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 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 (Fig. 1). These devices offer performance and footprint 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.

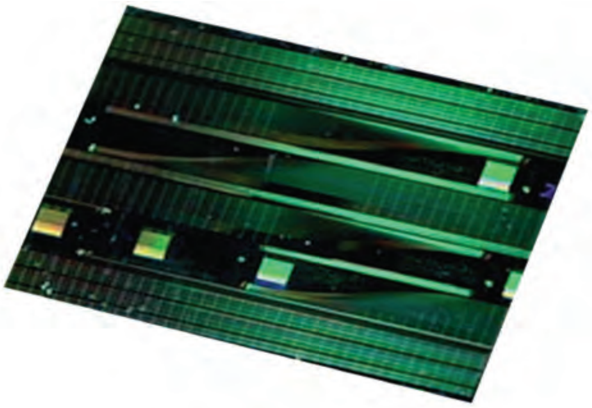

Fig 1: The As_2S_3 optical chip developed by CUDOS for performing ultra-high bandwidth, all-optical signal processing by using its high nonlinearity, which has an ultra-fast response time. Source: ABC Catalyst (03/09/2009) http://www.abc.net.au/catalyst/stories/2675781.htm

Nonlinear optical signal processing team.

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 with an ultra-fast response, 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 (Fig. 2); and film processing to create state-of-the art low loss optical waveguides with ultra-high nonlinearity (Fig. 1).

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 2010 to generate optical signals at the higher bit-rate of 1.28 Tb/s (Fig. 4). This is now a state of the art system in terms of generating such a high signalling baud rate.

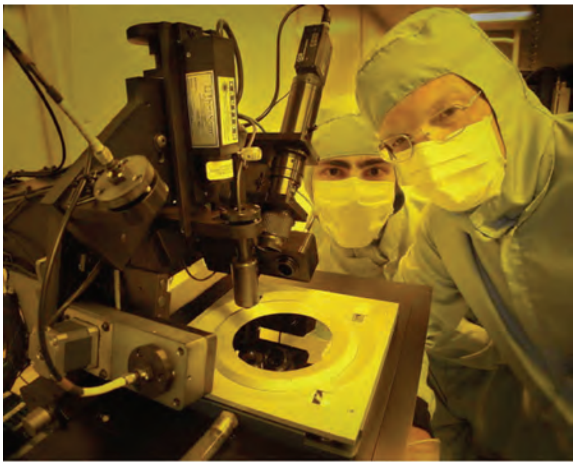

Fig 2: Deposited thin films of chalcogenide glass undergoing characterization before photolithographic etching into rib waveguides.

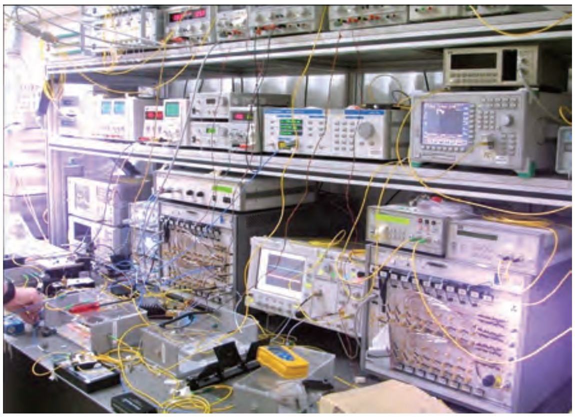

Fig 3: High-speed optical communication facility for generating, transmitting and detecting high-speed optical signals with serial bit-rate up to 1.28 Tb/s. This system enables the testing of the bit-error rate performance of the nonlinear optical devices in broadband signal processing applications.

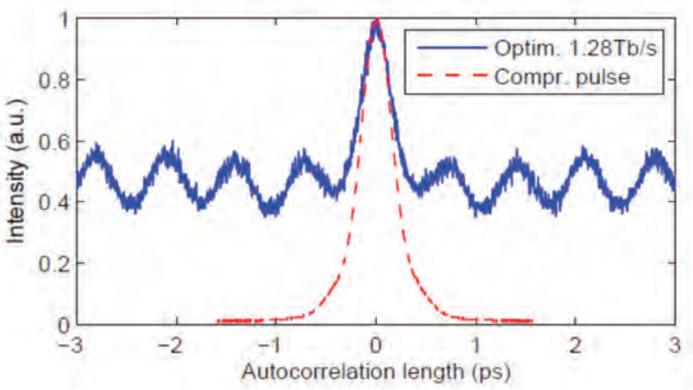

Fig 4: Waveforms of an ultra-high speed 1.28 Tb/s optical signal generated from a source of pulses of 275 fs duration.

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 2010

In broad terms, our 2010 goals were to increase the nonlinear response of the dispersion-shifted, highly nonlinear planar rib waveguides fabricated in chalcogenide glass by reducing the optical losses, and optimizing the annealing conditions to minimize the photosensitivity. The target outcome from these improvements would be the demonstration of more challenging all-optical signal processing functionality, such as low power all-optical switching and logic.

A key milestone towards this goal would be the design of a suitable on chip taper structure that is capable of overcoming the main source of loss stemming from the mode field mismatch for coupling between the waveguide and standard single mode fibre. The design would aim to reduce losses from the current ≈5 dB per facet to below 1 dB per facet for the existing rib waveguide dimensions of 2×0.85 μm. A parallel effort would also aim to reduce the ≈0.5 dB/cm propagation loss for the waveguide TM mode by improving the fabrication process to produce smoother surfaces for the rib waveguide etched from an As_2S_3 film. This in turn would enable a higher nonlinearity to be harnessed over longer propagation distances without the need for boosting the launched optical power.

The gain in nonlinear response from these improvements would translate to higher power efficiency for nonlinear processes such as FWM between the signal and a CW pump. This is a key objective for enabling all-optical signal processing with transparency to both the bit-rate and data modulation format, including phase encoded signals such as DPSK. Other demonstrations would be the optical processing of WDM signals, and the capability to perform multiple impairment monitoring for optical signals at ultra higher bit rates up to 1.28 Tb/s, as well as for signals encoded by phase modulation rather than conventional intensity modulation.

Achievements and highlights for 2010

Chalcogenide waveguides

The focus in 2010 was to further improve the state of the art dispersion-shifted chalcogenide waveguides by reducing their losses and optimizing the annealing process to minimize their photosensitivity. Annealing studies revealed that performing so-called "green burning" of the thermally deposited As_2S_3 films was effective in relaxing the chemical bonds so that its state became closer to that of bulk As_2S_3 glass. This in turn translated to favourable changes in its optical properties towards the bulk, such as a higher refractive index and lower photosensitivity. Other advances include optimizing the waveguide fabrication process to significantly reduce the propagation losses for the 2×0.85 μm As_2S_3 rib waveguides from 0.5 down to ~0.3 dB/cm. The key to this was minimizing the waveguide surface roughness by applying an Al_2O_3 coating to the As_2S_3 surface, and applying a SU8 coat to protect the As_2S_3 material during photolithography. Another important milestone was the successful design of a vertical taper structure capable of reducing the coupling loss between the As_2S_3 waveguide and standard single mode fibre from the current 5 dB/facet to below 1 dB/ facet. Importantly, this design can be implemented with the existing fabrication process.

Nonlinear optical signal processing

The improved performance of the lower loss As_2S_3 waveguides was highlighted in various nonlinear signal processing demonstrations. One was the harnessing of the optical chip's nonlinearity to generate the light intensity spectrum (i.e. the RF spectrum) over multi-terahertz frequencies for ultra-high bit rate signals as high as 1.28 Tb/s [1,2]. The all-optical scheme, which is based on the nonlinear Kerr effect on the signal inducing XPM of a co-propagating CW probe, was used to measure and quantify signal distortions such as chromatic dispersion and noise. This in turn was used as shown in Fig. 5(a) to provide a feedback control signal to a programmable dispersion compensator for enabling automatic dispersion compensation [2], which is crucial for such high bit rate signals whose pulse width is only a fraction of a picosecond. Fig. 5(b) shows the light intensity spectrum generated by a 6 cm long As_2S_3 optical chip for an input 1.28 Tb/s optically time division multiplexed (OTDM) signal. In this case, the level of signal distortion was inferred by monitoring the spectral power of the high frequency clock tones, which provided the means for its feedback optimization. Parallel efforts also demonstrated for the first time the capability of applying the scheme to simultaneously monitor both the dispersion and noise of phase encoded signals instead of conventional intensity modulated signals [3].

The RF spectrum measurement technique was also demonstrated for the first time using a silicon optical chip [4]. This was an important outcome because of silicon's strong potential for photonic integration and low fabrication cost. Furthermore, the demonstration with an ultra-high bit rate 640 Gb/s OTDM signal proved the capability of silicon to perform high-speed signal processing without significant impact from its typically significant nonlinear losses, which is otherwise its main disadvantage compared to As_2S_3. An analysis of the RF spectrum generation scheme for different nonlinear platforms including common highly nonlinear fibre has shown that the planar As_2S_3 waveguide has achieved the best performance to date in terms of the highest measurement accuracy, broadest bandwidth and flexibility of the signal wavelength [5]. These merits stem from its combined high nonlinearity, short length and dispersion shifted design.

Other key outcomes included the first demonstration of using the $\chi^{(3)}$ nonlinearity of a planar waveguide to perform parallel all-optical phase conjugation of a WDM phase encoded signal within a long distance optical fibre link [6]. In that demonstration, a single 6 cm long As_2S_3 waveguide was inserted near the midpoint of a 225 km link of standard single mode fibre in order spectrally invert a three channel WDM 40 Gb/s DPSK signal. This single optical chip enabled the entire chromatic dispersion of the 225 km link to be completely cancelled without the need for conventional dispersion compensation modules (Fig. 6). In parallel efforts, the chalcogenide waveguide also demonstrated the capability for on-chip erasure, which is an important milestone towards realizing ultra-fast logic on a monolithic optical chip platform [7].

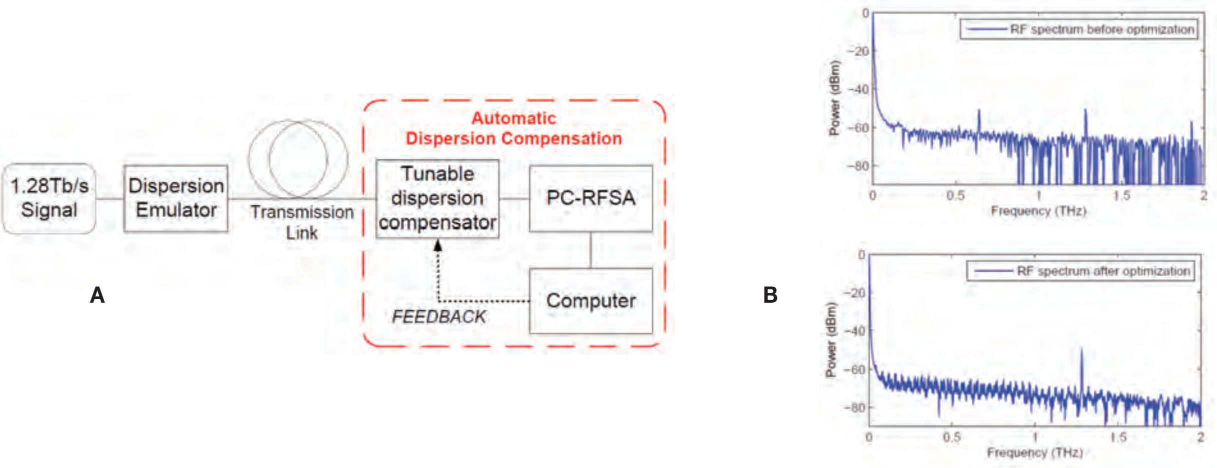

Fig 5: (a) Experimental set-up for automatically equalizing the signal distortion of a 1.28 Tb/s OTDM signal by using a novel feedback control circuit, which incorporates a chalcogenide planar waveguide as a photonic chip RF spectrum analyzer (PC-RFSA). The all-optical device is capable of measuring the signal light intensity spectrum over multi-terahertz frequencies to reveal waveform distortions such as dispersion and noise. (b) Light intensity spectrum of the 1.28 Tb/s OTDM signal generated by XPM of a CW probe in the highly nonlinear chalcogenide waveguide, for enabling the monitoring and feedback optimization of the signal after transmission. The left and right figures show the spectrum before and after feedback optimization, respectively, whereupon the signal chromatic dispersion is optimally compensated.

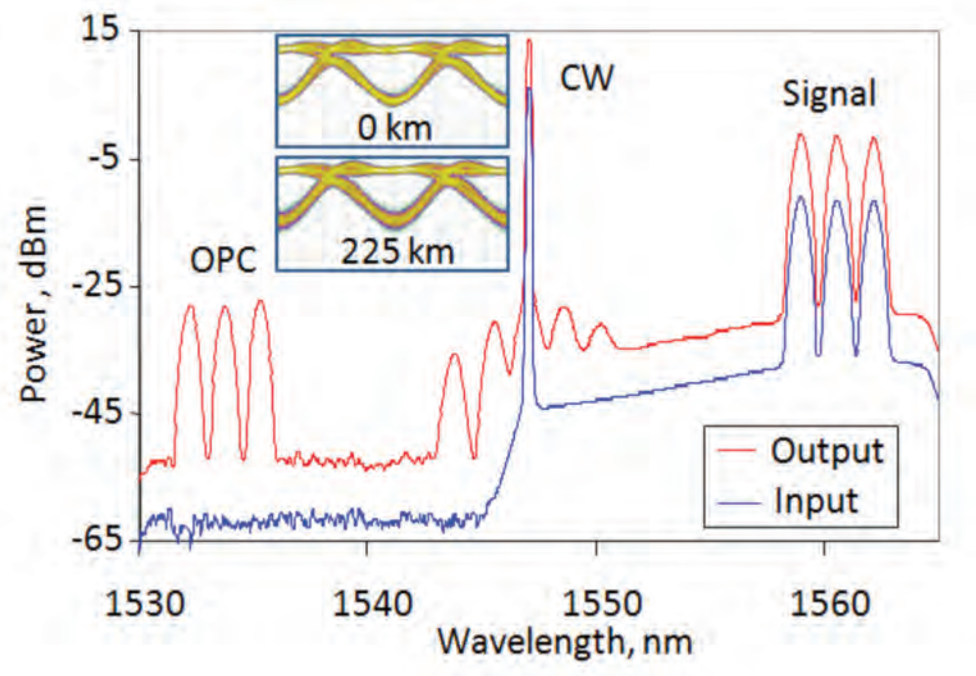

Fig 6: Optical spectrum measured at the output of a 6 cm long chalcogenide planar waveguide showing the FWM of a 3×40 Gb/s return-to-zero (RZ) DPSK signal with a CW pump beam to produce the optical phase conjugate (OPC) at shorter wavelengths. Inserting the optical chip within a 225 km long optical fibre link enabled the total link dispersion to be completely cancelled. The inset highlights the small distortion of the 40 Gb/s eye diagram at the link output in comparison to the input (for the centre channel after DPSK demodulation).

References

1. T.D. Vo, H. Hu, M. Galili, E. Palushani, J. Xu, L.K. Oxenløwe, S.J. Madden, D.-Y. Choi, D.A.P. Bulla, M.D. Pelusi, J. Schröder, B. Luther-Davies, and B.J. Eggleton, "Photonic chip based transmitter optimization and receiver demultiplexing of a 1.28 Tbit/s OTDM signal", Optics Express, vol. 18, pp. 17252-17261, 2010.

2. J. Van Erps, J. Schröder, T.D. Vo, M.D. Pelusi, S. Madden, D.-Y. Choi, D.A. Bulla, B. Luther-Davies, and B.J. Eggleton, "Automatic dispersion compensation for 1.28Tb/s OTDM signal transmission using photonic-chip-based dispersion monitoring", Optics Express, vol. 18, pp. 25415-25421, 2010.

3. T.D. Vo, J. Schröder, M.D. Pelusi, S.J. Madden, D.-Y. Choi, D.A.P. Bulla, B. Luther-Davies, and B.J. Eggleton, "Photonic chip based simultaneous multi-impairment monitoring for phase-modulated optical signals", Journal of Lightwave Technology, vol. 28, pp. 3176-3183, 2010.

4. B. Corcoran, T.D. Vo, M.D. Pelusi, C. Monat, D.-X. Xu, A. Densmore, R. Ma, S. Janz, D.J. Moss, and B.J. Eggleton, "Silicon nanowire based radio-frequency spectrum analyzer", Optics Express, vol. 18, pp. 20190-20200, 2010.

5. M.D. Pelusi, T.D. Vo, and B.J. Eggleton, "Accuracy of waveform spectrum analysis for ultrashort optical pulses", IEEE Transactions on Microwave Theory and Techniques, vol. 58, pp. 3059-3070, 2010.

6. M.D. Pelusi, F. Luan, D.-Y. Choi, S.J. Madden, D.A.P. Bulla, B. Luther-Davies, and B.J. Eggleton, "Optical phase conjugation by an As_2S_3 glass planar waveguide for dispersion-free transmission of WDM-DPSK signals over fiber", Optics Express, vol. 18, pp. 26686-26694, 2010.

7. R. Pant, T.D. Vo, C. Xiong, M.D. Pelusi, S.J. Madden, B. Luther-Davies, and B.J. Eggleton, "Ultrahigh bandwidth, on-chip all-optical pulse erasure using $\chi^{(3)}$ process in a nonlinear waveguide", Optics Letters, vol. 36, pp.298-300, 2011.