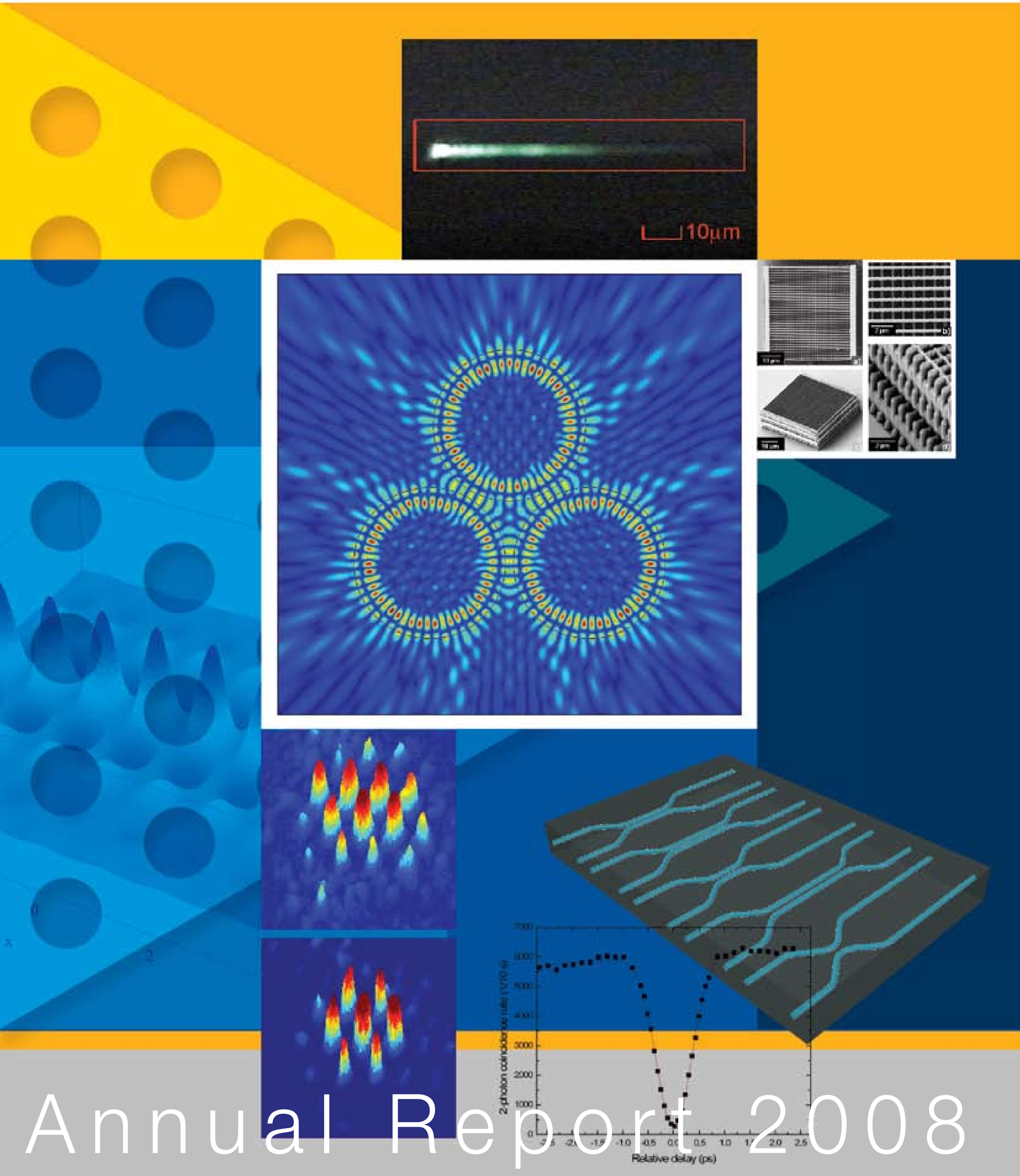
# CUDOS

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




# Annual Report 2008

## 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 and high performance instruments for analyzing high-speed signal and ultra-short pulses. 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 both broadband signal diagnosis (including higher resolution optical sampling oscilloscopes and THz bandwidth RF spectrum analyzers) as well as 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. These devices offer performance and footprint (see Fig.1) that will underpin signal processing solutions of future communication systems and broadband signal analyzers. 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 is assisted through strong collaboration with local industry and partner universities for applying advanced photonic concepts to meet the demands of future optical communications, microwave photonics, and defence system applications.

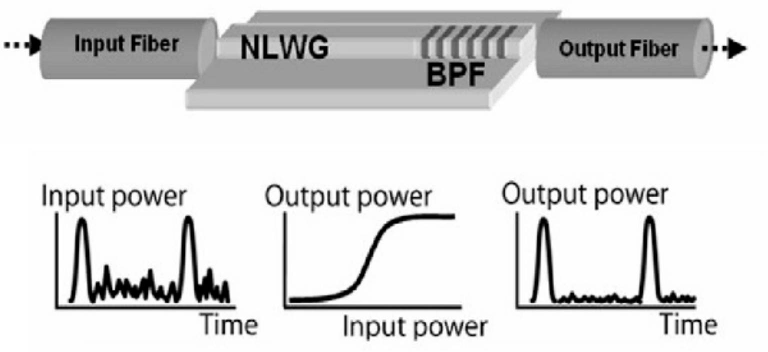



**Fig 1. All-optical signal regenerator concept exploiting optical Kerr effect in nonlinear waveguide (NLWG), which has a bandpass optical filter (BPF) integrated in the same device.**

**Nonlinear Optical Signal Processing**

## CUDOS strategy/competitive advantage

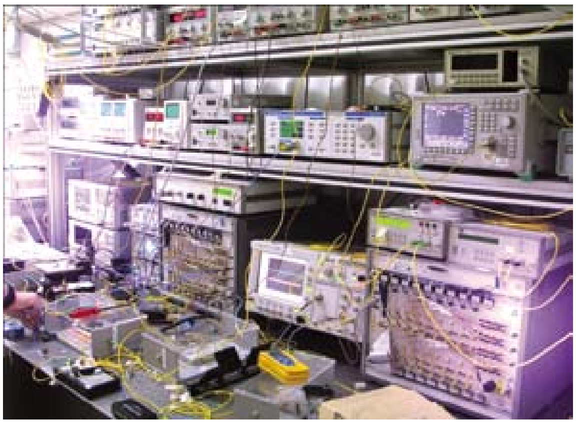
Our key strategy and competitive advantage is based on the use of chalcogenide glass. Optical waveguides made from this material combine high refractive index, large third order nonlinearity and good photosensitivity as well as low loss across the telecommunication wavelength band. These features enable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

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 using commercially available fibres as a step toward 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 applications of all-optical optical signal wavelength conversion and regeneration is tested at Sydney using a high-speed optical communication system (Fig. 3), which is currently capable of generating signals of 320 Gb/s serial bit-rate, and is in the process of being upgraded to 640 Gb/s.

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



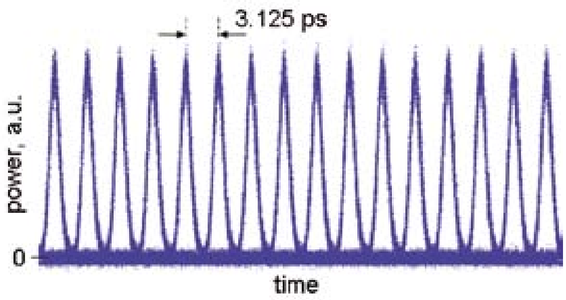



**Fig 3. High-speed optical communication facility and eye diagram of 320 Gb/s optical signal measured on a high-resolution optical sampling scope. This system enables testing bit-error rate performance of nonlinear optical devices.**

## Collaborative links

Progress toward our center's goals has been enhanced through collaboration with both industry partners (Finisar) and university groups including DTU Fotonik at the Technical University of Denmark.

## Goals for 2008

In broad terms, our 2008 goals were to fabricate chalcogenide waveguides with combined higher nonlinearity coefficient and lower chromatic dispersion in order to improve their performance in nonlinear signal processing applications at bandwidths beyond the conventional 40 Gb/s speed limit of opto-electronic systems.

The key milestone for planar waveguide fabrication was to build upon the successful development of low loss $As_2S_3$ waveguides by reducing the physical rib dimensions to shrink the mode size. This increased the nonlinearity coefficient allowing nonlinear signal processing with lower optical power or shorter waveguides. It also enhanced waveguiding dispersion with an opposing sign to the large material dispersion of chalcogenides glasses, enabling a net smaller dispersion parameter for supporting more broadband phase and group velocity matching for FWM and XPM respectively. Our approach was to reduce the rib height by reducing the deposited film thickness while modifying the fabrication process to maintain reasonably low propagation losses.

A parallel objective was to design a new photolithography mask incorporating a "race-track" circuit design on the same size wafer to allow fabrication of waveguides longer than the previous longest 24 cm that had been produced from $As_2S_3$ films with record low loss (0.05 dB/cm). This would harness a larger nonlinearity to produce more effective signal processing of higher bit-rate signals with lower optical powers for the benefit of applications such as all-optical signal regeneration.

A new chalcogenide waveguide fabrication process was also investigated based on the newly established electron-beam lithography system at ANU. This enabled fabrication of much finer (sub micrometre) features than the contact photolithography method. This provides a unique route to further shrink the mode size to obtain extremely large nonlinearity coefficients for signal processing with lower powers in more miniature photonic circuits.

Novel chalcogenide glass compositions were also explored as a means of raising 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. Focus remains on the Ge-As-Se mixture and finding the optimum Ge concentration.

A parallel development was the investigation of buried-channel waveguides as a practical means for realizing polarization independent photonic circuits. This would involve investigating different chalcogenide glasses as a suitable cladding material.

Tapering of chalcogenide glass fibres was investigated as an alternate platform for obtaining low loss dispersion-shifted waveguides with enhanced nonlinearity coefficient. We used a custom developed taper rig system to shrink the fibre diameter to smaller dimensions. The reduced mode size simultaneously enhanced both the nonlinearity coefficient and waveguiding dispersion in a similar manner to thin-film planar rib waveguides. As for planar waveguides, this assists signal processing in terms of more broadband phase and group velocity matching for FWM and XPM respectively.

The target outcomes for both the fabricated planar and fibre waveguides were nonlinear signal processing applications highlighting the performance advantages of shorter length, dispersion-shifted and highly nonlinear waveguides. Our recently upgraded 320 Gb/s optical communication facility was used in experiments such as wavelength conversion of 40 Gb/s signals over a broader wavelength tuning range, low power time-division demultiplexing of high-speed (160-640 Gb/s) signals and broadband performance monitoring of 320 Gb/s signals using 5-6 cm length photonic chip waveguides. Fundamental aspects of broadband phase-matched four-wave mixing, parametric amplification and supercontinuum generation were also targeted for investigation.

## Achievements and highlights for 2008

### Chalcogenide waveguides

A key fabrication milestone was the development of the dispersion-shifted $As_2S_3$ photonic chip waveguide [1-4] whose schematic is shown Fig. 4(a). The approach was to reduce the thickness of deposited $As_2S_3$ films by nearly a factor of 3 to ≈0.85 µm. Doing so shrunk the mode size which in turn raised the nonlinearity coefficient, and increased the waveguiding dispersion with a counter-sign to the large material component of $As_2S_3$ glass (equal to -364 ps/nm/km at 1550 nm wavelength) resulting in a smaller net dispersion parameter. Nonlinearity coefficients as high as 9900 /W/km (more than quadruple that of previous waveguides and over 6000 times larger than standard single mode fibre) were produced for the narrowest 2 µm wide rib. Furthermore, the dispersion parameter was reduced by more than an order of magnitude to as low as 28 ps/nm.km and with anomalous sign as shown in Fig. 4(b). The expected increase in propagation losses for fabricating such small dimension waveguides was mitigated through fabrication advances to achieve losses of between ≈0.25-0.5 dB/cm for rib widths of between 2-4 µm. The higher loss compared to previous generation waveguides (0.05 dB/cm) is expected to be partly due to scattering off the rib top surface. Another milestone achievement was the design of a new photo-lithography mask incorporating a 40 cm "race-track" for extending the range of practical circuit lengths from 6 to 40 cm within the same 6 cm size chip.

Dispersion-shifted waveguides were also successfully fabricated from the advanced ternary chalcogenide glass of As-Se-Ge. The near tripling of the nonlinear refractive index compared to $As_2S_3$ is favourable for lower power nonlinear signal processing. While propagation losses are comparable to $As_2S_3$, the power handling and stability need further investigation to determine its suitability for high-repetition rate signal processing. Other parallel achievements included progress toward fabricating chalcogenide "nanowires" by electron beam lithography and investigating suitable overclad chalcogenide glasses for buried channel waveguides.

In a separate development, a 5 cm length sample of commercial $As_2S_3$ fibre was tapered to narrow its waist diameter from 140.5 µm down to just 1.9 µm (a factor of 74 reduction). This was achieved over a uniform 5 cm length [5], highlighting the potential for realizing extremely compact highly nonlinear devices with an optical fibre platform. The corresponding smaller mode size favourably increased the nonlinearity coefficient by over an order of magnitude from 661 to 7850 /W/km. It also induced significant waveguiding dispersion of counter sign to the material component of -367 ps/nm.km resulting in a net smaller dispersion parameter of -85 ps/nm.km. The taper was spliced to standard single mode fibre by epoxy glue to achieve a remarkably low fibre-to-fibre insertion loss of just 4 dB, which is critical for achieving low power signal processing in such compact devices.

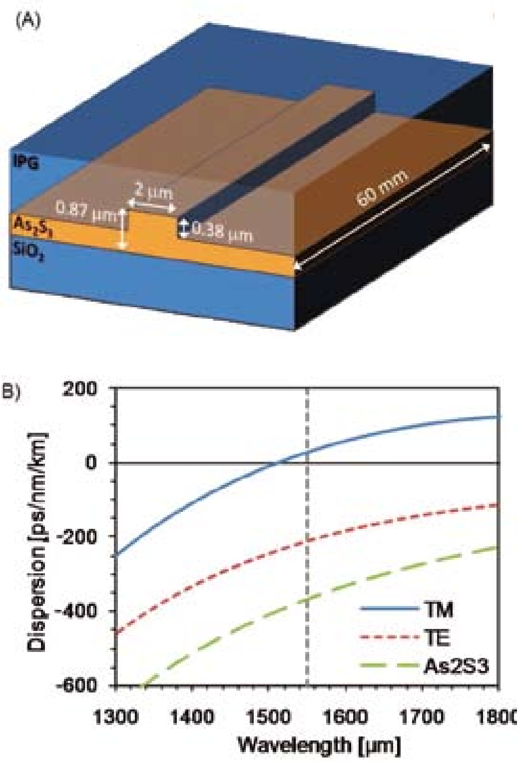



**Fig 4. (Top) device illustration of a 6 cm length dispersion-shifted $As_2S_3$ planar waveguide of 2 µm rib width and (bottom) calculated group velocity dispersion of fundamental TM and TE modes compared to material dispersion of $As_2S_3$ highlighting the dispersion-shifted design enabled by reducing the $As_2S_3$ film thickness**

## Nonlinear optical signal processing

The performance advantages of the dispersion-shifted planar rib waveguides were highlighted in various signal processing experiments using the 320 Gb/s optical communication facility. These included wavelength conversion of 40 Gb/s signals over a wider wavelength tuning range [1] which relied on the short length (6 cm) dispersion-shifted waveguide for broader bandwidth group-velocity matching between co-propagating waves. Consistent FWM and XPM in the output optical spectra of Fig. 5(a) were observed for a wide range of wavelength separation between the tunable cw laser and 40 Gb/s signal. The short (2 ps) signal pulses that were used could accommodate a 160 Gb/s data rate. The quality of the wavelength converted signal obtained after optically filtering the FWM component was validated by the signal eye diagram in Fig. 5(b) captured from a sampling oscilloscope as well as error-free bit-error rate measurements. Improving the efficiency will require investigation of the propagation losses and improved fibre coupling schemes.

Dispersion-shifted waveguides were also applied to low threshold supercontinuum [3] and broadband parametric amplification [4] in experiments that further highlighted the advantage of using compact low dispersion waveguides. These devices also proved advantageous for high performance time-division demultiplexing of 320 Gb/s signals. The improved phase-matching between the signal and co-propagating pump source produced a FWM idler which was optically filtered to produce a replica 10 Gb/s tributary channel from the signal. Time-division demultiplexing using chalcogenide waveguides was also demonstrated at a even higher bit-rate of 640 Gb/s in an experiment performed in collaboration with the DTU Fotonik group at the Technical University of Denmark. The striking result further showcased the waveguide's ultra-fast capability [6].

Another application demonstrating the broadband capability of the dispersion-shifted $As_2S_3$ waveguides was its use as a RF spectrum analyzer [2]. Experiments revealed a multi-terahertz bandwidth that far exceeds the capability of conventional opto-electronic RF spectrum analyzers. Furthermore, unlike with highly nonlinear fibres, this first demonstration of a photonic chip-based spectrum analyzer provided the combined performance advantages of broader measurement bandwidth, improved accuracy by avoiding pulse dispersion, and wider wavelength operating range. Its suitability for characterizing high-speed signals was shown by application to 320 Gb/s signal analysis which revealed features not evident from a conventional optical spectrum measurement alone, such as 160 GHz amplitude modulation distortion as shown in Fig. 6. Its effectiveness as a dispersion monitor of high-speed signals was also demonstrated.

Experiments were also performed using the tapered fibre platform to highlight the advantage of extreme tapering for producing dispersion-shifted waveguides with very high nonlinearity and low insertion loss (≈4 dB). Time-division multiplexing of a 160 Gb/s signal required a total launch power of below 25mW [5] which is an order of magnitude lower than what was recently reported for planar chalcogenide waveguides of the same length. Fig. 7 shows the high quality extraction of a 10 Gb/s tributary obtained after filtering the FWM idler from the waveguide output optical spectrum.

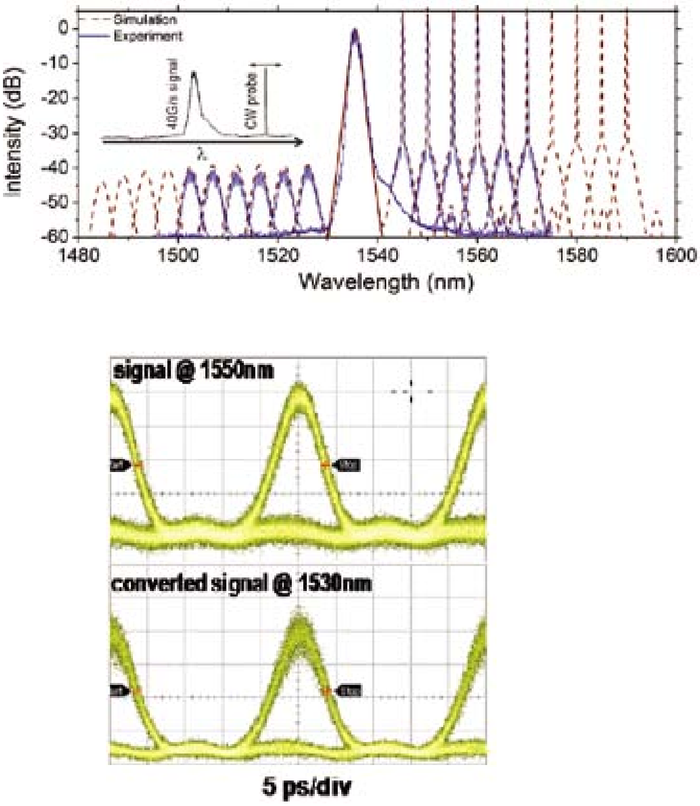



**Fig 5. Broadband wavelength conversion of 40 Gb/s signals in a 6 cm length $As_2S_3$ rib waveguide. (a) Overlaid output optical spectra measurements showing XPM and FWM of a 40 Gb/s signal (2 ps pulses at 1535 nm wavelength) with a co-propagating cw laser tuned to various wavelengths. (Dashed curve) numerical simulation of the wavelength converter with the same waveguide and input signal parameters. (b) Measured sampling scope eye diagrams of (top) 40 Gb/s signal input at 1550 nm wavelength and (lower) output after conversion to 1530 nm wavelength.**

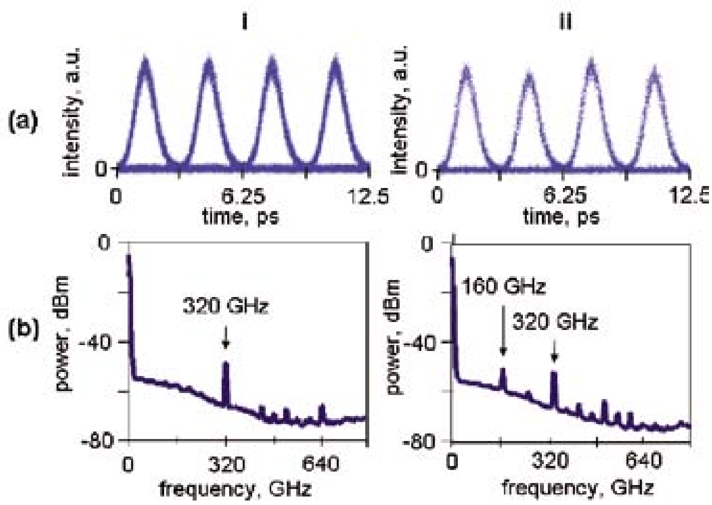



**Fig 6. Broadband measurement traces of 320 Gb/s signals generated by either (i) optimum or (ii) non-optimum time-division multiplexing when captured as (a) "eye diagrams" from a high resolution optical sampling scope and (b) RF spectra from the photonic chip based RF spectrum analyser, which reveals amplitude modulation distortion at 160 GHz frequency.**

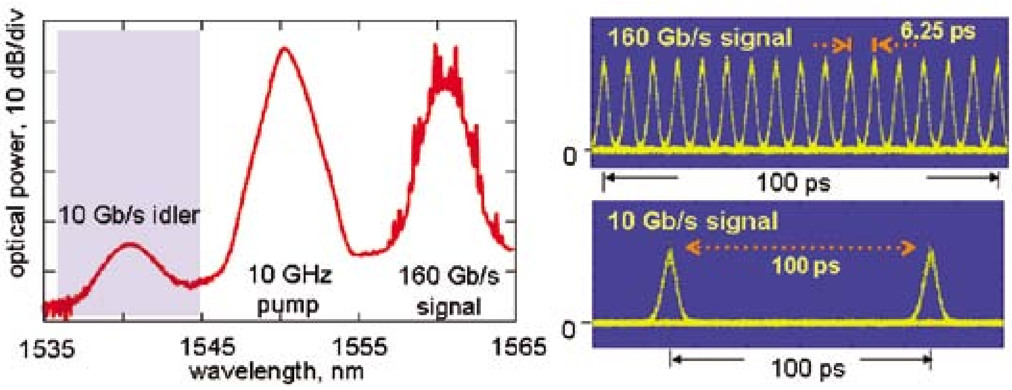



**Fig 7. Demonstration of low power (25 mW) time-division demultiplexing of a 160 Gb/s signal in a 5 cm length tapered $As_2S_3$ fibre (a) Output optical spectra showing generation of a 10 Gb/s idler by FWM between the signal and 10 GHz pump pulse train, and (right) high-speed sampling scope images of (b) (upper) 160 Gb/s input signal and (lower) 10 Gb/s tributary channel contained in the FWM idler after optically filtering the waveguide output spectrum.**

## Targets for 2009

Drawing on progress in 2008, our objectives in 2009 will be the development of advanced chalcogenide waveguides enabling a wider range of signal processing functions at high bit-rates of 320 Gb/s (and above) for both conventional and advanced data modulation formatted signals (such as DPSK), as well as lowering the required optical power, while maintaining high broadband performance.

Central to these goals will be fabricating dispersion-shifted waveguides exhibiting higher nonlinear Kerr effect for enhancing applications such as performance monitoring, wavelength conversion, optical parametric amplification, supercontinuum generation and optical phase conjugation. Research of novel applications of nonlinear signal processing in areas of signal regeneration, performance monitoring, broadband signal analysis and high-resolution optical sampling will be investigated initially using highly nonlinear silica fibres as a proof of principle demonstrator platform.

The key milestone for waveguide fabrication will be investigating the origin of the observed higher propagation losses for the dispersion-shifted $As_2S_3$ waveguides and its dependence on the deposited film thickness. Schemes for lowering fibre coupling losses will also be considered as a means for improving the device insertion loss.

A parallel approach will be the ongoing investigation of novel chalcogenide compositions as a step towards developing waveguides exhibiting higher nonlinearity coefficient than previous $As_2S_3$ devices of comparable physical dimensions. Focus will be on the optimized Ge of Ge-As-Se while exploring other promising ternary glasses.

Processing of $As_2S_3$ waveguides by the new electron beam lithography etch system will continue with the objective of achieving a "nanowire" device demonstrating a dramatic enhancement of the nonlinearity coefficient for enabling nonlinear signal processing or more broadband phase and group velocity matched processes with lower power requirements or much shorter interaction lengths.

A parallel milestone will be the development of a buried channel waveguide as a step towards realizing polarization independent photonic chip circuits for more flexible nonlinear signal processing.

The target outcomes will be higher performing signal diagnostic tools and monitors including broadband photonic chip based RF spectrum analyzers and high resolution optical sampling oscilloscopes. Supercontinuum generation and parametric amplifiers will be investigated taking advantage of the broadband phase-matched parametric processes enabled by the virtual "lumped" nonlinearity and broadband low dispersion of the waveguide. This will be applied to ultra-fast clock recovery and time-division demultiplexing at bit rates approaching 320 Gb/s for both conventional return-to-zero data modulation format, and advanced formats such as DPSK.

Nonlinear signal processing will also be performed using tapered chalcogenide fibres to highlight the broadband capability enabled by its dispersion-shifted design and enhanced nonlinearity. Improved power handling will also be investigated for enabling robust operation for other high bit-rate signal processing applications.

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