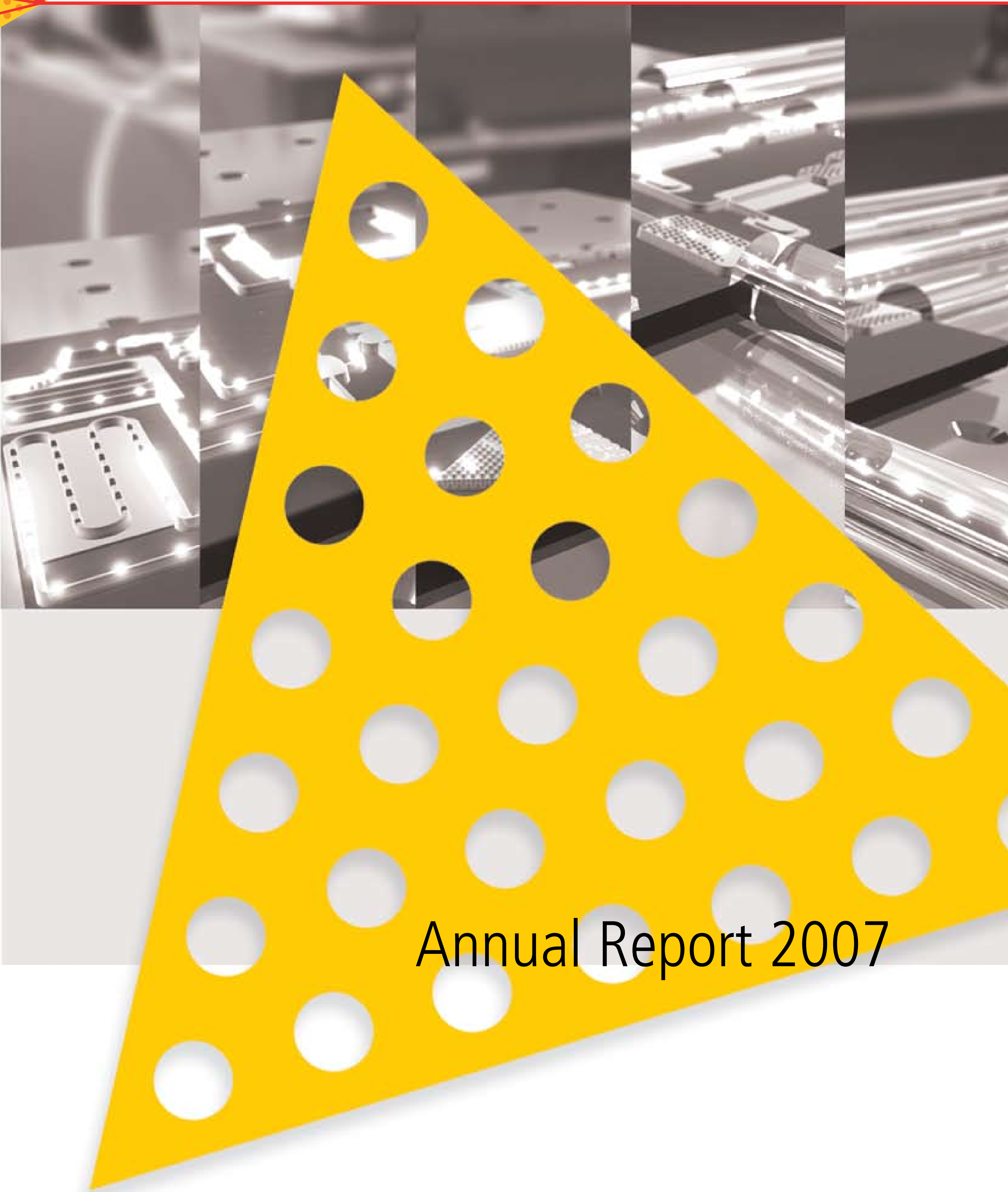
CUDOS The Centre for Ultrahigh bandwidth Devices for Optical Systems (CUDOS)

An Australian Research Council Centre of Excellence



Annual Report 2007

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 40Gb/s); wavelength converters for application in reconfigurable optical networks and integrated optical performance monitors for use in dynamic provisioning and active compensation in high speed dynamic networks. 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 (see Fig.1) that will underpin signal processing solutions of future communication systems. The physics of these devices is based on cross phase modulation (XPM), Four Wave Mixing (FWM) 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 on applying advanced photonic concepts to meet the demands of future optical communication and defence systems.

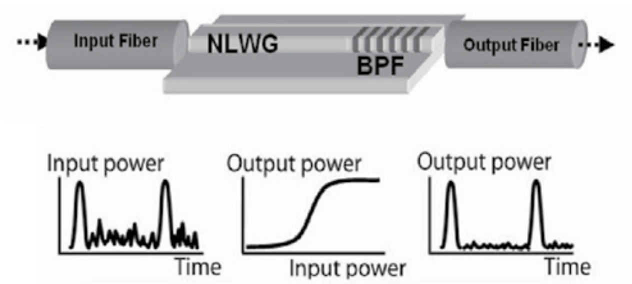


Fig 1: All-optical signal regenerator concept exploiting optical Kerr effect in nonlinear waveguide (NLWG), which has a bandpass optical filter (BPF) integrated in the same device.

CUDOS strategy/competitive advantage

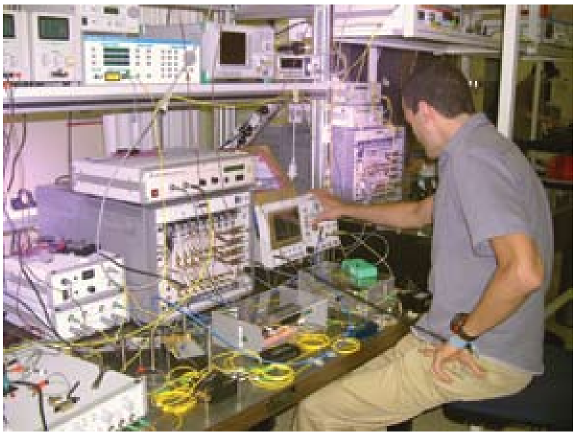
Our key strategy and competitive advantage is based on the use of chalcogenide glass. Optical waveguides made from this material combine high refractive index, large third order nonlinearity and good photosensitivity as well as low loss across the telecommunication wavelength band. These features enable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

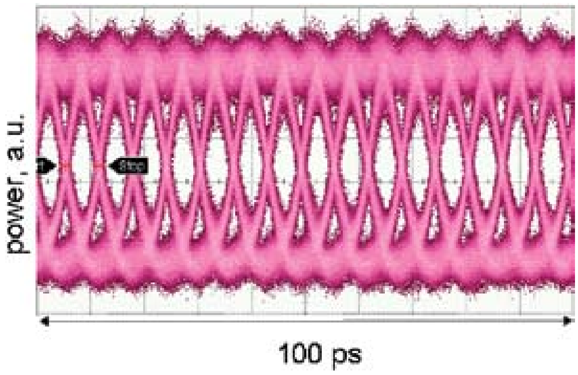
We have unique skills and facilities to undertake this work. ANU combines expertise and world-class facilities for the fabrication of novel glasses; studies of their basic physical and optical properties; film production and characterization; and film processing to create state-of-the art low loss optical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

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 optic 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 (Fig. 3).

Fig 2: Steve Madden using track coating and lithography tools for chalcogenide waveguide fabrication.





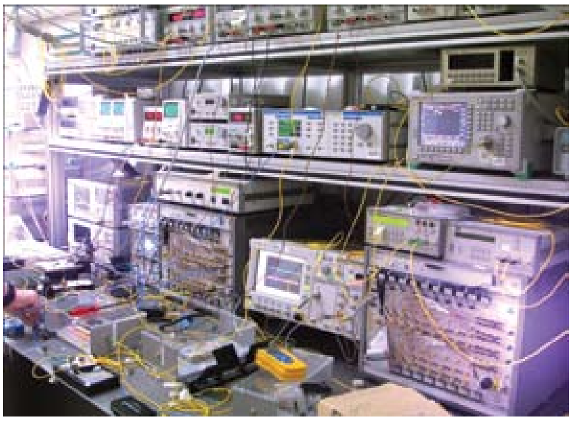


Fig 3: 160 Gb/s facility and eye diagram of 160 Gb/s optical signal measured on high-speed sampling-oscilloscope for testing bit-error rate performance of nonlinear optical devices.

Collaborative links

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

Goals for 2007

In broad terms, our 2007 goals were to further improve our capabilities for fabricating compact, low loss and highly nonlinear Chalcogenide waveguides and to demonstrate their application in nonlinear signal processing at bit rates beyond the conventional 40 Gb/s speed limit of opto-electronic systems.

The main objectives for fabricating planar As_2S_3 waveguides were to extend the propagation length and reduce the waveguide propagation losses to below the previous figure of 0.25 dB/cm for 5 cm straight waveguides by improving the thin film deposition and dry-etching processes. These combined advances would give greater nonlinearity due to the Kerr effect without raising optical power requirements for signal processing at higher bit-rates.

A parallel fabrication task was to explore novel Chalcogenide glass compositions that could increase the nonlinear refractive index beyond that of As_2S_3, from ~110 times that of silica toward 500. While the existence of such glasses is known, the challenge is finding a composition that can do so without compromising the stability, and optical power handling of the material. Research has focussed on the Ge-As-Se mixture, and finding the optimum Ge concentration. A key objective was to fabricate waveguides from a Ge optimized material and test its performance with high bit rate signals.

The fabricated planar waveguides were evaluated in nonlinear signal processing experiments using the recently developed 160 Gb/s optical communication facility. The target applications were all-optical regeneration of 10 Gb/s signals, broadband wavelength conversion of 40 Gb/s signals, and time-division demultiplexing of a 160 Gb/s signal into its tributary 10 Gb/s channels. The eventual integration of bandpass optical filters on a Chalcogenide chip draws on the in-house Bragg grating writing expertise to achieve more complex optical circuits and functionality on a compact photonic chip.

In parallel with the planar photonic chip platform, Chalcogenide fibres were tapered to increase their nonlinearity coefficient. Reducing the cross-sectional optical mode by the custom tapering approach allows nonlinear signal processing in shorter devices, reducing the impact of dispersion in broadband applications.

An additional goal was to investigate novel nonlinear signal processing functions that could underpin future applications of integrated optical devices. This includes all-optical performance monitoring at higher bit-rates and processing of advanced data modulation format signals such as differential phase shift keying (DPSK). Proof-of-concept experiments were carried out using highly nonlinear silica fibres.

Achievements and highlights for 2007

Chalcogenide waveguides:

A key fabrication milestone success was the development of a longer 22.5 cm length As_2S_3 planar waveguide with record low propagation losses of 0.05 dB/cm (Fig. 4) [1]. The increase in length (by more than a factor of four over the previous generation straight 5 cm waveguides) was achieved by a new photolithographic mask design that incorporated an advanced serpentine shape on a 7 cm size chip by exploiting the high refractive of As_2S_3 to maintain mode confinement around the tight radius (~3 mm) bends without compromising propagation losses. These advances both lead to nonlinear signal processing at higher bit-rates. The reduction in propagation losses by more than a factor of four over previous As_2S_3 waveguides was largely due to improvements in thin-film deposition to produce higher quality films with fewer defects, achieved by switching from ultra-fast laser deposition to a customized thermal deposition process [1]. Another contributing factor was the improvement in the photolithographic dry-etching process to reduce sidewall roughness of the rib waveguides by more than a factor of two, largely by optimizing the etching chemistry [1]. Rib waveguides of 4 µm width were etched from films of thickness between 0.9-2.6 µm to produce effective mode areas of between 7-2.5 $µm^2$. The corresponding nonlinear coefficients determined from the ultra-high nonlinear refractive index of As_2S_3 given by n_2 = 2.92 x 10-18 cm^2/W were between 4700-1700 /W/km [1].

The combined high nonlinearity, longer device length and low propagation loss are significant steps toward our ultimate goal of reducing power requirements for enabling all-optical signal processing at bit-rates of 160 Gb/s and beyond.

In exploring novel Chalcogenide glass compositions for pushing the nonlinear refractive index beyond that of As_2S_3, planar waveguides were successfully fabricated from an optimized Ge doped composition of As-Se-Ge with reasonably low propagation losses of 0.17 dB/cm. This was despite the existence of undesirable Se clusters forming in the films. The nonlinear transmission of high bit rate signals was observed to be significantly stronger than for the As_2S_3 waveguides with comparative input optical power. However, annealing studies are necessary to determine if the stability of the material and its overall power handling can be improved to match As_2S_3's performance in high bit rate applications. Nevertheless, the significantly higher nonlinearity and its more favourable fabrication are promising steps.

In a separate development, a 7 cm length sample of commercial As_2Se_3 fibre was tapered to narrow its fibre diameter from 165 to 75 µm uniformly over a 19 cm length. The corresponding reduction in the effective mode area from 37 to 20 µm^2 favourably increased the nonlinearity coefficient from 1200 to 2270 /W/km, allowing signal processing with a shorter device length. A 16 cm length segment of the taper was spliced to standard single mode fibre by epoxy glue achieving fibre-to-fibre insertion loss of 5 db, and as low as 2.5 dB.

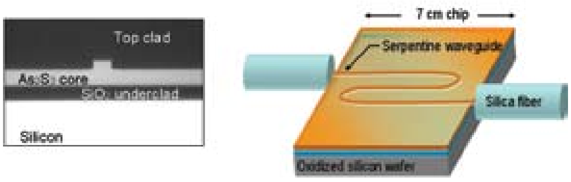


Fig 4: (Left) Scanning Electron Microscope image of the low loss Chalcogenide planar waveguide fabricated from a thermally deposited film of As_2S_3 and (right) device illustration showing the 22.5 cm long serpentine shaped rib of 4 µm width.

Nonlinear optical signal processing

Using the 160 Gb/s optical communication facility, we successfully demonstrated a range of high bit-rate all-optical signal processing functions with the planar and tapered waveguides, including waveguide conversion and optical time division multiplexing.

Measurements with the 22.5 cm length As_2S_3 planar waveguide demonstrated broadband wavelength conversion of a 40 Gb/s signal by cross phase modulation with a co-propagating continuous wave laser (Fig. 5a) [2]. The broad wavelength tuning was due to the reduced impact of dispersion largely thanks to the short device length. Measurements of the wavelength converted 40 Gb/s signals (Fig. 5b) revealed a waveform with a clear open eye and a bit-error rate power penalty of just 1 dB. The capability for applying the technique to higher bit rates was demonstrated by the effective wavelength conversion of an 80 Gb/s signal as shown in Fig. 6.

Similarly, wavelength conversion based on cross phase modulation was successfully performed for 40 Gb/s signals using the 16 cm length of tapered As_2Se_3 fibre [3]. The short device length again reduced the impact of dispersion, enabling a broader wavelength tuning range. Results showed significant improvement over previous experiments with an un-tapered one metre length of the same fibre. These experiments are the first reported to date of a successful application of Chalcogenide waveguides to broadband wavelength conversion at such high bit rates.

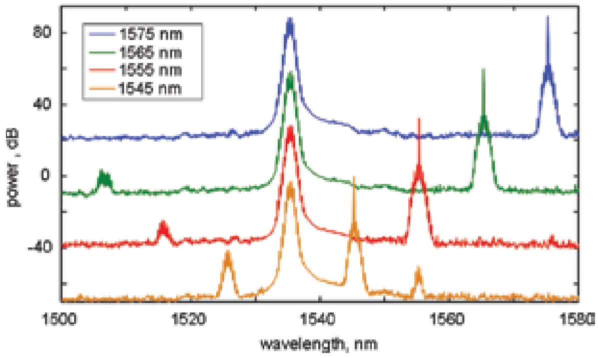


Fig 5a: Output optical spectra from a 22.5 cm length As_2S_3 rib waveguide showing the XPM of a 40 Gb/s signal (at 1535 nm wavelength) onto a co-propagating cw laser tuned to various wavelengths.

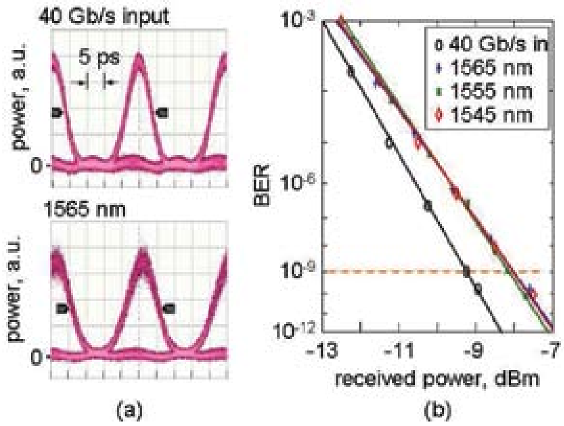


Fig 5b: High-speed sampling oscilloscope showing eye diagrams of a 40 Gb/s signal undergoing wavelength conversion from 1535 to 1565 nm wavelength by optically filtering the XPM broadened spectra from a 22.5 cm long As_2S_3 rib waveguide, along with the plot of its bit-error rate (BER) performance showing less than 1 dB power penalty at a BER of 10^{-9}.

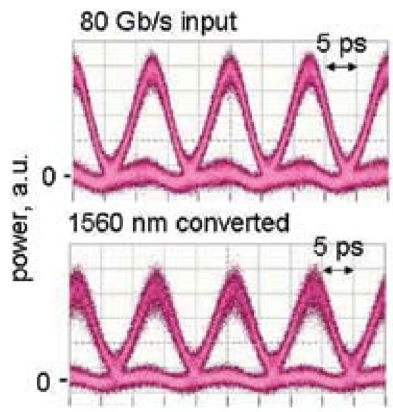


Fig 6: High-speed sampling oscilloscope showing eye diagrams of a 80 Gb/s signal undergoing wavelength conversion from 1550 to 1560 nm wavelength by optically filtering the XPM broadened spectra from a 22.5 cm long As_2S_3 rib waveguide.

We used all optical signal processing to time-demultiplex a 160 Gb/s signal to extract the tributary 10 Gb/s channels. The demultiplexing was achieved by four wave mixing of the 160 Gb/s signal with a propagating pump pulse at 10 GHz repetition rate. The high performance operation is shown in Fig. 7 by the clear extraction of a 10 Gb/s channel. Maximum mixing efficiency was achieved with a 5 cm device length waveguide [4]. This result is the shortest length demonstration of optical Kerr effect based signal processing at such high bit rates reported to date.

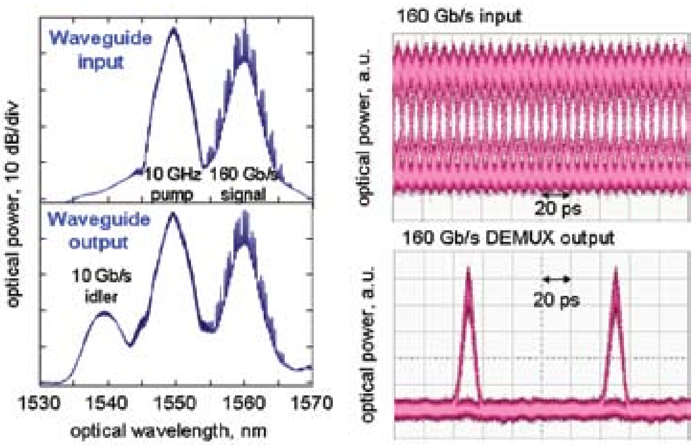


Fig 7: (Left) Optical spectra at input and output of a 5 cm length As_2S_3 rib waveguide showing generation of a 10 Gb/s idler by FWM between a 160 Gb/s signal and 10 GHz pump pulse train, and (right) high-speed sampling scope images showing 160 Gb/s time-division demultiplexing (DEMUX) operation by optically filtering the 10 Gb/s idler from the waveguide output spectra.

The optimal geometrical dimensions for exploiting four wave mixing in Chalcogenide waveguides were studied by detailed numerical analysis. We showed that the large material dispersion of Chalcogenide glasses can be offset to zero or reverse sign by a counter waveguiding dispersion term, which grows significantly as the waveguide dimensions approach the order of the optical wavelength (less than several microns). The device implications for parametric gain and wavelength conversion via FWM were investigated, highlighting the potential for broadband amplification and wavelength conversion [5].

In other novel approaches for nonlinear signal processing, all-optical performance monitoring of the optical signal-to-noise ratio (OSNR) using a nonlinear optical loop mirror [6] was successfully applied to higher bit rates up to 160 Gb/s. This was a significant advance over original experiments performed at 40 Gb/s. Experimental results showed similar performance, highlighting how the ultra-fast Kerr effect enables operation at bit-rates well beyond the processing speed limits of conventional opto-electronic systems. The operation of the device was also investigated for 40 Gb/s signals with the advanced DPSK (Differential Phase Shift Key) data modulation format.

During 2007, the optical communication facility was upgraded to enable generation of the DPSK formatted signals. This allows characterization of highly nonlinear waveguides at ultra-high bit-rates with a variety of data modulation formats including conventional on-off keying.

Targets for 2008

Drawing on progress in 2007, our objectives in 2008 will be the development of advanced Chalcogenide waveguides enabling signal processing at higher bit-rates up to 320 Gb/s with advanced data modulation formats such as DPSK, while simultaneously lowering the required optical power.

Central to these goals will be the fabrication of smaller dimension waveguides for both increasing the nonlinear Kerr effect and engineering the normal dispersion parameter. This will be advantageous for broadband applications, or exploiting FWM for optical parametric amplification, supercontinuum generation and optical phase conjugation. Research on novel applications of nonlinear signal processing in areas of signal regeneration, performance monitoring and optical sampling will be investigated using highly nonlinear silica fibres as a proof of principle demonstrator platform.

A key milestone for planar Chalcogenide waveguide fabrication will be increasing the nonlinear Kerr effect attainable. We plan to extend the waveguide length from 24 cm to 50 cm through the design of a new photolithographic etch mask. We will also shrink the waveguide dimensions to reduce the cross-sectional mode area. This will increase the nonlinearity but also allow the waveguides to be dispersion engineered for four wave mixing applications. This will be tackled by reducing the film thickness during deposition. Additionally, a new electron beam writing system will be established to enable etching of waveguides to narrower (sub-micron) widths beyond the print resolution of the photolithographic system.

The process for fabricating planar waveguides from advanced glass compositions with higher nonlinear refractive index (for potentially lower operating power) will be improved to achieve better power handling and overall waveguide stability. A proof of concept buried channel waveguide will also be developed to demonstrate polarization independence in all-optical signal processing applications.

We will continue work on the tapered Chalcogenide fibres with the objective of further reducing the fibre diameter to a regime where not only the nonlinear coefficient is greatly enhanced by the reduced mode area but the waveguiding dispersion grows significant and offsets the inherent large material dispersion toward zero. The target experiment will be nonlinear signal processing at high bit rates by four wave mixing, but we will need to overcome the power handling limits of narrower tapers.

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