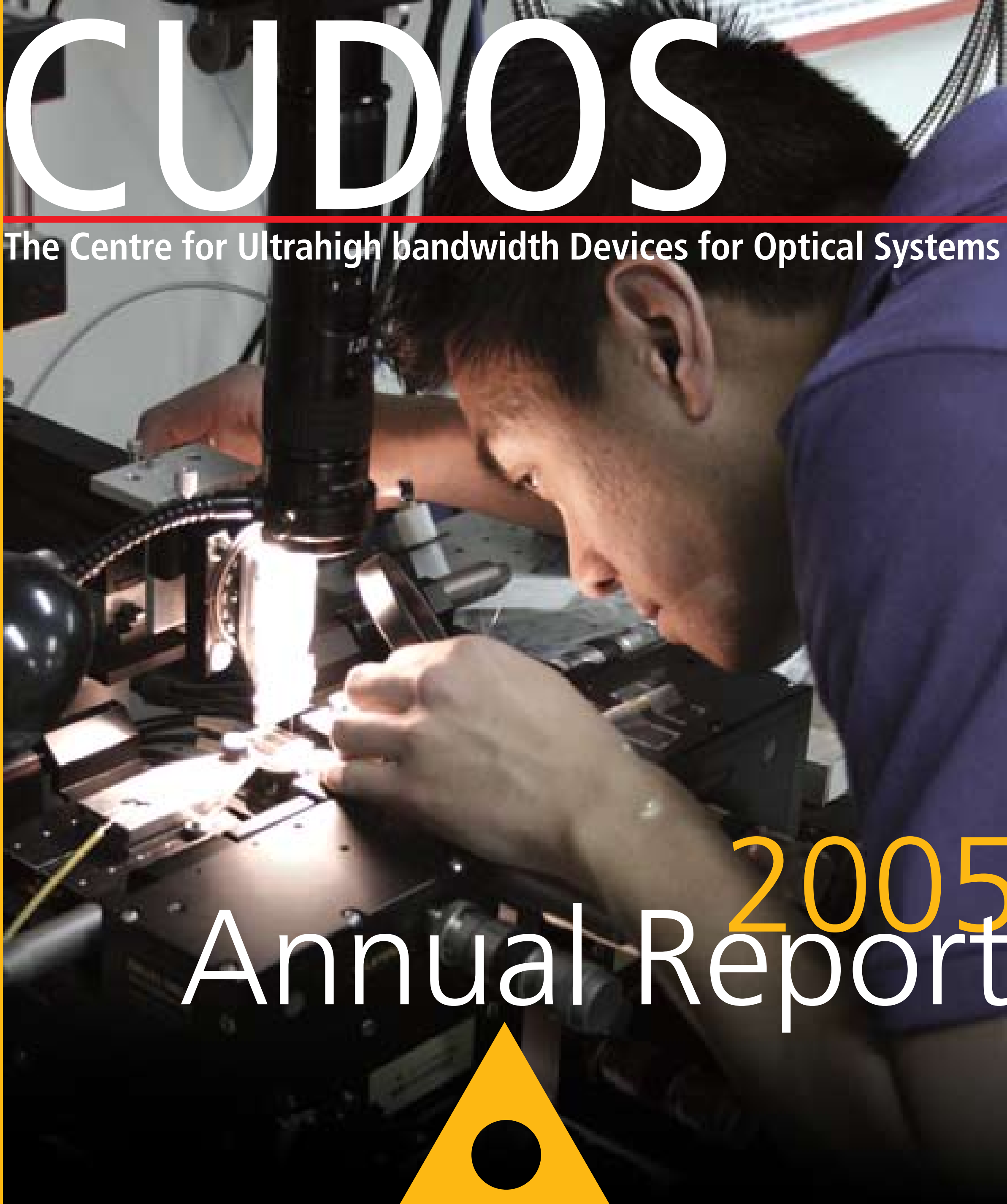
CUDOS

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



2005 Annual Report

ANU Node Report (Laser Physics Centre)

Barry Luther-Davies

ANU Laser Physics group

Researchers in the Laser Physics Centre are involved in the fabrication of planar waveguide devices and photonic crystals in chalcogenide glasses and also supply structures and devices to other researchers in CUDOS – primarily those at the University of Sydney. The research involves 8 faculty members and 3 PhD students supported by six technical staff with funding from several programs of the Australian Research Council and the ANU.

The Centre's focus on using chalcogenide glasses to make photonic devices is motivated by the attractive optical properties of this unusual class of material. The glasses have sufficiently high refractive index (2-3) to make them suitable for fabricating high index contrast waveguides as well as photonic crystals. They also have relatively large third order optical nonlinearity which is essential for all-optical devices. The main challenge with chalcogenides arises from the fact that they are not as well investigated as oxide glasses, and contain weak chemical bonds that allow structural rearrangement within the glass matrix in response to external stimuli. This effect is particularly pronounced in chalcogenide glass films used for device fabrication. Thus a major challenge exists to identify glasses and films that can be used to fabricate stable all-optical structures.

The new staff members who joined CUDOS in late in 2004 and early 2005 (Choi, Wang, Zha) provided a new impetus to our research. The new glass chemistry facility, operated by Congji Zha and Anita Smith, commenced production of chalcogenide glasses with different compositions; supporting a program to optimise glass properties for photonic applications. The work of our glass chemists benefits from our relationship with CUDOS partner investigator Professor Kathleen Richardson's group now at Clemson University in the USA, who are the leading international experts in chalcogenide glass. Amrita Prasad joined as a PhD student in March and is involved in extensive characterization of these new glass samples.

The arrival of Dr Rongping Wang provided additional materials expertise that we are applying to understand the characteristics of chalcogenide films that are often quite different from bulk glass. We are hoping to identify strategies to relax the bond structure of the films back to that of the more stable bulk form of the material.

Device fabrication is challenging because virtually no work has been performed outside CUDOS to structure chalcogenide films into photonic devices. The ultra-fast pulsed laser deposition (UFPLD) approach, invented by Luther-Davies, Gamaly and Dr Rode at ANU, delivers high quality glass films with properties generally superior to those produced by thermal evaporation used elsewhere. Drs Steve Madden and Duk Choi have contributed their considerable expertise gained in industry to device fabrication and are developing reliable processes tailored for these glasses. Optimised photolithography and dry etching is leading to devices with improved quality and repeatability.

Our approach to fabricating photonic crystal membranes in chalcogenides is somewhat unusual. Photonic crystals are periodic structures that must be fabricated with a combination of exceptional dimensional accuracy (at the few nm level) and with optically smooth interfaces. E-beam lithography combined with dry etching is generally used to make structures in silicon but relies on the vast knowledge accumulated from the processing of silicon chips to achieve these demanding requirements. Since chalcogenide processing is nowhere near as well developed, we have chosen to use a single step process based on the use of a customised focused ion beam mill to make photonic crystals. PhD student, Mr Darren Freeman, with the assistance of Sally Stowe from the ANU's electron microscopy unit, is making exceptional progress using this approach.

In August we said goodbye to one our PhD students, Ms Yinlan Ruan, who successfully completed her project on Chalcogenide Planar Waveguide Devices for All-optical Processing. Yinlan has joined Professor Monro's new group at the University of Adelaide.

ANU Node Report (Nonlinear Physics Centre)

Yuri Kivshar

Researchers of this team are involved into both theoretical and experimental studies of the fundamental physics of periodic photonic structures, including the basic properties, stability, generation and propagation of nonlinear localized modes in optically-induced photonic lattices, arrays of optical waveguides, and all-optical switching and routing in photonic-crystal circuits. The research involves 5 staff members and 4 PhD students supported by 1 technical staff.

Our main concept is to employ our deep expertise in solving various problems of nonlinear physics to analyse the key projects of the light transmission and routing in photonic crystals, and other types of periodic photonic structures. The main goal is twofold. First, we predict and analyse the most fundamental and intriguing effects in photonic structures that may be used for logical and switching manipulation of light beams and pulses. Second, we provide a solid theoretical background to several experimental groups, including our experimental team headed by Prof. Krolikowski and Dr. Neshev. In addition, we analyse different ways for optimizing subwavelength photonic-crystal waveguides, and study different nonlinear devices based on the tunable nonlinear Fano resonance and its generalizations. The main challenge is the development of semi-analytical tools that allow for a very efficient optimization of realistic photonic-crystal circuits.

With the aim to expand into the experimental research, we have invited Robert Fischer from Germany who with an overseas scholarship will become our new PhD student in 2006. Robert's expertise is complementary to ours and will allow initiation of new projects. As evidence of our success in the experimental projects, our work on tunable negative refraction in photonic lattices has been selected for the December special issue "Optics in 2005" of Optics & Photonics News that highlights the most exciting optics research to have emerged in the preceding 12 months.

Our theoretical group is among the strongest in the world. The studies carried out in 2005 included research on spatial gap solitons in periodic photonic structures as well as light propagation in quasi-one-dimensional waveguide circuits embedded in 2D and 3D photonic crystals for switching and routing logic operations. We experimentally demonstrated novel linear and nonlinear effects including dynamic tunability of Bloch wave dispersion, negative refraction, optical Bloch oscillations and Zener tunnelling.

Macquarie Node Report

Michael Withford

Macquarie Group

The Macquarie University node has two main research thrusts: laser written structures inside a range of optical materials and studies of radiation dynamics. The laser writing program follows a two-pronged approach, developing new processing techniques and applying these to the fabrication of photonic devices. The radiation dynamics program also follows a two pronged approach, investigating the properties of emitters located within off-the-shelf photonic crystal structures and developing new platforms for advanced radiation dynamic studies using self assembly methods.

Within the laser writing program there are six different projects. These include the study of direct laser processing of 1- and 2-D photonic crystals in polymeric materials, direct writing of lightwave structures inside passive and active glasses using femtosecond lasers, ultrafast laser writing of fibre Bragg gratings in non-photosensitive optic fibres, development of a sub 25 fs ultrafast laser for femtosecond laser / material interaction studies, optimisation studies of lightwave devices using lithography, and field poling of quasi phase matched crystals based on a novel laser processing technique. These activities underpin the development of components performing amplification, regeneration and multiplexing functions, and relate directly to the Centre's vision of all-optical micro-processing. A new collaboration with the University of Sydney also arose out of this program this year. Drs Libin Fu, Jeremy Bolger and Graham Marshall collaborated successfully to write a resonant Bragg grating feature inside a photonic crystal fibre using a femtosecond laser – phase mask inscription approach. In addition, new research linkages were established with Dr Stuart Jackson at OFTC on high power fibre laser development. Milestones arising from our activities in 2005 include:

- Fabrication of a 2 dB waveguide amplifier in Er:Yb doped phosphate glass;
- Fabrication of 2- and 3-D 1xN splitters in bulk glass using femtosecond laser direct writing methods;
- Fabrication of 1st order, 13 μm periodically-poled lithium niobate (PPLN) using a laser-based processing method;
- Fabrication of strong gratings, with low off-resonance losses, in both photosensitive and standard optical fibre using femtosecond laser point by point inscription methods;
- Rapid prototyping of 1-D photonic crystal rib waveguide structures using lithography and laser processing.

In 2005 the radiation dynamics program combined both experimental and modelling studies of the emission behaviour of laser dyes confined within a hollow core photonic crystal fibre. This work continued the collaboration between the University of Sydney and Macquarie University, with David Fussell showing that resonant features observed in Sam Myer's work could only be explained by theory based on Local Density of States (LDOS). The self assembly project team has also developed 3D opals from polymer microspheres with typical diameters of 300 nm. These opals will be used as templates for producing inverse opals with a full bandgap. This project established a new research collaboration with chemist Dr Andrew Jackson (ANU), an expert on self assembly of nano spheres. Milestones from this program include:

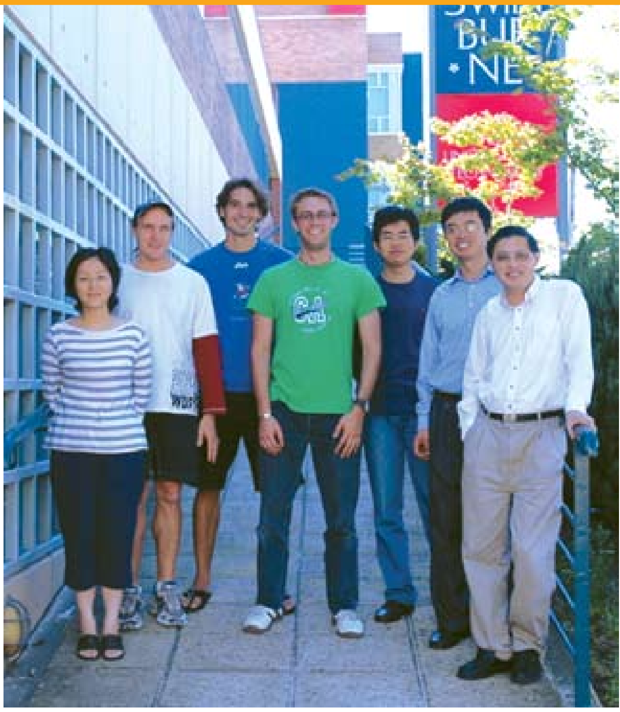
- Experimental validation of LDOS modelling methods for describing band-gap behaviour in tapered photonic crystal fibres.
- Improved control over the long range order of self assembled opals.

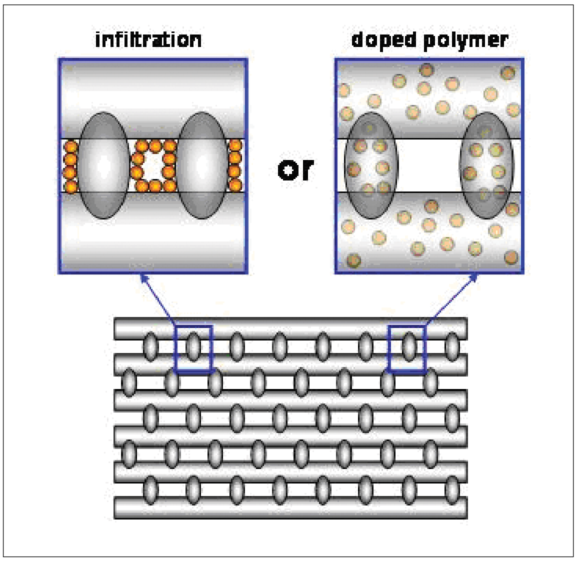
In 2005 the Macquarie University node had 14 members. We were fortunate to be joined by new ARC APDF Dr Alex Fuerbach, funded to develop a new state-of-the-art ultrafast laser for furthering our laser / material studies and laser direct-write project. While this project is not part of CUDOS, Alex will work closely with the CUDOS team and the results of his research will be of interest to the Centre. New PhD students Doug Little and Luke Stewart, and Honours student Nem Jovanovic also started this year. Our numbers were also boosted by several international visitors including Dr Adel Rahmani from CNRS, France, Assoc. Prof. Peter Balling from Aarhus University, Denmark, and Mr Juha Pietarinen, Joensuu University, Finland and Mr Steffen Hahne from the University of Applied Sciences, Jena, Germany. Finally, we farewelled Dr Marie Wintrebert-Fouquet who left us to join new start up company BluGlass developing new hosts for solid state lighting.

Swinburne Node Report

Min Gu

Swinburne Group





▲ **Methods for incorporation of quantum dots (shown in yellow): infiltration and doping.**

The Melbourne node of CUDOS is located at the Centre for Micro-Photonics (CMP), which is part of Swinburne University of Technology. At the CMP we have four laser and photonics labs, a chemistry lab and a biology lab available for experimental investigations. The Melbourne node is coordinated by the CUDOS chief investigator Min Gu and includes four researchers, two PhD students and one administrative staff member, all paid either partially or fully from the CUDOS funding.

Our contribution to the CUDOS program covers both experimental and theoretical investigations. In our theoretical work we closely collaborate with other CUDOS groups at ANU, UTS and Sydney University.

At the CMP we concentrate on the design, fabrication and characterisation of 3D photonic crystal structures. We apply several direct laser writing methods for fabrication – two-photon polymerisation and laser induced micro-explosion techniques. With two-photon polymerisation we have been able to fabricate 3D photonic crystals that have a band in the near infrared at 1.21 μm and possess strong superprism properties including negative refraction. This was a key achievement of the CUDOS Flagship project, 3D Photonic Crystals. Applying the micro-explosion method we have fabricated photonic crystals with embedded defect structures that can be used as high quality, tunable micro-resonators. Besides photonic crystal fabrication we also investigate and synthesise novel optical materials such as high refractive index polymers and quantum-dot doped resins. We have developed two methods for incorporation of quantum dots into 3D polymer crystals structures (see figure), which is an important component of the Swinburne-led Flagship project.

In 2005 we extended our femtosecond laser fabrication facilities with a regenerative amplifier system combined with an optical parametric amplifier providing pulse energies of several micro-joules over a tuning range that covers the whole visible and near- to mid-infrared wavelength region. This system will mainly be used for the fabrication of photonic crystals in materials such as lithium niobate and for photonic crystal characterisation.

During 2005 we said farewell to Dr Martin Straub who left Australia to seek new challenges in Germany. In January, Dr. Craig Bullen took up a postdoctoral position at the CMP and has contributed to the CUDOS project significantly by producing specialised quantum dots. In August, Mr. Jiafang Li joined the CUDOS project as a PhD student. Mr Li won second prize in the PhD student competition at the 4th CUDOS Workshop. Our PhD student Michael Ventura was awarded the 1st prize for best presented results at the Australasian Conference on Optics, Lasers and Spectroscopy (ACOLS). In December, Dr. Jesper Serbin and Dr. Guangyong Zhou were awarded prestigious postdoctoral fellowships of the Australian Research Council. As a result, they will focus on the fabrication of 3D photonic crystals in high refractive index materials. Our strong collaboration with other CUDOS nodes was continued in 2005, including several visits of ANU and Sydney University members to the CMP and seminars organised to present research results and discuss them with our CUDOS partners. Two joint papers resulting from these CUDOS collaborations were published in 2005.

The international collaboration activity was expanded in 2005. Min Gu visited the University of California, Santa Cruz, for collaboration on liquid crystal doped polymer devices. He also spent one month in the University of St. Andrews for photonic collaboration, supported by an EPSRC Visiting Professorship. We also continued our close collaboration with the Fraunhofer Institute for Silicate Research in Germany regarding new materials for photonic crystal fabrication.

UTS Node Report

Lindsay Botten

UTS Group

The UTS node of CUDOS is sited within the University's Department of Mathematical Sciences and is headquarters to the Centre's Computational Modelling program. This program has significant collaborations within CUDOS, providing strong analytical and computational support to a number of theoretical and experimental studies. The UTS group has strong expertise in theoretical and computational modelling of periodic and aperiodic electromagnetic systems. While the group has broad expertise in a range of computational techniques (e.g., finite element and finite difference time domain techniques), its particular and distinctive strength lies in the development and application of semi-analytic methods which are based on multipole techniques and Bloch mode tools – an area in which the group is ackowledged internationally, and where our capabilities were highlighted in the 2005 Science Review of CUDOS. Such semi-analytic methods allow us to capture the essential physics of complex photonic systems (e.g., a photonic crystal device), in a way that generalises, in a straightforward manner, well known structures and devices from various areas of optics (e.g., from thin film optics). While semi-analytic models may lack some of the generality of purely computational techniques (in terms of the range of geometrical configurations that can be dealt with), the "up side" of their use is excellent computational efficiency, very high accuracy and, above all, outstanding physical insight into the scattering and diffraction processes involved, together with an ability to provide definite answers to difficult questions that are not otherwise accessible.

The UTS team has strong collaborations with the theoretical group at Sydney University and also with experimental groups at ANU, Sydney, Swinburne and Macquarie, particularly through its involvement with theoretical and computational support of flagship projects. During 2005, the UTS group comprised six researchers (four of whom are wholly or partially funded by CUDOS) and one PhD student. Much of the work undertaken by the group meshes closely with the Photonic Circuits project and the mutual interaction involves the joint supervision of some four theory students (3 PhD and 1 Honours) at Sydney and UTS during 2005.

Over the past year, the major research foci of the UTS node have been

- The development of a sophisticated, new Bloch mode theory and associated computational tools for modelling propagation in photonic crystal slabs and the characterisation of Fano resonances in PC slabs. This work is associated with the Optical Switch Flagship project and involves collaboration with the fabrication group at ANU and the experimental group at Sydney.
- The characterisation of efficient, very low reflection coupling into rod-type PC structures. This work, undertaken in collaboration with the Sydney theory team, has explained the very efficient coupling using a semi-analytic theory and has been applied to the development of an efficient auto-collimating beam combiner, which has been verified by full 3D FDTD simulation.
- Comprehensive studies of the radiation dynamics of photonic clusters, which have shown a remarkable sensitivity of the local density of states and radiation shift to cluster size and shape.
- Major extensions to the semi-analytic tool suite to handle generalised defect modes, and substantial enhancements to the linear PC Modelling suite through the implementation of FEM-Bloch mode tools which continue to be widely used in the prototyping of PC devices with our Sydney colleagues within the photonic circuits program.