CUDOS

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

ANNUAL REPORT 2006

NONLINEAR OPTICAL SIGNAL PROCESSING

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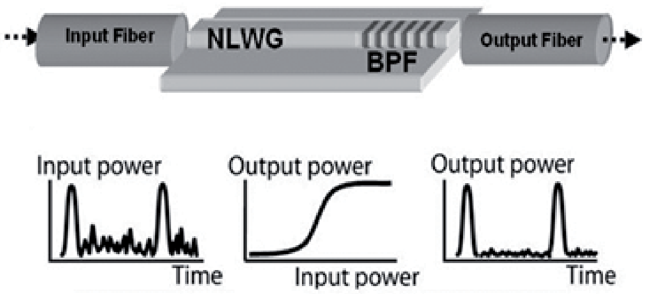
Four year vision/long term goal and motivation

We aim to develop innovative, compact, integrated signal processors to provide cost-effective solutions for next generation ultrahigh-bandwidth networks. Specifically, we aim to demonstrate three crucial component technologies: optical regenerators operating at ultra-high bit rates (greater than 40 Gb/s); wavelength converters for application in reconfigurable optical networks and integrated optical performance monitors for use in high speed dynamic networks for dynamic provisioning and active compensation. The CUDOS innovation and approach is based on novel miniaturized optical signal processing devices fabricated in two dimensional planar substrates of chalcogenide and lithium niobate. These devices offer performance and footprint unmatched by any other platform or technology (see Figure 1) and will underpin the signal processing solutions of future communication systems. The device physics is based on self and cross phase modulation, four wave mixing and Raman scattering with dispersion engineering in strongly confined waveguides and resonant elements.

Progress towards the Centre's goals will be assisted through strong collaboration with NICTA, DSTO and local industry to apply advanced photonic concepts for the demands of future optical communication and defense systems.



▲ **Figure 1. All-optical signal regenerator concept exploiting optical Kerr effect in nonlinear waveguide (NLWG), which has a bandpass optical filter (BPF) integrated in the same device.**

CUDOS strategy/competitive advantage

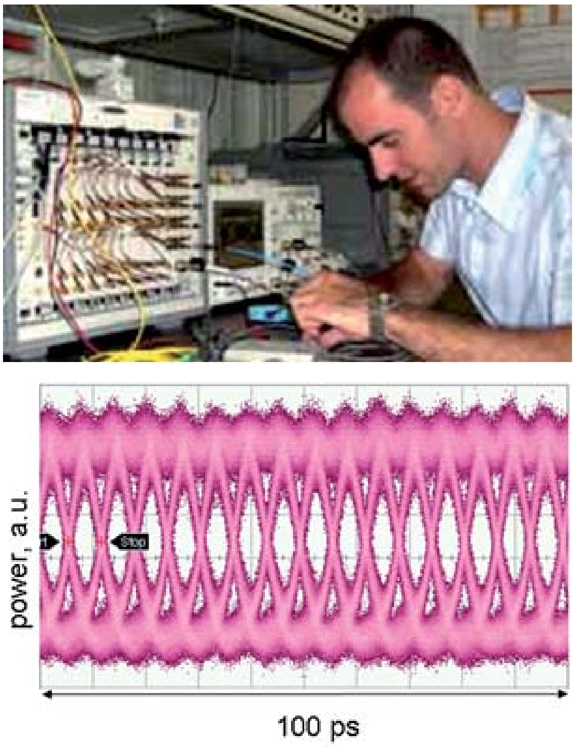
Our key strategy and competitive advantage is based on the use of chalcogenide glass and innovative nonlinear signal processing concepts. Optical waveguides made from this material combine high refractive index, large third order nonlinearity and good photosensitivity as well as low loss across the telecommunication wavelength band. These features enable unprecedented signal processing functionality based on the optical Kerr effect to be achieved in compact waveguide devices.

We have unique skills and facilities across two Universities to undertake this work. ANU combines expertise and world-class facilities for the fabrication of novel glasses; studies of their basic physical and optical properties; film production and characterization; and film processing to create state-of-the art low loss optical waveguides with ultra-high nonlinearity (Figure 2).

▲ **Figure 2. Track coating and lithography tools for chalcogenide waveguide fabrication.**

At Sydney, nonlinear signal processing for all-optical regeneration and optical performance monitoring are being investigated by first using commercially available fibres as preparation to implementing these functions in compact waveguide devices. The optical Bragg grating filters written into the waveguides draw on extensive in-house expertise for writing optical Bragg grating filters in optical materials. A custom laser system writes strong filters in chalcogenide waveguides by exploiting the photosensitivity of the refractive index.

The performance of the integrated devices in all-optical applications of optical signal wavelength conversion and regeneration is tested at Sydney using a high-speed 160 Gb/s optical communication system (Figure 3).



▲ **Figure 3. 160 Gb/s facility and eye diagram of 160 Gb/s optical signal measured on high-speed sampling-oscilloscope for testing bit-error rate performance of nonlinear optical devices.**

Collaborative links

The strong links within the Centre on this project are being broadened to include collaborators with a greater end user focus. National ICT Australia (NICTA) and the Defence Science and Technology Organisation (DSTO) are joining the CUDOS collaboration in 2007 as part of this process.

Goals for 2006

In broad terms, our 2006 goals were to improve our fabrication capabilities for integrated regenerators, and to demonstrate optical processing functions in fibre as a step towards eventual integration in planar chalcogenide substrates.

The two key fabrication tasks are to develop low loss ultra-high nonlinear waveguides in chalcogenide substrates, and to produce deep gratings with a range of spectral characteristics in these waveguides. To reduce the loss in the waveguides we investigated new chalcogenide compositions, improved film processing techniques and improved lithography leading to narrower line widths. Gratings that have been written include long (40 mm) Bragg gratings, sampled Bragg gratings and long-period gratings.

The nonlinear signal processing functions we aimed to demonstrate in highly nonlinear optical fibre were first, optical performance monitoring at bit rates of 40 Gb/s using a nonlinear optical fibre loop mirror and second, all-optical wavelength conversion in ultra-high nonlinear chalcogenide glass fibre.

We also upgraded the bit-rate capability of the optical communication facility from 40 to 160 Gb/s to enable performance testing of the nonlinear signal processing applications in both fibre and waveguide platforms at higher data speeds.

Achievements and highlights for 2006

Chalcogenide glass waveguides

We studied the composition of glasses to optimise nonlinearity, absorption loss, glass transition temperature and stability. In doing so, we gained valuable insight into how the Ge-As-Se glass structure evolves. Raman spectra measurements showed that as the Ge content increases, the glass evolves from a distinct layer stack structure with low transition temperature to a more uniform three dimensional structure with higher transition temperature. We succeeded in adjusting the As and Ge content for AMTIR-1 glass to achieve significant enhancement of the glass nonlinearity at 1550 nm.

Annealing studies of chalcogenide films deposited on substrates by ultrafast pulsed laser deposition were carried out using photoelectron spectroscopy while the refractive index and thickness were monitored using an SCI Filtmtek wafer mapper as the films were annealed. The results showed that prolonged annealing at high temperatures (300ºC for >3 hours) favourably relaxed the glass toward a refractive index matching the bulk. However, surface oxides were produced in the process, degrading film quality. More recent studies showed that annealing under high vacuum can suppress such side-effects. Ion assisted deposition has not yet proven effective in changing the film bond structure to a bulk-state form, but has been successful in greatly improving the film adhesion by using it to clean the substrate before deposition.

Wall roughness is a critical determinant of the overall waveguide loss. We developed two different approaches for reducing wall roughness, namely, changing the plasma etch chemistry and re-coating a thin film of As_2S_3 after etching. Optical microscopy verified that the surface roughness for either approach was reduced by a factor of two. We calculate that this will reduce the waveguide loss by a factor of three.

The attack of As_2S_3 films by standard photo-resist developers was mitigated by two new approaches- first, by applying a thin (~50 nm) layer of more robust glass, namely AMTIR-1, on top of As_2S_3 prior to processing, and secondly, using developer resistant back AR coating (BARC) as a protective 200 nm thick film below the photo-resist. After development of the photo-resist, the BARC is removed by oxygen prior to etching the chalcogenide films.

Signal processing in fibre

Nonlinear signal processing experiments with nonlinear devices based on waveguide as well as fibre platforms were carried out. We conducted a detailed numerical study of the influence of two-photon absorption (TPA) on all-optical regeneration and showed that the performance of the self-phase-modulation-based regenerator could actually benefit from TPA for improving 40 Gb/s optical signal by smoothing the nonlinear power transfer function [1]. This surprising observation contrasts with the detrimental effect of TPA on nonlinear switching.

Theoretical and experimental studies also proved that a regenerator based on self-phase modulation can achieve 3 R regeneration (re-amplification, re-shaping, and re-timing), and simultaneously improve the signal bit error rate even when placed directly before the optical receiver [2], in contrast to other power-transfer function based regenerators.

In fibre based experiments, a novel method for all-optical performance monitoring of optical signal-to-noise ratio (OSNR) was demonstrated using a nonlinear optical loop mirror [3] (Figure 4a). Experimental results (Figure 4b) showed that the nonlinear power transfer function can discriminate OSNR over a dynamic range of more than 25 dB for 40 Gb/s signals with different data modulation formats such as non-return-to-zero, carrier-suppressed return-to-zero, and return-to-zero (RZ).

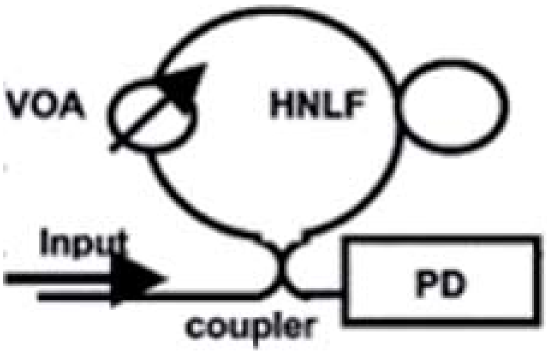


Figure 4a. An OSNR monitor schematic using a highly nonlinear fibre (HNLF) and variable optical attenuator (VOA) connected in a nonlinear optical fibre loop mirror. For a given average input power, the average output optical power measured on the slow photodetector (PD) depends on OSNR.

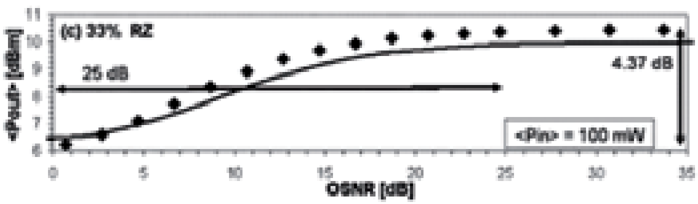


Figure 4b. Measured performance of OSNR for 40 Gb/s RZ signal by measuring average output power from NOLM.

In another fibre based experiment, the all optical wavelength conversion technique (Figure 5a) was demonstrated using a 1 metre length of As_2Se_3 chalcogenide glass fibre whose ultra-high Kerr nonlinearity is higher than any other fibre. Bit error rate measurements at 10 Gb/s showed only 1.4 dB system penalty for wavelength conversion of the 7 ps pulses over a 10 nm range around 1550 nm [4] (Figure 5b).

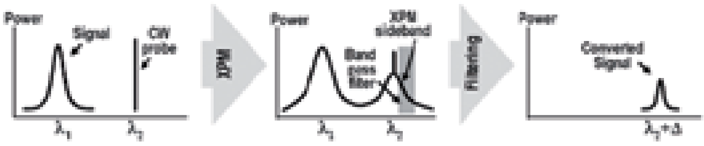


Figure 5a. General principle of all-optical wavelength conversion by using cross phase modulation of signal pulse onto cw probe and then filtering broadened spectrum at desired output wavelength.

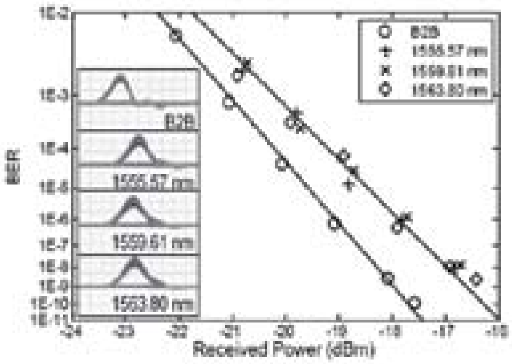


Figure 5b. measured 10 Gb/s bit error rate performance of wavelength conversion in 1m As_2Se_3 fibre with only 1.4 dB power penalty against back to back measurement at 1550 nm.

All-optical wavelength conversion of a 5.4 ps optical pulse over a 10 nm wavelength range around 1550nm was also demonstrated in a 5 cm long As_2Se_3 chalcogenide glass rib waveguide [5]. Frequency resolved optical gating measurements showed good converted pulse quality, no limitation to the conversion range of the device from waveguide dispersion.

A high quality sampled Bragg grating was written into a highly photosensitive chalcogenide (As_2S_3) rib-waveguide using a custom built scanning Sagnac interferometer system [6] (Figure 6). The induced refractive index change of the waveguide was estimated to be over 0.03, and the corresponding waveguide grating (Figure 7) exhibited comparable strength and bandwidth to the best sampled gratings ever produced in silica optical fibre.

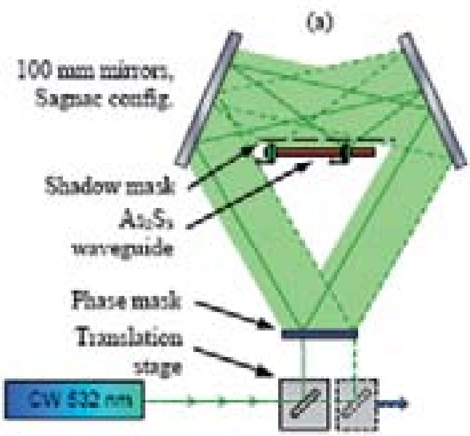


Figure 6. Schematic of custom built scanning Sagnac interferometric system for writing Bragg gratings in waveguides.

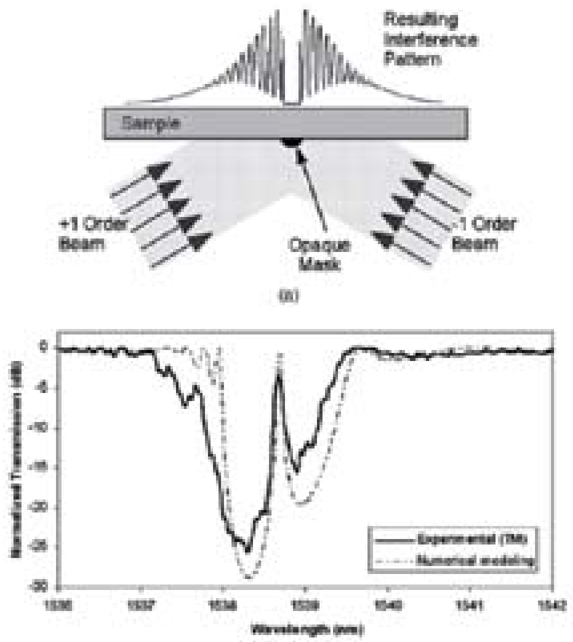


Figure 7. Mechanism of introducing a defect into a chalcogenide integrated waveguide grating structure to obtain a phase-shifted grating and (b) experimental transmission spectrum (solid curve) of the resulting phase-shifted grating (TM polarization) versus the spectrum obtained from modeling (dashed–dotted curve).

Targets for 2007

Drawing on progress in 2006, our aim will be to exploit advances in thin-film deposition and photo-lithography to develop longer length low loss waveguides with smaller mode area to enhance nonlinearity and lower the launch power requirements for applications in all-optical regeneration and wavelength conversion at high bit rates. The custom Bragg grating writing facility will be modified to enable integration of high quality optical filters suitable for these applications. The bit-error rate performance of the waveguides will be tested using the 160 Gb/s optical communication facility when used for optical signal regeneration, wavelength conversion and time-division de-multiplexing.

Specific objectives for the waveguide project for 2007 are:

- All-optical regeneration in 24 cm waveguide at bit rates of 10-40 Gb/s.
- All-optical wavelength conversion in 9-24 cm waveguides at bit rates of 10-160 Gb/s.
- All-optical de-multiplexing of 10 Gb/s channel from 160 Gb/s optical signal in an integrated waveguide configuration.

Research on the fibre platform devices will continue in parallel, focusing on demonstrating the potential of the nonlinear optical loop mirror device to monitor optical signal to noise ratio at higher bit rates of 160 Gb/s. Also, a fibre device will be designed and tested for all-optical signal regeneration in an optical communication link, in co-operation with our NICTA collaborators.

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