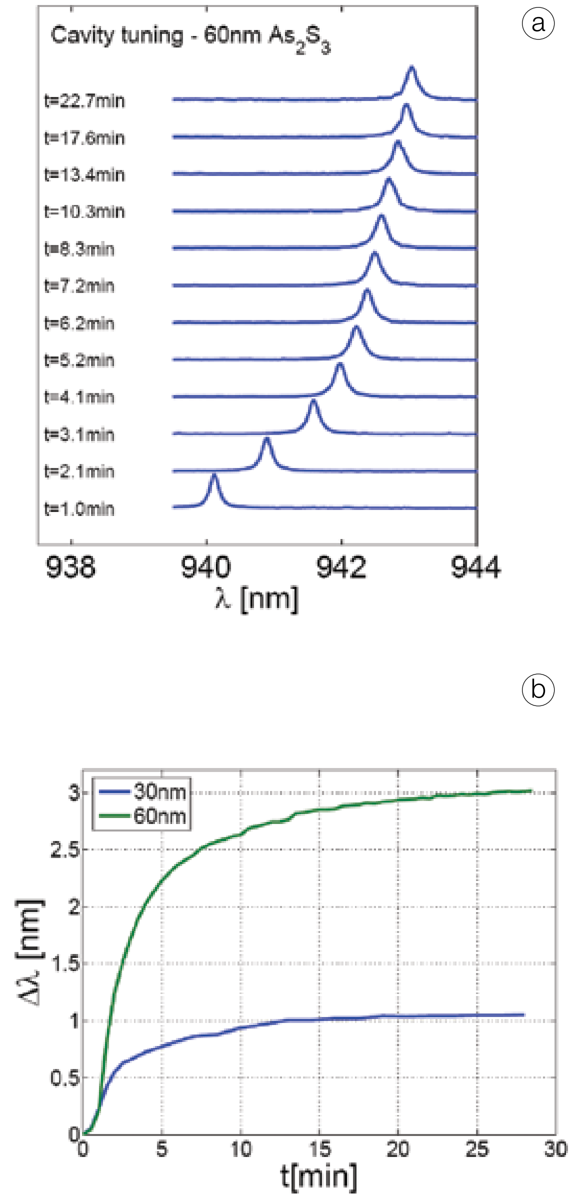

Fig 4: (a) Spectra showing the shift of the cavity resonance because of the photodarkening of the 60nm thick chalcogenide layer. (b) Time dependence of the cavity resonance for 60nm and 30nm As_2S_3

We continued our study of Fano resonances in PC slabs. The effect on the broadening and location of Fano resonances resulting from a Gaussian beam incident on a photonic crystal constructed from chalcogenide glass supported by a thin layer of silicon nitride was investigated using an existing plane wave-based code. The Gaussian beam was represented as an expansion of plane waves of specific polar and azimuthal angles of incidence. Preliminary results show that relative to earlier plane wave simulations, the investigated resonance broadened significantly and shifted position to lower wavelengths.

Fabrication

After refining our system to correct drift in the focused ion beam mill used for producing accurate 2D photonic crystal patterns in chalcogenide films (positioning error is now estimated to be 1 nm down from 5 nm), we successfully developed a new carbon coating approach to control sample charging during milling [14]. Before optical testing, the carbon layer was easily removed by exposure to an Ar/O_2 microwave-excited plasma, unlike earlier work with Au which required wet etching to remove. Figure 5

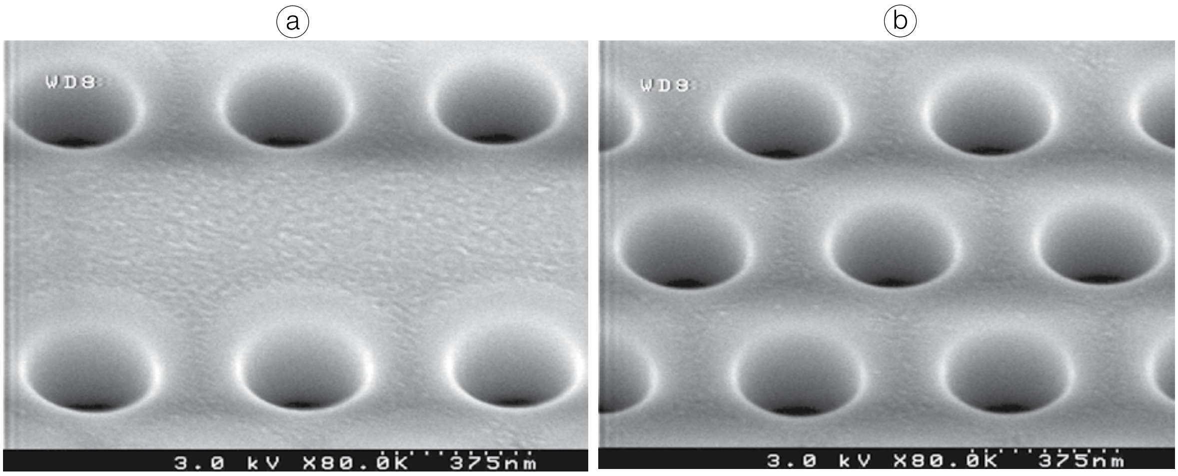

Fig 5: SEM micrograph of a) a photonic crystal L3 cavity b) a photonic crystal waveguide fabricated by FIB milling

presents SEM images acquired after carbon removal. The roughness observed on the top surface was present before FIB milling. It serves to demonstrate the polishing effect of the FIB, near the edges of the holes.

In collaboration with the Kaist group of Professor Yong-Hee Lee and former CUDOS student Yinlan Ruan, it has been demonstrated that standard e-beam lithographic process combined with Chemically Assisted Ion Beam Etching (using Cl_2 and Ar etchant) could also be used to create 2-D chalcogenide glass photonic crystals. 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.

Targets for 2008

So far all our 2D chalcogenide PC structures have been realized in a single PhC membrane configuration. In 2008 we will begin the transition from single device in a single membrane towards an actual integrated photonic circuit in chalcogenide with cascaded photonic crystal elements (PC cavities and waveguides) coupled to a conventional TIR circuit (integrated nanowires). To achieve this, strong efforts will be devoted to the development of a fabrication process for realising chalcogenide photonic crystal using e-beam lithography technique both at ANU and St Andrews.

We will pursue our efforts in 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 PC 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, a new range of alternative resonators in chalcogenide will be investigated. Chalcogenide microspheres, ring, toroidal rings will be created and their potential impact in areas as diverse as sensing, MIR sensing, all optical switching assessed.

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