CUDOS

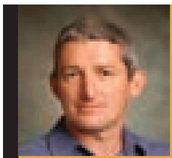
Photonic Material and Micro-fabrication Program

Annual Report 2004

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

An Australian Research Council Centre of Excellence

Photonic Materials and Micro-fabrication Program



Program Manager: Michael Withford

The objectives of this program are to develop platforms for the production of microphotonic devices for optical signal processing, including:

- **New approaches to microfabrication of photonic crystalline structures made by self assembly of spherical sub-micron particles and also by machining, using a focused ion beam, a periodic array of holes in a planar silicon substrate.**
- **New, highly nonlinear optical materials – chalcogenide glasses. These have been produced both in bulk and also as thin film substrates suitable for processing into planar waveguide and other 2D structures.**
- **A novel approach based on nonlinear absorption of high intensity femtosecond laser pulses for writing optical waveguides in bulk material.**

Combinations of these platform technologies have been used to demonstrate a number of key precursors to optical processing using nonlinear optical effects. A number of preliminary results for particular applications are reported elsewhere, particularly in the Optical Devices and Applications program. A key result reported here is the production of nonlinear phase shift of 3.5 π in a chalcogenide rib waveguide 60 mm in length.

The activities in the program are organised into two projects. The laser micro-machining and self-assembly activities are headquartered at Macquarie, while the nonlinear materials and focused ion beam lithography project is based at the ANU. The outcomes from both project are strongly coupled to projects in the Optical Devices and Applications program, and have strong theoretical support from the Photonic structures and Microphotonics programs.

Mick Withford

Laser Microfabrication and Microengineering Project

Project Leader: Mick Withford

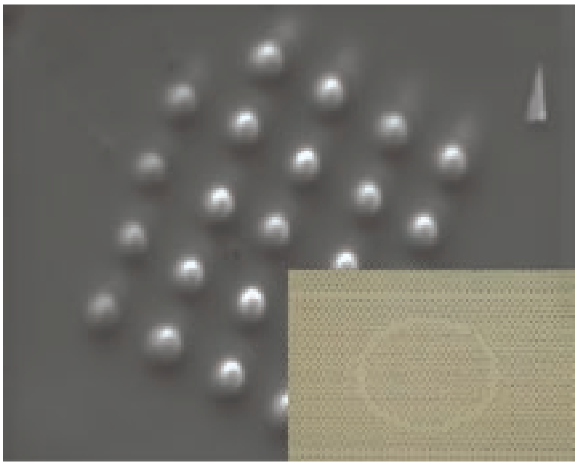
Our aim is to develop advanced methods for micro-engineering a range of linear, nonlinear and high gain materials using both "top down" (i.e. wet etching, laser material removal and modification) and "bottom up" (eg. self assembly) micro-processing techniques Our goals include developing novel methods for direct writing optical waveguides and compact waveguide amplifiers, planar photonic crystals and quasi-phase matched materials for incorporation into integrated photonic devices. These efforts have been strengthened considerably by the completion this year of a new Photonic Microfabrication Laboratory at Macquarie and a new scanning tunnelling microscope.

The new CUDOS Photonic Microfabrication Laboratory at Macquarie.

Fabrication of 2-D photonic crystal slab waveguide structures using novel laser microfabrication techniques

Lee, Withford, Dawes

Advanced laser micro-processing techniques are being developed that permit direct-write fabrication of planar photonic crystal structures. In particular, we are inscribing microstructures into polymer films that are then used as templates during fabrication of photonic crystals by casting, self assembly or vapour deposition. This stepwise manufacturing method has advantages over other methods because combined optical fibre/photonic crystal devices can be fabricated using this technique.



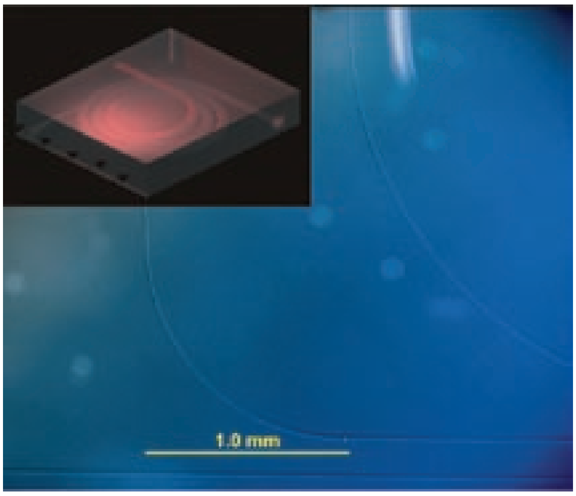
▲ **Planar photonic crystal structure fabricated using micro-casting and sacrificial templates. Inset shows a planar ring resonator design generated using direct write methods.**

A highlight of the year has been the development of a novel processing method employing sacrificial layers that allows the fabrication of periodic features as small as 200 nm in diameter with aspect ratios of 1:20.

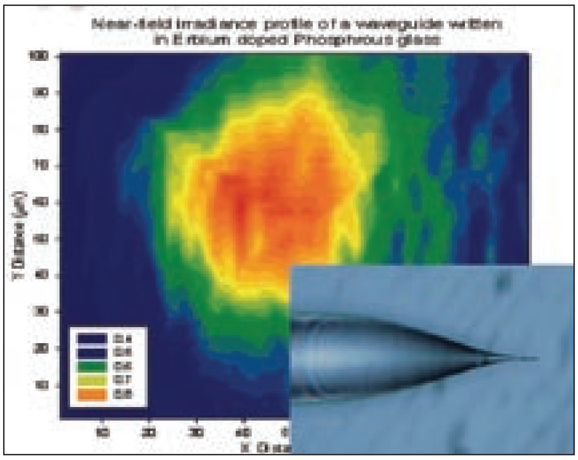
Femtosecond laser direct writing of waveguides in doped glasses

Ams, Little, Marshall, Piper, Dawes, Withford

A tightly focused ultrafast laser beam can be used to modify the refractive index of bulk glass. In this project we utilise this principle with a computer-controlled scanning mechanism to write waveguides and more complex photonic devices inside passive and active glasses. Highlights of this year include the successful demonstration of 50:50 couplers in undoped phosphate glass and single mode waveguides in erbium doped phosphate glass. A new writing technique has been developed that is well suited for 3D integrated waveguide optics. This technique will enable the fabrication of highly compact waveguide amplifiers and oscillators inside these active glasses.



▲ **Phase contarst image showing optical waveguides written inside silica uing the focused output of an ultrafast laser. A conceptual view of our goal, an ultra-compact waveguide amplifier, is shown in the inset.**



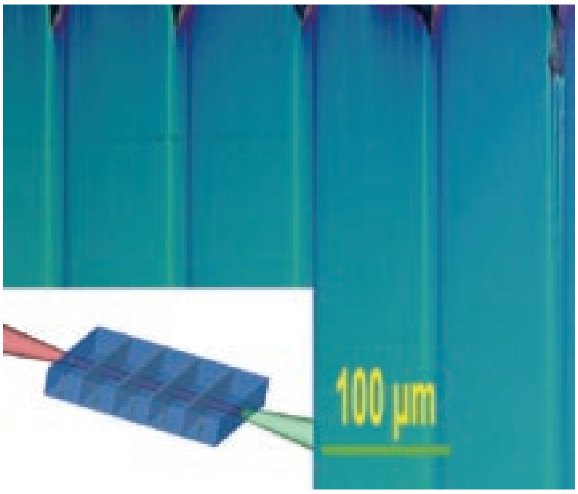
▲ **False colour image of the mode field propagating through a waveguide written in erbium doped phosphate glass. This image was recorded with a tapered fibre tip (inset), with effective aperture of 350 m, using near-field scanning optical microscopy (NSOM).**

We have mapped the near field output from these femtosecond-written waveguides using a surface near-field optical microscope specifically tailored to this application with fibre tips optimised for evanescent coupling and an additional rotation capability for improved divergence measurements.

Novel techniques for fabricating periodically poled lithium niobate

Johnston, Withford

During 2003 we showed that topographical surface electrodes in periodically poled lithium niobate (PPLN) formed by nanosecond laser machining evolve differently to those made with conventional lithographic methods. In particular, domain inversion originates from a single nucleation spike whereas other approaches give two nucleation spikes that eventually merge. This approach can potentially produce shorter periods and offer better control over domain growth. This year we have focused on developing femtosecond laser micro-processing methods. These have enabled us to



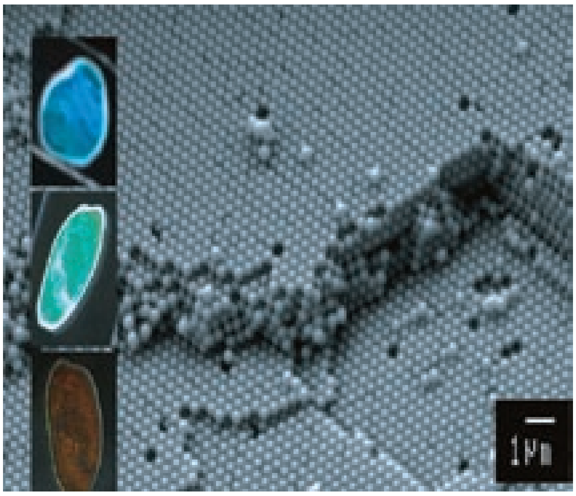
▲ **Cross-sectional view of periodically poled lithium niobate fabricated using the topographical electrode technique. Inset shows a schemetic illustrating frequency conversion using one of our samples.**

produce quasi phase matched structures with poled regions as small as 4 micrometres, for applications in novel optical processing.

Self assembly of photonic crystals using luminescent microspheres

Stewart, Marshall, Withford

One of the most successful methods for making photonic crystals is a "bottom-up" approach using evaporative self-assembly of microspheres. Well known examples of photonic crystals fabricated in this way are opals exhibiting a visible bandgap. In this project novel opalline structures were designed and fabricated from solutions of microspheres. A key outcome in 2004 was the successful design and fabrication of an opal with a bandgap overlapping the luminescence of embedded micro-spheres. This provides an attractive experimental approach to studying the radiation dynamics of 3D photonic crystals and developing hybrid photonic crystal devices.



▲ **Electron micrograph of a self assembled plymer opal with a period of 400 nm. Several bandgaps, at blue, green and red wavelengths (insets), are observed for this opal.**

Nonlinear Materials Project

Project Leader: Barry Luther-Davies

In this project we are developing innovative approaches to producing chalcogenide glasses, which are highly nonlinear optical materials. The glasses are being processed to form waveguides and photonic crystals by a computer-controlled focused ion beam which selectively removes material from the surface of a planar substrate. The ability to build photonic structures using nonlinear optical material is a key technology platform for CUDOS.

We have used this approach to produce high quality two dimensional photonic crystals in silicon as well as chalcogenide glass, and also to machine a Bragg grating into the upper surface of a rib waveguide. Outcomes from this work feed into other CUDOS projects, especially those led by Dr Blows on Nonlinear Waveguides and Devices and Dr Moss on Photonic Integrated Circuits and Planar Waveguides.

Barry Luther-Davies

Production of bulk samples of chalcogenide glass

Smith, Richardson (CREOL)

The glass chemistry facility at ANU was established as a key part of the CUDOS research infrastructure to provide a wider range of chalcogenide glasses than are available commercially. Using our facility we can fine tune the glass composition to enhance properties such as the third-order nonlinearity, the glass transition temperature, the band edge; etc. A high

▲ **Anita Smith in the new glass production laboratory at the ANU.**

quality boule of Arsenic Trisulphide was successfully produced in November as a test of the equipment. Dr Congji Zha was appointed as a glass chemist to work with Anita Smith in the preparation and characterisation of materials.

Film production by pulsed laser deposition

Luther-Davies, Rode, Gamaly, Jarvis, Kolev, Madsen (PhD student), Duering (Fraunhofer ILT)

Ultra-fast pulsed laser deposition remains our major tool for producing high quality chalcogenide glass films suitable for waveguide fabrication. Obtaining films of sufficient quality remains a challenge especially when long waveguide structures are required for applications like Raman amplifiers. As a result we continue with fundamental studies of ultra-fast pulsed laser deposition to identify the factors that control the quality of films deposited using this method.

This year we identified several key physical processes that can affect both the ablation threshold and the state of the laser-ablated plume produced by high repetition rate picosecond pulses. In particular we showed that non-thermal ablation, which is normally only associated with femto-second pulses, in fact occurs when using pulses as long as several tens of picoseconds.

We demonstrated that the phase state of the plume is adversely affected by the presence of low intensity wings on the beam used for ablation. These allow condensation to occur in the plume, resulting in contamination by macroscopic particles which can be deposited on the sample surface. To alleviate this, we changed the operating parameters of our high power laser system to provide higher energy single pulses which can be spatially shaped to provide a flat-topped intensity distribution at the target surface.

Chalcogenide waveguides

Ruan, Madden, Luther-Davies, Weitang Li

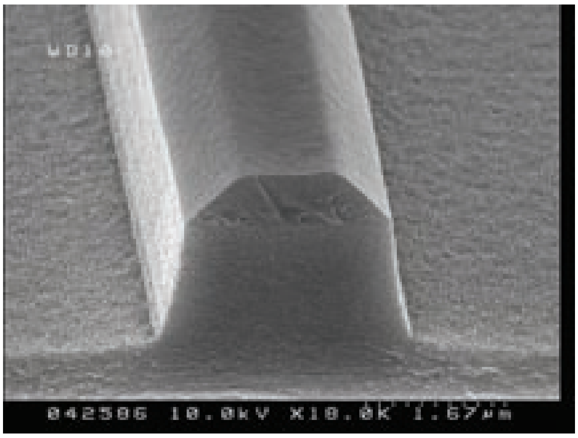
Highly nonlinear optical waveguides are needed to develop compact regenerators, amplifiers and other nonlinear photonic devices. Chalcogenide glasses offer considerable promise with their wide range of transparency and high nonlinearity. We produced rib waveguides in Arsenic Trisulphide films with vertical and relatively smooth sidewalls (hence low loss) using plasma dry etching. The losses determined by the cut back method are as low as 0.25 dB/cm for guides with width around 4 μm. We fabricated single mode waveguides up to 60 mm long with mode areas less than 8 μm^2.

Nonlinear phase changes of up to 3.5 π were seen in these waveguides consistent with spectral broadening of 10 ps pulses from an optical parametric oscillator at 1530 nm with peak powers of several hundred watts at 1530 nm. We can improve on this already significant result by reducing optical losses to below 0.1 dB/cm, enabling us to increase the optical path length and achieve strong nonlinear response at peak powers of around one Watt.

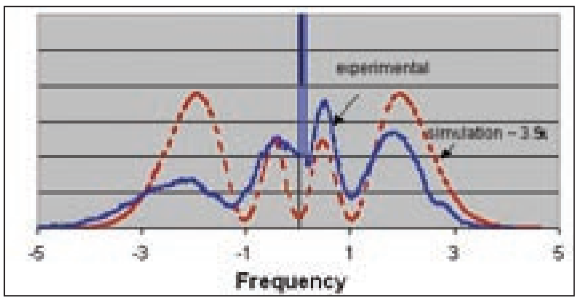
2-D Photonic crystals in chalcogenide glasses using focused ion beam milling

Freeman, Madden, Luther-Davies, Krolikowski

A rich range of optical processing opportunities arises when conventional waveguides are integrated with photonic crystals.

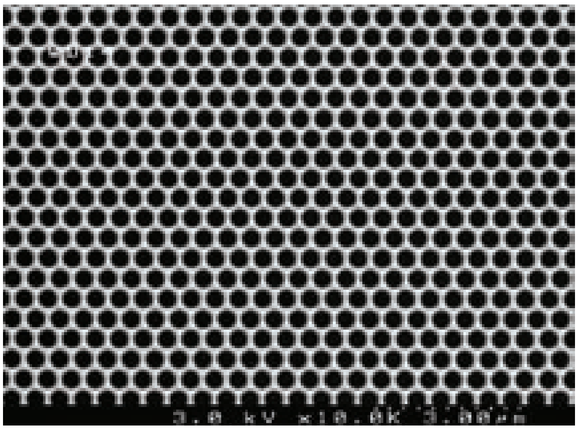


▲ **SEM micrograph showing the profile of As_2S_3 waveguides etched by ICP using a photoresist mask.**

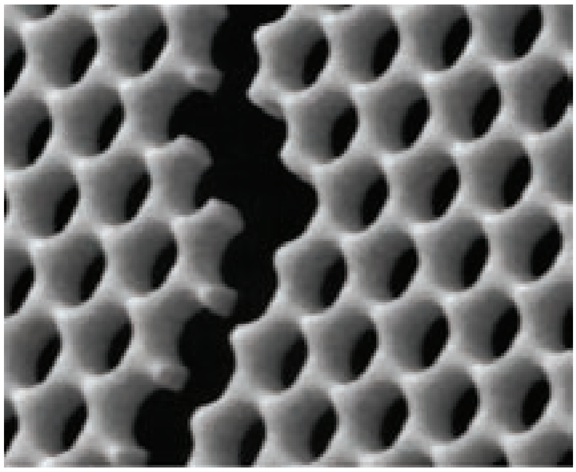


▲ **Output spectrum from a 6cm long As_2S_3 waveguide showing spectral broadening due to self phase modulation consistent with a nonlinear phase shift of ≈3.5π. The input pulses were generated by an pulsed optical parametric amplifier seeded with a CW source which results the CW spike in the spectrum at the centre frequency.**

To address these opportunities we are developing techniques to fabricate high quality photonic crystals in chalcogenide films as well as conventional low loss waveguides. During 2004 we successfully produced 2-D lattices in free-standing AMTIR-1 chalcogenide glass films using the novel approach of focused ion beam (FIB) milling. Our FIB system consists of an Orsay Physics “Canion 31M Plus” FIB mounted to the specimen chamber of a JEOL JSM-6460LV scanning electron microscope (SEM). The FIB produces a tightly focused beam of Ga+ ions, which can be deflected electronically over a field size of over 0.5 mm, controlled via an external analogue input. We developed a pattern generator and control software to enable fully flexible 2D scanning.



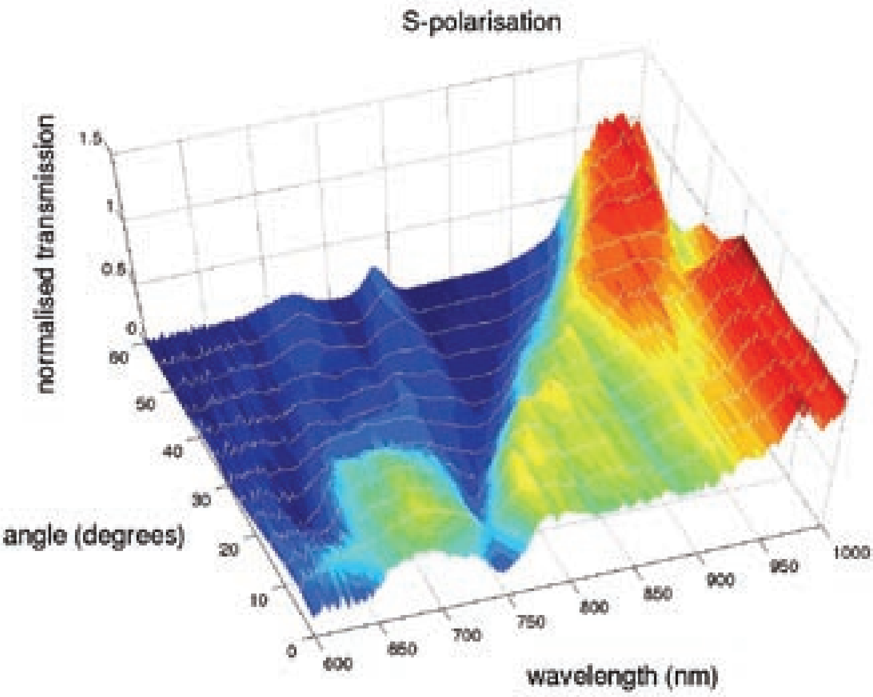
▲ **A SEM image of a photonic crystal lattice milled into a 300 nm thick AMTIR-1 glass film using the FIB. The RATTICE CONSTANT is 500 nm and hole diameter 300 nm.**



▲ **Image of a broken section of the Photonic crystal lattice.**

Photonic crystal lattices were milled either in free standing AMTIR-1 films mounted in TEM grids or into films supported by 50 nm thick SiN films produced on a Si wafers. Triangular lattices with periods between 500 nm and 1micron were fabricated with the largest lattices containing over 46,000 holes and extending over an area about 100 µmx100 µm. Each hole requires a 200 ms exposure at 85 pA of beam current, corresponding to a milling rate of 6.36 µm3/min. The results (see images) demonstrate that spectacularly high quality 2D crystals can be produced with this technique.

We have probed optical resonances in these films in the $\Gamma - K$ plane to provide information on the band structure.



▲ **The optical transmission of the lattice shown above as a function of wavelength and angle of incidence showing features representing the band structure of the lattice.**