# CUDOS

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

# ANNUAL REPORT 2006

# WAVEGUIDE AMPLIFIERS AND OSCILLATORS

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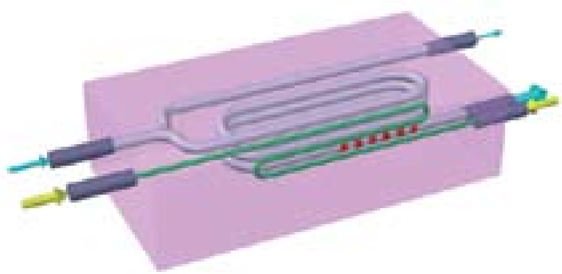
## Four year vision/long term goal and motivation

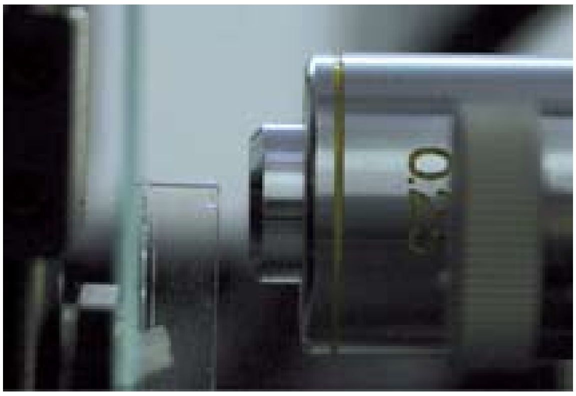
Our aim is to develop commercially viable microphotonic devices for metropolitan area networks (with NICTA) and robust microphotonics for defense applications (with DSTO) using laser direct write micro-fabrication to modify the internal properties of bulk glass substrates. By using an ultrafast laser focused to a small, intense spot and translated under computer control with respect to a target sample, we can inscribe waveguides integrated with discrete components such as amplifiers, couplers and filters into one piece of glass in a single step micromachining process. This produces an embedded microphotonic system with high inherent stability. Inscription in active glasses allows the development of compact photonics devices with amplification.



▲ **Figure 1. Conceptual illustration of an embedded waveguide amplifier written in rare earth doped bulk glass. This device includes evanescently coupled signal and pump waveguides, and an intra-core grating.**

Our four year research plan is targeted towards building examples of Photonic Integrated Circuits (PICs) using this fabrication platform. We will first demonstrate simple gain devices into which we progressively integrate other functionalities. A conceptual illustration of one such device is shown in Figure 1. It consists of a coiled signal mode waveguide embedded in active glass. A second waveguide, evanescently coupled to the first, is used to deliver pump laser light into the gain medium. The device also features a grating which could be used for pump light rejection or gain flattening, and waveguides that are mode matched to standard optical fibre pigtails. Specific milestones set out within our plan include demonstration of;

- Compact waveguide amplifier with gain >10 dB
- Single wavelength, monolithic waveguide laser (average power >1 mW)
- Multi-wavelength (≥4 λ), monolithic waveguide laser (average power >1 mW)
- Efficient 1 x N power splitters (N=8, 16, 32, 64)
- Coupled grating waveguides
- High power multi-wavelength waveguide laser (average power >10 mW per λ)



▲ **Figure 2. Enlarged image of a waveguide being written sub-surface in a glass sample by femtosecond laser light.**

## Strategy

Laser direct write methods for inscribing 3D lightwave circuits in bulk glass have the potential to challenge conventional fibre and planar waveguide-based optical processors. Over the last five years the number of research groups (from more than a dozen countries) working in this field has risen significantly.

We have a scientific and technological edge over our competitors in the field. On the scientific side, we have a fundamental understanding of ultrafast light/matter interactions and key insights into the parameters influencing transmission losses in laser direct-write waveguides. On the technical side, over 10 years of experience in high precision motion control has allowed us to engineer a state-of-the-art ultrafast laser fabrication facility, complemented by a sophisticated optical diagnostics facility comprising 12 axis motorized nanopositioning stages integrated with a swept wavelength system and tunable lasers. Unique features of our fabrication platform include excellent phase and position control, permitting integration of narrow linewidth gratings, and a processing range spanning 150x10x2 mm. This capability will position our team at the leading edge of international efforts in this field for many years to come. As testimony to this claim, we were the first to report, from a number of research groups in this field, a direct-written waveguide Bragg grating [4].

## Collaboration

This is a collaborative project between researchers at Macquarie University, ANU and the University of Sydney that will involve our Partner Investigators at NICTA and DSTO. During 2006 Dr Adel Rahmani (CNRS France) joined the project as a visiting scientist funded by an ARC Linkage Fellowship. His expertise in near-field scanning optical microscopy builds on an existing project using this diagnostic to map the cross sectional profile of the waveguides and optimize the writing parameters.

The compact amplifier devices fabricated at Macquarie will be evaluated using bit error rate tests at the CUDOS node of the University of Sydney. Integrated multi-wavelength waveguide lasers will be developed for systems testing by partner investigator DSTO. We anticipate collaborating with NICTA on 1 x N power splitters and RMIT on device packaging and rare earth ion in-diffusion.

## Goals for 2006

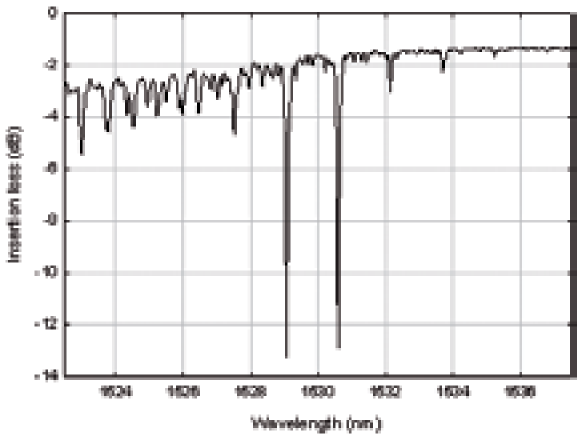
Our main goals during the year were to reduce the propagation losses of laser written waveguides and to develop a grating writing capability based on this fabrication platform. These goals underpin the high gain waveguide amplifier and waveguide laser milestones described above. A core objective was the production of a laser direct-written waveguide with a Bragg grating to demonstrate the capability of our approach for integrated fabrication.

## Achievements for 2006

An investigation of the influence of laser beam polarization on the optical properties of direct-written waveguides was completed during 2006 [1]. This study was motivated by recent reports of periodic nanostructures that are oriented in the same direction as the linear polarization of the incident laser. We established a link between the polarization of the incident beam and the transmission losses of the resultant waveguide. S- and P- polarized ultrafast light were shown to produce waveguides with similar transmission properties, whereas circularly and elliptically polarized light would produce waveguides with less than half the propagation loss of those written with linear polarized light. In the same study we showed that the refractive index changes induced by ultrafast laser radiation continue to increase as a function of the local energy deposition, independently of the temporal manner in which it was delivered.

These insights enabled the group to improve on its previous benchmarks to realize waveguides exhibiting losses < 0.39 dB/cm in fused silica. We are also undertaking studies to understand the role of filamentation of the focused ultrafast laser radiation on the optical properties of the resultant waveguides.

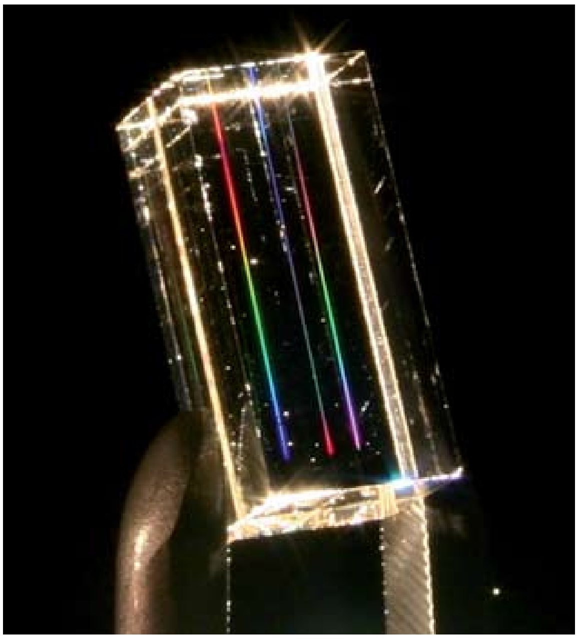
A new Near-field Scanning Optical Microscope system was built and commissioned in 2006. This was purpose-designed for deconvolving the fine spatial structure of laser direct-written waveguides.



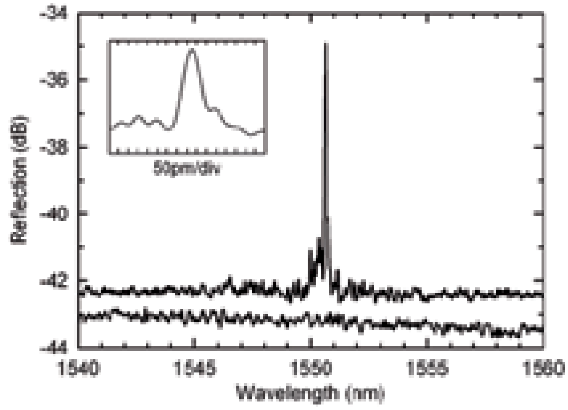

▲ **Figure 3. Sampled grating (50% duty cycle) with a $\pi/2$ phase shift that suppresses the carrier wave.**

During 2006 we also continued to improve our ability to produce Bragg gratings with different functions in a wide range of glass types. Detailed studies in optical fibre examining the growth dynamics of gratings as a function of incident energy showed that refractive index change are due to two different mechanisms with differing rates of growth (as a function of applied power) and different optical characteristics. The results allowed us to optimise the point-by-point grating writing techniques used to inscribe gratings in bulk glass [2, 3].

We successfully demonstrated narrow line width (FWHM 50 pm) gratings, sampled gratings in single mode optical fibre, phase shifted gratings (see Figure 3) and FBG resonator mirrors in a high average power (7 W) fibre laser.



▲ **Figure 4. Image showing a set of waveguide Bragg gratings fabricated inside a block of fused silica. The visible light is produce by diffraction off the intra-core point-by-point grating.**




▲ **Figure 5. Reflection spectra from a waveguide Bragg grating (upper curve) and a waveguide-only structure (lower curve). The inset shows the WBG curve on an expanded abscissa.**

We achieved our principal milestone for 2006 of fabricating a waveguide Bragg grating (WBG) where both the waveguide and grating structure are written using a single fabrication platform [4]. In our experiment a waveguide was written 450 μm below the surface of a fused silica substrate using 2.0 μJ pulses focused through a 0.46 NA objective. A 10 mm long, 2nd order (period 1.073 μm) point-by-point grating was then integrated with the waveguide (see Figure 4). The resultant WBG at a wavelength of 1.55 μm exhibited a –3dB linewidth of 100 pm. The off resonance losses for the WBG were similar to that for a laser direct-written waveguide with no grating, implying the gratings were very low loss (see Figure 5). Mode mismatches between the waveguide and standard SMF input probes prevented us from measuring the absolute strength of this grating.

Our femtosecond micromachining station is very heavily used. To provide more capacity we commissioned a new Ti:sapphire oscillator, developed in collaboration with Femtolasers GmbH from Austria [5]. This system employs a chirped pulse oscillator that allows the generation of sub-50 fs laser pulses with energy in excess of 100 nJ, high enough to reach the ablation threshold in a wide range of many dielectric materials. Pulses ~8 fs long have been generated with this system, which to our knowledge are the shortest laser pulses in Australia. The high repetition rate of 11 MHz (our current amplifier system operates at 1 kHz) will enable the writing of microphotonics systems on timescales measured in minutes instead of hours. We have verified that refractive index changes can be inscribed in chalcogenide glasses using this laser.

▲ **Figure 6. One of the key-elements of the chirped-pulse oscillator, a 2-inch diameter dielectric mirror which forms part of a so-called Herriott-cell, used to increase the resonator length to more than 27 m. Eight intracavity laser spots can be seen around its circumference.**

## Targets for 2007

Our first milestone for 2007 will be to demonstrate a high gain (10 dB) compact waveguide amplifier. This device will form the basis for demonstrations of monolithic waveguide oscillators, with intra-core gratings, producing 1 mW average power at wavelengths in the C-band. We plan to build on this capability to design and fabricate monolithic multi-wavelength waveguide oscillators matching the interests of DSTO for robust laser systems of this type. In addition, a new experimental study is planned investigating the characteristics of coupled WBGs in collaboration with Prof. Kivshar's group at the ANU.

## References

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