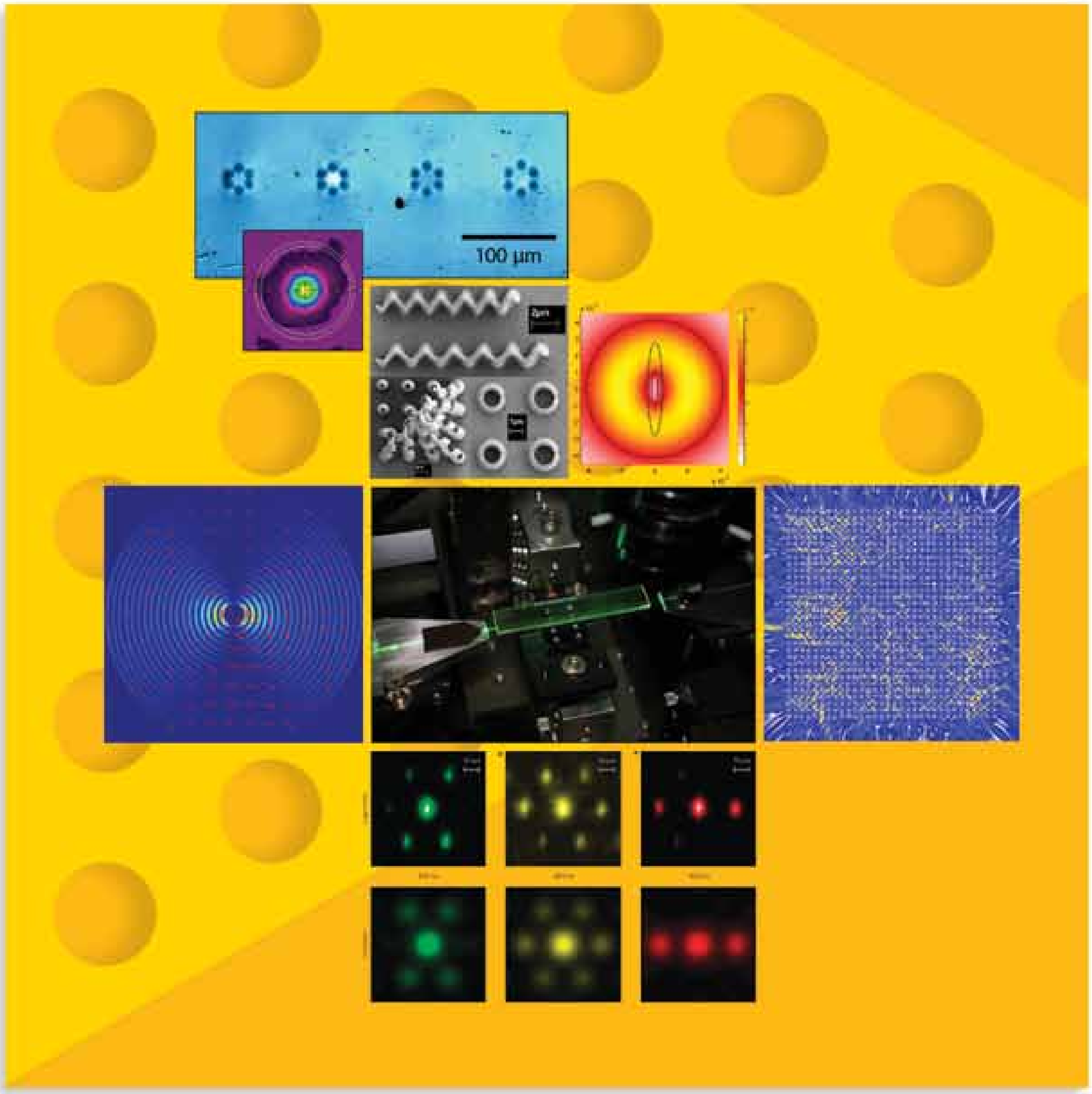
ANNUAL 2009 REPORT



CUDOS

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

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 signals 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) and for advanced data modulation formats, (such as differential phase-shift keying (DPSK)), and high capacity wavelength division multiplexed (WDM) signals; 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 will be 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.

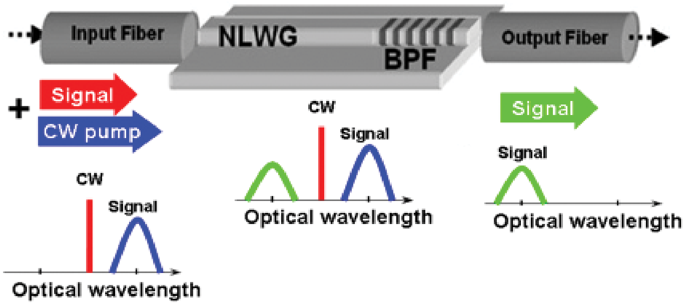

Fig 1. Concept of a phase preserving wavelength converter based on CW pumped FWM by the ultra-fast optical Kerr effect in a nonlinear waveguide (NLWG), which has a bandpass optical filter (BPF) integrated in the same device.

CUDOS strategy/competitive advantage

Our key strategy and competitive advantage is based on the use of chalcogenide glass. Optical waveguides made from this material

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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 to be achieved in compact waveguide devices via the optical Kerr effect 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 wavelength conversion and regeneration of optical signals is tested at Sydney using a high-speed optical communication system (Fig. 3), which was upgraded in 2009 to produce higher-speed (640 Gb/s) signals, and is currently in the process of being upgraded to 1.28 Tb/s.

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

Fig 3. High-speed optical communication facility for generating, transmitting and detecting high-speed data signals with serial bit-rate up to 640 Gb/s. This system enables the testing of the bit-error rate performance of the nonlinear optical devices in broadband signal processing applications.

Collaborative links

Progress toward our centre'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 2009

In broad terms, our 2009 goals were to build upon the successful fabrication of the dispersion-shifted, highly nonlinear As_2S_3 waveguides in 2008, and investigate different approaches for further enhancing their nonlinear response. A primary objective was to study the origin and possible mitigation of the propagation and coupling losses for As_2S_3 waveguides. This would be an important step for performing a wider range of nonlinear signal processing functions at bandwidths beyond the conventional 40 Gb/s speed limit of opto-electronic systems. A target milestone was obtaining sufficient four-wave mixing (FWM) of the signal for a CW (rather than pulsed) pump source of moderate optical power (below several hundred milli-Watts). This in turn would enable phase-preserving processing of signals encoded with advanced data modulation formats, such as DPSK.

The targeted approaches were to investigate the contribution to propagation losses from the waveguide surface roughening produced during the fabrication process. A suitable on-chip taper structure would also be designed to improve the coupling loss from standard single mode fibre. Application of a suitable anti-reflection coating to the waveguide end-facets was also targeted for countering Fabry-Perot effects, which impact the propagation of narrow spectral linewidth optical sources (as in the case of CW pumped FWM).

A parallel objective was to customize the electron-beam lithography system to fabricate smaller rib structures in Chalcogenide glass to further enhance the nonlinearity coefficient by an order of magnitude over the current 2 μm wide rib waveguides. This would require fabricating smooth, nano-scale features, beyond the capabilities of the standard contact photolithography approach currently in use. The enhanced nonlinearity coefficient for the smaller size mode would enable signal processing with lower powers in more miniature photonic circuits.

Fabrication of dispersion-shifted waveguides from the advanced ternary glass system of As-Se-Ge was also targeted for exploiting its much higher nonlinear index compared to As_2S_3. Studies in 2008 showed this material to be a promising candidate for its higher nonlinear refractive index (approaching 500 times silica compared to ~110 times for As_2S_3) and comparable stability, and power handling to As_2S_3. In parallel, fabrication of a proof of concept buried-channel waveguide in chalcogenide was also targeted as a step toward realizing polarization independent optical circuits.

The outcome objectives for the chalcogenide chips were demonstrations of higher performing signal processing for broadband signals. The devices would be tested using the 640 Gb/s optical communication facility at USyd to perform phase preserving wavelength conversion of signals encoded with advanced data modulation formats (such as DPSK) and high bit-rates (from 40 to 640 Gb/s). Achieving high performance optical phase conjugation was targeted for demonstrating the capability of chalcogenides to perform parallel regeneration of WDM signals in long-haul fibre transmission systems. Other objectives include the demonstration of high-speed, all-optical clock recovery and ultra-high speed signal processing at bit-rates of 640 Gb/s and beyond.

Experiments would also demonstrate the capability of chalcogenides for high performance ultra-fast signal analysis. The targeted applications include the realization of an all-optical sampling oscilloscope with a very short temporal resolution (well below the typical ~1 ps resolution of commercial systems), and demonstration of an RF spectrum analyzer for monitoring the performance of higher bit rate (640 Gb/s) signals, and short (femtosecond) pulses. The novel capability of using the broadband RF spectrum data to retrieve the autocorrelation waveform of both ultra-short pulses and high-speed data signals (as an alternative approach to the standard conventional scanning delay Michelson interferometer) would also be investigated to provide advanced optical performance monitoring functionality.

Achievements and highlights for 2009

Chalcogenide waveguides

The focus in 2009 was to build upon the successful fabrication of the dispersion-shifted chalcogenide waveguides in 2008, and investigate the impact of the surface roughening of As_2S_3 waveguides on their propagation losses. This involved a detailed study and customization of various stages of the waveguide fabrication process, including the optimization of the glass thermal annealing temperature, as well as use of different protective layers in the lithographic process to prevent roughening of the waveguide core/cladding interfaces from chemical attack. A suitable anti-reflection coating for the waveguide end-facets was also successfully developed based on TiO2/Si02 for preventing Fabry Perot interference effects during the propagation of narrow spectral line-width optical sources (such as CW lasers). These combined advances yielded lower propagation losses by a factor of two to ~0.3 dB/cm (for the TM mode of a dispersion-shifted, 2 μm wide rib waveguide etched into a 0.85 μm thick film of As_2S_3), and suppressed Fabry-Perot effects for CW laser propagation. Furthermore, a significantly higher power handling was observed, reaching the unprecedented levels of 0.5W (average) coupled in the waveguide itself. On-chip inverse taper structures were also designed, as an important first step toward overcoming the large coupling losses to standard optical fibre for future waveguides (currently ~5 dB per facet for coupling to a mode of ~1 μm2 effective area).

Other advances include the novel fabrication of dispersion-shifted waveguides in the unique glass composition of $Ge_{11.5}As_{24}Se_{64.5}$ with its higher nonlinear index (about triple that of As_2S_3). This involved further customization of the recently established electron-beam lithography system to produce "nano-waveguide" planar waveguides with a core size of 630 nm × 520 nm. Detailed studies of this optimized material in 2008 found it to have comparable optical power handling capability to As_2S_3. The fabricated nano-waveguide with a combined higher nonlinear index and smaller effective mode area demonstrated a record-breaking nonlinearity coefficient (15 times that of the dispersion-shifted 2 μm rib waveguides fabricated in As_2S_3), and propagation losses of ~2.2dB/cm for the TM mode. Their capability for low power supercontinuum generation was shown.

Buried channel waveguides using a $Ge_{11.5}As_{24}Se_{64.5}$ core and As-S cladding were also successfully fabricated with losses of 0.2 dB/cm; marking an important step toward realizing polarization insensitive nonlinear signal processing.

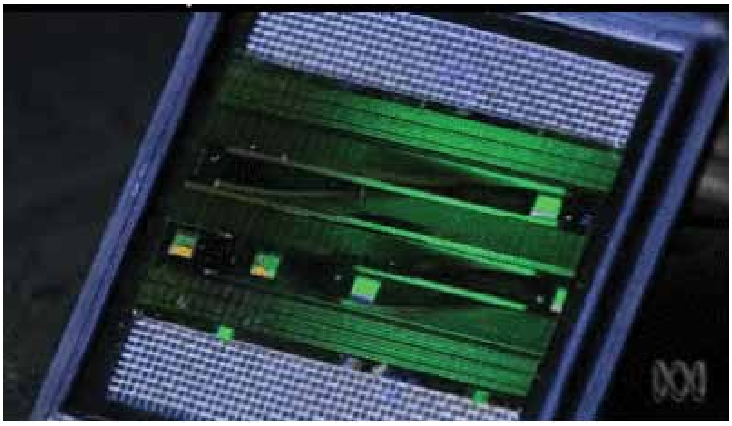


Fig 4. Image of the 6 cm size As_2S_3 optical chip fabricated at ANU, consisting of a series of straight and serpentine shaped planar waveguide of various rib widths for tailoring the total dispersion to enable broader bandwidth signal processing. Source: ABC Catalyst (03/09/2009) (http://www.abc.net.au/catalyst/stories/2675781.htm)

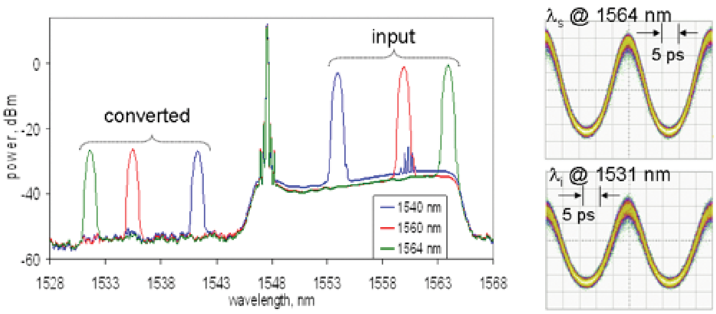
Nonlinear optical signal processing

The improved As_2S_3 planar rib waveguides with a combined lower loss, higher power handling and anti-reflection coated end facets, enabled FWM by a CW pump source in chalcogenide glass for the first time. This in turn enabled a series of phase-preserving signal processing experiments using the high-speed optical communication facility. Results included the first demonstration of wavelength conversion of DPSK signals by the optical Kerr effect in a planar waveguide [1], as shown in Fig. 5. The capability for even higher bit rate (160 Gb/s) operation for on-off keying format signals was also shown. These experiments laid the ground work for demonstrating the regeneration of a WDM signal encoded as DPSK, by performing optical phase conjugation in a chalcogenide waveguide positioned along a long distance fibre transmission link [2]

The performance advantages of the improved dispersion shifted As_2S_3 waveguides were also highlighted in collaborative experiments with DTU in Denmark, in demonstrating time-division demultiplexing of a signal with a record high serial bit rate of 1.28 Tb/s. The high performance achieved relied on the broadband low dispersion of the short length, dispersion-shifted As_2S_3 waveguide to fully exploit the ultra-fast nonlinear response. The same waveguides also demonstrated a broadband capability for ultra-fast signal characterization. Experiments included an ultra-fast optical sampling oscilloscope with <500 fs temporal resolution [3], for enabling the "eye diagram" measurement of a high-speed 640 Gb/s bit-rate signal, as shown in Fig. 6. Optical sampling of 640 Gb/s signals was also demonstrated using a 5 cm length tapered fibre of As_2S_3 glass [4], which stands as the shortest length fibre device used for optical sampling ever reported to date.

The multi-terahertz bandwidth RF spectrum analyser that was first demonstrated in 2008 was further investigated in 2009 for analysing higher bit-rate (640 Gb/s) signals and short pulses. New experiments showed the capability of using the measured broadband RF spectrum trace to retrieve an accurate autocorrelation waveform of both femtosecond pulses [5] and high-speed signals [6], as shown in Fig. 7. The temporal waveform obtained by performing an inverse Fourier transform of the measured RF spectrum data provided a unique alternative approach for autocorrelation analysis compared to using a scanning delay, Michelson interferometer. The operation yielded advanced performance monitoring functionality, including the capability to measure multiple impairments of broadband signals (such as its level of noise, timing jitter and dispersion), in a single measurement simultaneously [6]. The demonstration of the technique for higher bit-rate (640 Gb/s) signals using a chalcogenide waveguide was also shown [7].

A novel scheme for monitoring the in-band noise of multiple channels of a WDM signal simultaneously in a single measurement was also conceived and demonstrated for the first time. The simple approach based on measuring the back-reflected Stokes wave generated for each channel by the nonlinear effect of Stimulated Brillouin scattering in a fibre, demonstrated the measurement of the in-band noise of a three channel 40 Gb/s signal. Results highlighted the advantages of a combined high sensitivity, and dynamic range in the power reading over a wide ranging noise level, as well as insensitivity to the polarization of the input signal [8].



A

B

Fig 5. Broadband wavelength conversion of a 40 Gb/s DPSK signals (by the concept in Fig. 1) using FWM of the signal with a CW pump source in a 6 cm length As_2S_3 rib waveguide. (a) Overlaid optical spectra measurements from the waveguide for the input signal tuned to various wavelengths between 1554-1564 nm (and the CW laser fixed at 1547 nm), to generate the signal at new (shorter) wavelengths. Optical filtering is used to extract the wavelength converted signal. (b) "Eye diagrams" of the 40 Gb/s signal as measured on a high speed oscilloscope following the DPSK demodulator, both (top) before and (lower) and after wavelength conversion from 1564 nm to 1531 nm.

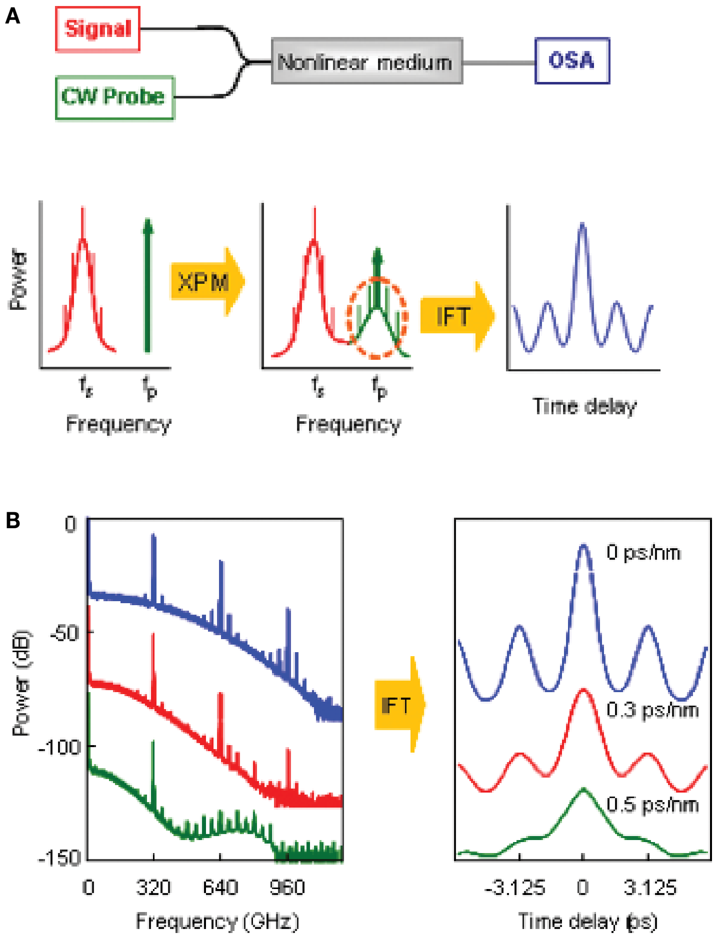


Fig 7. (a) Concept of the multi-terahertz bandwidth RF spectrum analyser based on measuring the XPM effect of the signal under test (at carrier frequency f_s) on a CW laser (of carrier frequency f_p) during co-propagation in a chalcogenide waveguide. The XPM sidebands observed on an optical spectrum analyser (OSA) around the frequency, f_p, correspond to the signal RF spectrum, which in turn is used to retrieve the autocorrelation trace by performing an inverse Fourier transform (IFT) operation numerically. (b) Experimental measurements showing the (left) RF spectra of a high-speed 320 Gb/s signal distorted by different levels of chromatic dispersion, and (right) the autocorrelation waveforms retrieved from the measured RF spectrum, revealing the temporal broadening due to dispersion.

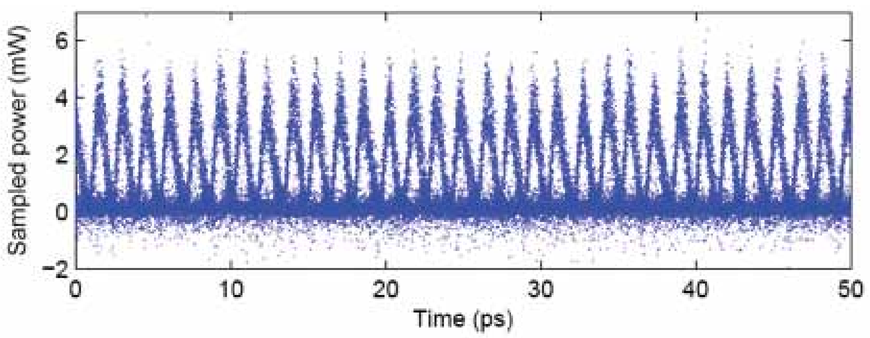


Fig 6. Optical sampling using a dispersion-shifted As_2S_3 waveguide for the nonlinear medium, to generate a high resolution "eye diagram" trace of a 640 Gb/s optical signal.

Targets for 2010

Drawing on progress in 2009, our objectives in 2010 will be to improve upon the fabrication of chalcogenide waveguides to enable a wider range of signal processing functions at high bit-rates of 640 Gb/s (and above) for both conventional and advanced data modulation formatted signals (such as DPSK), as well as higher-capacity WDM signals.

Central to these goals will be fabricating dispersion-shifted waveguides exhibiting even higher nonlinear response (optical Kerr effect) to enhance the broadband performance of 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 also be pursued based initially on using highly nonlinear silica fibres as a proof of principle demonstrator platform.

The approaches for increasing the nonlinear response include fabricating waveguides in advanced glass compositions that can provide a higher nonlinear index than As_2S_3, while maintaining a comparable robustness, power handling, and low photo-sensitivity at the signal wavelength (around 1.55 μm). The design and fabrication of smaller dimension (nanoscale) dispersion-shifted planar rib waveguides in the proven As_2S_3 glass will also be explored, drawing on the progress in 2009 on using the new electron beam lithography system for Ge-As-Se. Fabrication of the on-chip taper designs of 2009 will be a crucial development for reducing the coupling losses to standard fibre, to raise the nonlinear response. Further progress toward demonstrating a buried channel waveguide for polarization insensitive, nonlinear signal processing applications will also be pursued.

The target outcomes will be the demonstration of higher performing signal diagnostic tools and multi-impairment monitors. These include the broadband RF spectrum analysis of high-speed phase encoded signals (such as DPSK), and an optical sampling oscilloscope with a record short temporal resolution (less than several hundred femtoseconds). Supercontinuum generation and parametric amplifiers will also be investigated taking advantage of the broadband phase-matched parametric processes enabled by the virtual "lumped" nonlinearity and broadband low dispersion of the waveguide. The waveguide will also be applied to ultra-fast all-optical clock recovery at bit rates of 160 Gb/s and above, and Tb/s signal processing, including packet header recognition, for both conventional return-to-zero data modulation format, and advanced formats such as DPSK. The use of CW pumped FWM for optical phase for broadband wavelength conversion of higher bit-rate signals, and parallel regeneration of higher capacity WDM signals via optical phase conjugation in long haul transmission links will be further investigated.

References

1. 1M.D. Pelusi, F. Luan, S. Madden, D.-Y. Choi, D.A. Bulla, B. Luther-Davies, B.J. Eggleton, "Wavelength Conversion of High-Speed Phase and Intensity Modulated Signals Using a Highly Nonlinear Chalcogenide Glass Chip," IEEE Photon. Tech. Lett, IEEE , vol. 22, no.1, pp. 3-5, Jan.1, 2010.
2. 1M.D. Pelusi, F. Luan, S. Madden, D.Y. Choi, D. Bulla, B. Luther-Davies, and B. Eggleton, "Optical Phase Conjugation in Chalcogenide Planar Waveguides for Compensating Signal Transmission Effects", Optical Fiber communication/National Fiber Optic Engineers Conference, paper OWW4, San Diego, CA, U.S.A., 2010.
3. J. Van Erps, F. Luan, M.D. Pelusi, T. Iredale, S. Madden, D.-Y. Choi, D.A. Bulla, B. Luther-Davies, H. Thienpont, and B.J. Eggleton , "High-Resolution Optical sampling of 640-Gb/s data using four-wave mixing in dispersion-engineered highly nonlinear As_2S_3 planar waveguides", J. Lightwave Technol., vol. 28, pp. 209-215, 2010.
4. F. Luan, J.V. Erps, M.D. Pelusi, E. Magi, T. Iredale, H. Thienpont, and B.J. Eggleton, "High-resolution optical sampling of 640 Gbit/s data using dispersion-engineered chalcogenide photonic wire", Electron. Lett. vol. 46, pp. 231–232, 2010.
5. M.D. Pelusi, T.D. Vo, F. Luan, S.J. Madden, D.-Y. Choi, D.A.P. Bulla, B. Luther-Davies, and B.J. Eggleton, "Terahertz bandwidth RF spectrum analysis of femtosecond pulses using a chalcogenide chip," Opt. Express 17, pp. 9314-9322, 2009.
6. T.D. Vo, M.D. Pelusi, J. Schröder, B. Corcoran, and B.J. Eggleton, "Multi-Impairment Monitoring at 320 Gb/s Based on Cross-Phase Modulation Radio-Frequency Spectrum Analyzer", IEEE Photon Tech. L., vol. 22, no. 6, March 15, pp. 428-430, 2010.
7. T.D. Vo, M.D. Pelusi, J. Schröder, F. Luan, S.J. Madden, D.-Y. Choi, D.A.P. Bulla, B. Luther-Davies, and B.J. Eggleton, "Simultaneous multi-impairment monitoring of 640 Gb/s signals using photonic chip based RF spectrum analyzer", Opt. Express, vol. 18, pp. 3938-3945, 2010.
8. A. Fu, M.D. Pelusi, and B. Eggleton, "Simultaneous monitoring of in-band optical noise for WDM signals using Stimulated Brillouin Scattering", Optical Fiber communication/National Fiber Optic Engineers Conference, paper OWB2, San Diego, CA, U.S.A., 2010.