CUDOS

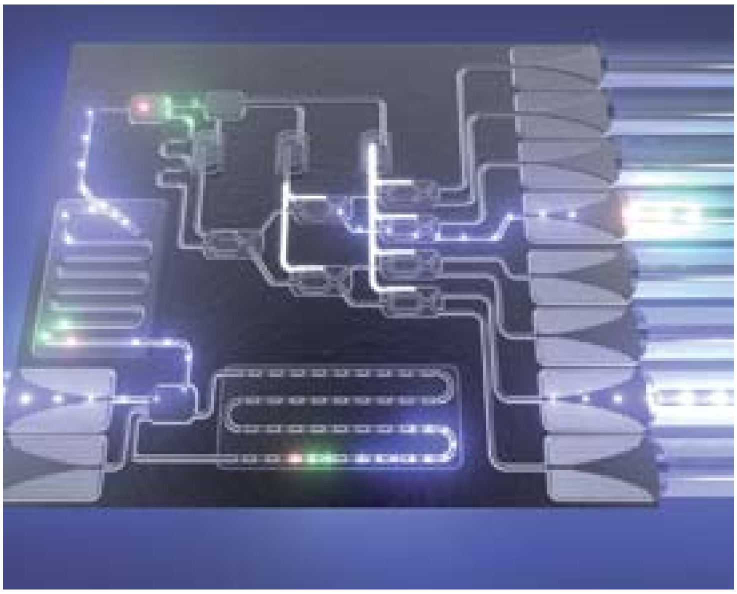
The Centre for Ultrahigh bandwidth Devices for Optical Systems (CUDOS)

ANNUAL REPORT 2006

Ben Eggleton, Research Director

This year was a landmark year for the CUDOS research program. Our Flagship projects, which were conceived in 2004 and initiated in 2005, delivered results of real significance in 2006. The cross-institutional nature of these projects could only have been achieved within a Centre of Excellence.

When the Centre commenced, our immediate aim was to develop the science and technology building blocks necessary for a long term focused program to develop a photonic chip (Figure 1 shows what such a processor might look like). Our research program at that time was organised into discipline-based projects and was reported on as such in the 2003 and 2004 Reports. As our science and technology facilities and capabilities became established and collaboration across the University nodes grew and strengthened, we developed the first of our Flagship projects. As of 2006 we have five Flagships focused on end user-inspired technologies – nonlinear optical signal processing including regeneration, a compact, ultrahigh bandwidth all-optical switch, tunable control of slow light, radiation control in three dimensional photonic crystals and a compact waveguide laser. Our fundamental research still sits at the heart of our program and is the wellspring from which our innovations flow, so each of our projects has a Science Leader (drawn from the Chief investigators) to provide the link between the fundamental science and the outcomes-focused Flagship activities, coordinated by a Project Manager. The role of the project managers is discussed in more detail later in this Overview.



▲ **Figure 1. Schematic of an All-optical Processor or Photonic Chip, by PhD student Sam Campbell.**

As an acknowledgement of this "coming of age", we have provided detailed reports of the 2006 achievements of each Flagship in this Annual Report. The Flagships derive their intellectual capital from the vigorous fundamental research driven by our Chief Investigators and their groups, so to provide a complete overview of the research conducted within the Centre we have also included a science report from each Chief Investigator. These reports follow; in this brief overview I survey the key outcomes from each Flagship and touch on highlights from our fundamental research activities.

Flagship research highlights

Slow light

This project is managed by Professor Martijn de Sterke.

Strong dispersion in materials like Bose-Einstein gases or photonic crystals has been capitalized on by a number of research groups to slow light to a fraction of its in vacuo value of 3.10^8 $m.s^{-1}$. However, there is an inverse relationship between the bandwidth over which the slowing occurs and the degree of slowing so that extremely slow light can only be achieved over a very narrow range of frequencies – which means that a short optical pulse, with its wide range of frequencies, is distorted in shape as it slows down. The Centre is investigating a different approach to slowing light that will overcome this limitation.

Our approach relies on the excitation of soliton pulses within a photonic crystal. The shape of a soliton pulse (by definition) does not change as it propagates, but the delay can be simply controlled by changing the length of the crystal. By introducing nonlinearity, the pulse can travel slowly and also remain undistorted over arbitrarily long propagation lengths by the formation of a soliton. In a paper published in Nature (Physics) during the year, we reported the observation of solitons in a fibre Bragg grating, and showed that sub-nanosecond pulses travel at 16% of the speed of light, without broadening. The delay in a 20 mm grating was more than twice the width of the pulse, and in experiments in 2007 we will extend these studies to longer gratings to achieve longer delays.

Dr Monat will commence in 2007 as an Australian Postdoctoral Fellow to work on slow light generation using an analogous approach but within 2D photonic crystal structures and manage the Slow Light Flagship. Dr Andrei Sukurokhov will take up an ARC QEII Fellowship to study slow light in nanostructured materials.

All Optical Switch

This project is managed by Dr Christian Grillet, who has a strong research background in photonic crystals from his work in CUDOS and prior to that, during his doctoral studies in France. Professor Barry Luther-Davies is the Science Leader. The aim is to develop a highly compact ultrafast optical switch for optical signals. In other words, the switching is driven either by the light itself or by an optical control pulse.

Efficient and rapid switching is crucial for next generation optical networks, which are laid out like a mesh. Switching, which is used at each node of the mesh to direct light along different paths to optimise utilization, becomes a ubiquitous function within the network.

The CUDOS approach has been to investigate switching mechanisms using resonant cavities or point defects in photonic crystals. The resonant coupling of light from a waveguide into a cavity can be engineered to lead to excitation of backward traveling modes in the waveguide or coupling of light to a second waveguide. This behavior is not seen off resonance, so switching can be achieved by varying the resonance conditions.

We use a focused ion beam or electron beam lithography to write waveguides and resonant cavities in photonic crystals produced from planar chalcogenide substrates. The nonlinearity of this material means that the resonant frequency of the cavity is a function of the optical intensity. Changes in the signal power (self-switching) or addition of a second control signal will change the refractive index and hence the resonant frequency.

During 2006 our research team, primarily from Sydney, the ANU and UTS, modeled different cavity designs and fabricated cavities and waveguides in chalcogenide photonic crystals suitable for optical switching experiments. We demonstrated an approach that evanescently coupled 98% of the light from an adiabatic silica taper into a chalcogenide photonic crystal waveguide. We also demonstrated a completely novel approach to tuning the resonant response of cavities in the photonic crystal using photosensitivity.

Nonlinear Optical Signal Processing

This project is managed by Dr Mark Pelusi, who has both industry and academic research experience in high bit rate optical networks. Professor Ben Eggleton is the Science Leader. The long term aim is to develop all-optical signal processing devices and technologies based on nonlinear optical phenomena with femtosecond response times, with a view for implementation in next generation ultrahigh bandwidth optical networks. Our first focus has been on the demonstration of an all optical signal regenerator, in which a noisy signal of ones and zeros is cleaned up ("regenerated") by removing the noise. A system with a nonlinear transfer function is required, in which ideally all signal amplitudes less than a threshold value are set to zero, and set to one at amplitudes above that. During 2006 we succeeded in demonstrating, for the first time, signal regeneration of high bit rate optical data streams in a chalcogenide waveguide. We measured the improvement in optical signal to noise from the regenerator, and demonstrated that it had the capacity for Tb/s processing.

The optical regeneration depends on the nonlinear behavior of light in chalcogenide glass due to the optical Kerr effect. The refractive index of the glass, which determines the propagation speed of the light, depends on the intensity of the light. This effect, practically instantaneous even on picosecond time scales, modulates the phase and broadens the spectrum of the light at high intensities, while low intensities are unaffected. Our approach to realizing a practical regenerator based on this principle has been first to use chalcogenide, with its large optical Kerr effect, then to increase the optical intensity by tight confinement of the light in a waveguide, and finally to use a Bragg filter to select a portion of the spectrally-broadened light.

The chip-based regenerator we developed was a team effort across two university groups. The chalcogenide planar substrates and the waveguides in the substrates were fabricated at the Australian National University. The Bragg gratings that provide the intensity-dependent spectral filtering were written into the waveguide with a facility at the University of Sydney. The combination of these unique technologies has placed CUDOS at the international forefront of research in this area, particularly since competitive efforts based on silicon or compound semiconductors are limited in their response time or affected by multi-photon absorption due to the quite different physical mechanisms associated with nonlinearity in these materials.

Compact Waveguide Lasers

The project is managed at Macquarie by Dr Graham Marshall, a researcher with a strong background in laser systems and micromachining. Associate Professor Michael Withford is the Science Leader. The group at Sydney has contributed expertise in Bragg gratings (modeling, fabrication and device characteristics) while the ANU group is involved in modeling novel integrated structures.

A femtosecond microfabrication technique has been developed at Macquarie University. Under appropriate laser irradiation conditions, local variations in refractive index are produced in a bulk material within the focal spot of the laser as a result of a multi photon process.

By translating the location of the focal spot in the material, the group has been able to produce optical waveguides and more complex structures including 1 by N splitters. They have written these waveguides in erbium doped glass and observed gain in this waveguide when pumped by a diode laser.

The group has also introduced Bragg gratings into the optical waveguides by writing a series of regularly spaced dot-like refractive index changes in bulk silica. This work, reported in Optics Letters, was the first demonstration of this capability and opens the door to an exciting development during 2007 – a waveguide laser with distributed Bragg reflectors, all written using the femtosecond micromachining technique. Gratings were also written for the first time into photonic crystal fibres using this approach.

3D Photonic Crystals

This project is managed by Dr Baohua Jia, a researcher at Swinburne University with expertise in microfabrication and microscopy. Professor Min Gu is the Science Leader. Our interest in three dimensional photonic crystals is driven by fundamental science opportunities and long term applications. The earliest work on photonic crystals pointed out the potential for substantially modifying the radiation dynamics of atoms (or nanoclusters) when placed within the 3D lattice of a photonic crystal. Researchers at Sydney and UTS have developed a theoretical approach to calculate these modified radiation properties based on the Local Density of States (LDOS) and applied this to problems of practical interest. A calculation of the radiation properties of coupled microcavities appeared in Physical Review Letters during the year.

The Centre has an active program at Swinburne in fabrication of 3D photonic crystals. Either a photo-polymerization process or a point-by-point laser micro-explosion technique is used, depending on the material. In the first case a solid 3D polymer microstructure is grown from liquid while in the second case a three dimensional regular array of micro-void spaces is produced in a solid material like lithium niobate. In both cases, a two photon process combined with ultrahigh resolution three axis mechanical stages are used to produce fine spatial features leading to photonic crystals with band gaps in the near infra red.

One focus of the Centre's fabrication effort is the demonstration of a full band gap (a spectral range over which transmission is zero for all incident angles). This can only be achieved in a 3D photonic crystal with a high refractive index contrast. The photo-polymerisation process produces polymeric materials whose refractive indices are too low, while the micro-void approach can produce 3D crystals in a range of materials and so is the preferred option. However, beam aberrations may compromise the quality of micro-voids in the layers deep within the material. The Swinburne group has developed novel microscopic imaging techniques to successfully produce 3D crystals in lithium niobate (n=2.3) and plans to apply the technique to other higher refractive index materials during 2007. The electrically tunable optical nonlinearities in lithium niobate open a range of opportunities for development of tunable microphotonic components.

A second focus is on a range of fundamental propagation effects expected in 3D crystals. The Swinburne group reported (in Advanced Materials in early 2006) the observation of a superprism in a polymer photonic crystal.

Fundamental research highlights

Prof Kivshar's group at ANU has been active in exploring, by experimental observation and theoretical analysis, a range of novel physical phenomena in optically induced lattices. These include the first observation of two-dimensional Bloch oscillations and Zener tunneling, one- and two-dimensional optical gap solitons and their enhanced mobility and tunable negative refraction. The activities appeared in four Physical Review Letters during the year and were reviewed in the yearly 'highlights' issue of Optics & Photonics News for 2006.

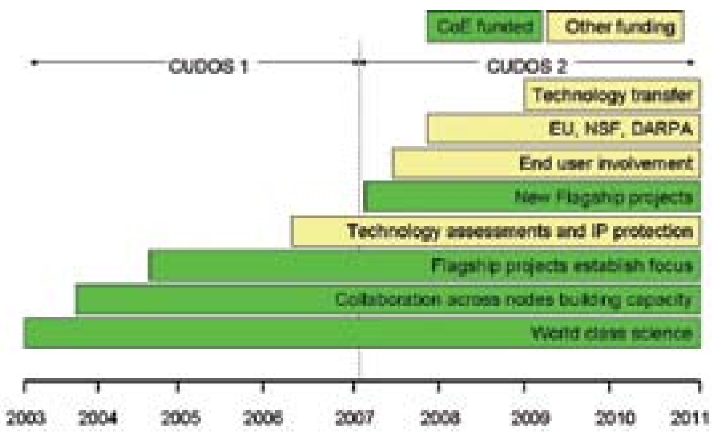
The outcomes of this work are relevant to experiments in the 3D lattices fabricated at Swinburne University, and over the coming year we will conduct experiments that build on the superprism observations to explore the sophisticated propagation effects predicted by Prof Kivshar, Prof Krolikowski and their team.

The Centre depends heavily on sophisticated numerical approaches to modeling wave propagation in micro-structures including photonic crystal fibres and two dimensional photonic crystals. During the year the theory teams at UTS and Sydney led by Profs Botten, McPhedran and de Sterke developed a novel technique able to model modes in genuinely infinite photonic structures. Referred to as the fictitious source superposition method, the technique was used to demonstrate unambiguously that the fundamental mode of a micro-structured optical fibre has no cutoff, thus resolving a problem of some considerable international debate.

Dr Boris Kuhlmey has extended the in-house photonic crystal simulation tools (CUDOS MOF Utilities) to study photonic crystal fibres whose holes are coated with arbitrary materials. Using this software and through analytic work, the Sydney group demonstrated novel, hybrid mechanisms for guidance of light in these fibres, and demonstrated that, when the holes are coated with metal, plasmonic resonances can be excited inside the fibre, with the prospect of realizing cheap ultra-sensitive all-in-fibre bio-sensors or absorptive polarizers. Related to this work was the first demonstration of gratings in photonic bandgap fibre.

Research program structure

2007 will be a transition year for CUDOS as we commence full implementation of a research management structure where Flagship projects are integrated with science activities led by the Chief Investigators. The Flagships are managed by researchers who in general are not Chief Investigators. To understand the reasons for this, it is appropriate to discuss the role of the Flagship project managers in some detail.



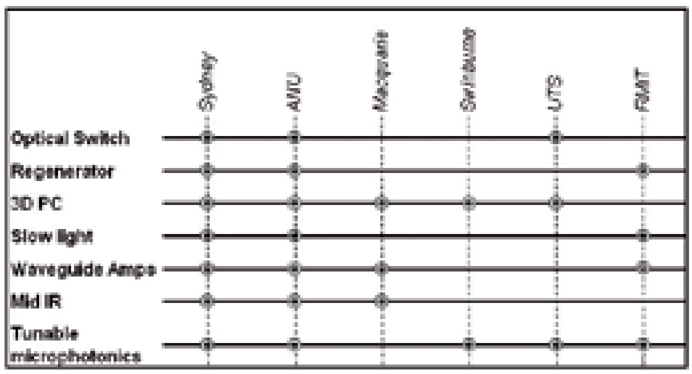
▲ **Figure 1. The complexity of the Centre increases as it matures, with new funding sources, but the fundamental research base continues to underpin all our activities.**

Role of Flagships in CUDOS

Figure 1 illustrates how the CUDOS program has evolved and is expected to evolve up until 2010. The Flagship projects can be seen as a bridge between the science programs on the one hand and stronger end user engagement and ultimately technology transfer on the other. This figure also illustrates how the range of funding sources for CUDOS will broaden as the range of activities built on our strong science base broadens. In doing this we ensure that the ARC Centre grant continues to support the science program and the associated Flagship projects, since the Centre's strength lies in the continued quality of its fundamental research.

Flagship project managers

Despite their obvious advantages, Flagship projects pose significant management challenges, as their activities may require coordination across many nodes of the Centre. To address this challenge, we have appointed project managers drawn mainly from the ranks of our junior research staff who play active roles in the Flagships. Responsibility for project management carries with it a host of duties – planning projects, negotiating resources with Chief Investigators, linking with our Partner Investigators, communicating within the project team, reporting to the Research Director and ultimately, reporting the outcomes of the project at meetings and in journals. To assist our project managers, the Centre is providing training in the principles of research project management as well as on-going mentoring.



▲ **Figure 2. Flagship Project collaboration across node groups.**

Project managers play the key coordination role in formulating a project plan that addresses the goals agreed between the Research Director and Chief Investigators involved in the project. The goal-setting process is illustrated in Figure 3. This illustrates the close coupling between the long term vision and yearly goals of the Flagship projects and the science goals for each Chief Investigator.

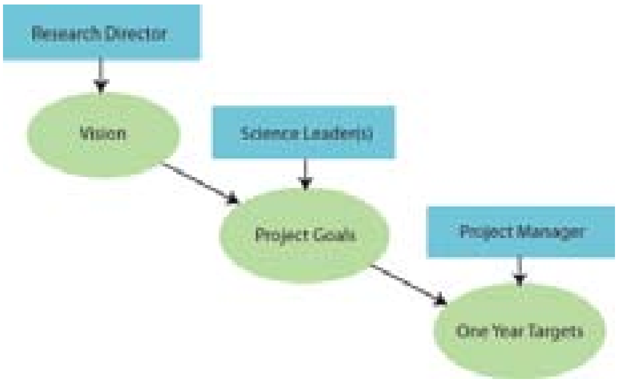


Figure 3. Research Director, Science Leaders and Project Managers input into long and short-term Centre goals.

Chief Investigators drive the Centre's science. In doing so, they build capacity and momentum over several years within science disciplines. Managers of the Flagship projects, on the other hand, draw on that capacity and momentum across a number of University nodes to deliver specific outcomes required within a much shorter period of time, typically a year or less. Both roles are absolutely crucial in a Centre of Excellence that achieves scale and focus in its research programs. The two roles have different objectives, and so should be undertaken by different sets of people.

As an example, science goals for which a Chief Investigator is responsible might include the development of a capability for fabrication of 2D or 3D photonic crystals in specific materials or the development of modelling tools for simulating resonant optical behaviour in photonic circuits within such structures. A Flagship project goal (for which the project manager is responsible) could build on these capabilities to, for example, achieve a 10 Gb/s all-optical switch and present this result as a post-deadline paper at a prestigious international conference during the next twelve months.

We believe that we have evolved to a structure that reflects and supports the complex collaborative inter-relationships that are necessary to fully capture the benefits of a Centre spanning six nodes with extensive national and international collaboration. It is particularly pleasing that creation of this structure offers a range of career development opportunities to our younger researchers.

CHALCOGENIDE PHOTONIC CRYSTAL ALL-OPTICAL SWITCH

Project Manager: Christian Grillet

Science Leader: Barry Luther-Davies

Contributing staff: Snjezana Tomljenovic-Hanic, Eric C Mägi, Benjamin J. Eggleton (Sydney), Steve Madden, Andrei Rode (ANU), Lindsay Botten, Ara Asatryan (UTS), Mike Steel (RSoft Inc)

Students: Darren Freeman (ANU), Michael Lee, Cameron Smith (Sydney), Michael Byrne (UTS)

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.