Error-free wavelength conversion via cross-phase modulation in 5 cm of As_2S_3 chalcogenide glass rib waveguide

M.R.E. Lamont, V.G. Ta'eed, M.A.F. Roelens, D.J. Moss, B.J. Eggleton, D.-Y. Choi, S. Madden and B. Luther-Davies

The first demonstration of all-optical signal processing at telecommunication data rates in chalcogenide glass waveguides is reported. Error-free wavelength conversion via cross-phase modulation in a low-loss, 5 cm-long As_2S_3 chalcogenide planar waveguide, over a 25 nm wavelength range at 10 Gbit/s, was achieved, yielding a Q-factor penalty of 2.3 dB.

Introduction: All-optical signal processing, particularly that based on the ultrafast (< 50 fs [1]) third-order susceptibility $\chi^{(3)}$, has attracted significant interest in recent years as a potential solution for the anticipated electronic bottleneck beyond 40 Gbit/s in ultra-high bandwidth optical communications systems. To date, however, all-optical signal processing has been mainly limited to fibre-based devices; only very recently have there been reports based on integrated waveguides. These include optical 2R regeneration [2] and wavelength conversion [3] in As_2S_3 chalcogenide glass waveguides (with its very large optical nonlinearity, n_2, and low two-photon absorption [4]) and four-wave mixing wavelength conversion in silicon [5, 6]. Chalcogenide glass, in particular, offers some significant advantages over silicon for all-optical processing in the form of much lower nonlinear (two-photon) absorption (higher figure of merit) and potentially much larger optical nonlinearity n_2.

To date, however, of the few reports of all-optical signal processing in waveguides, almost all have been based on low duty cycle optical pulses, primarily because of peak optical power requirements. In this Letter, we present the first demonstration of all-optical signal processing in integrated chalcogenide glass waveguides at full telecommunication data rates. We report error-free all-optical wavelength conversion, essential to enable agile and reconfigurable optical network architectures, using a technique of cross-phase modulation that was first demonstrated in silica fibre by Olsson *et al.* [7] and more recently in highly nonlinear glass fibre [8, 9]. Here, we achieve error-free wavelength conversion at 10 Gbit/s in a 5 cm-long As_2S_3 chalcogenide glass planar waveguide, over a 25 nm wavelength range, yielding a Q-factor penalty of 2.3 dB.

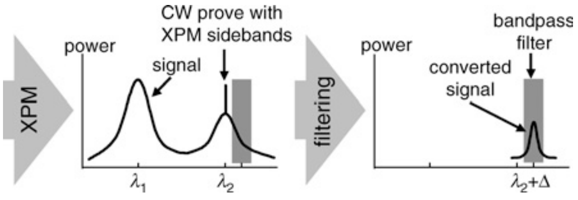

Fig. 1 *Principle of XPM sideband filtering*

Amplified signal pump creates XPM sideband on CW probe after propagation through nonlinear medium (left). Further sideband is filtered using passband filter to convert signal (right)

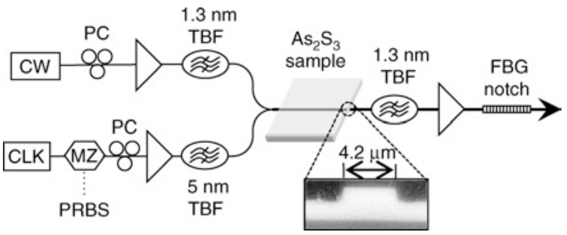

Fig. 2 *Experimental setup*

Containing 10 GHz clock (CLK), Mach-Zehnder modulator (MZ), pseudorandom bit sequencer (PRBS), polarisation controllers (PC), tunable bandpass filters (TBF), fibre Bragg notch grating (FBG notch)

Principle of operation: Fig. 1 demonstrates the use of cross-phase modulation (XPM) sideband filtering for wavelength conversion. An amplified pulsed signal propagates through a nonlinear medium and generates an index change via the nonlinear index coefficient, n_2. This causes a chirp in a co-propagating CW probe via XPM, generating sidebands on either side of the probe. By filtering out one of these sidebands, any return-to-zero data in the pulsed signal is translated to a wavelength just off the CW probe wavelength. The target wavelength can be adjusted by tuning the CW probe's wavelength, although the tuning range will be limited by the walk-off length. The group velocity mismatch between the signal and probe will cause one to 'walk-off' from the other. This reduced interaction length is given by

$$L_W = T_0/(D\,\Delta\lambda) \qquad (1)$$

where T_0 is the exponential half width of the pulse, D the dispersion and $\Delta\lambda$ the converted wavelength shift. One can see that, if the device length was equal to the walk-off length and the dispersion and pulse width remained similar, a device that can achieve the necessary performance in a shorter length would have a larger wavelength tuning range.

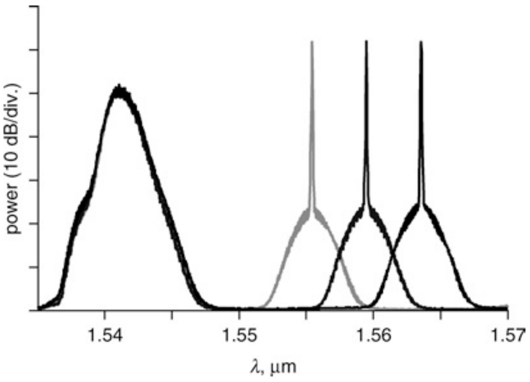

Fig. 3 *Spectra showing cross-phase modulation sidebands with probe set to three different wavelengths*

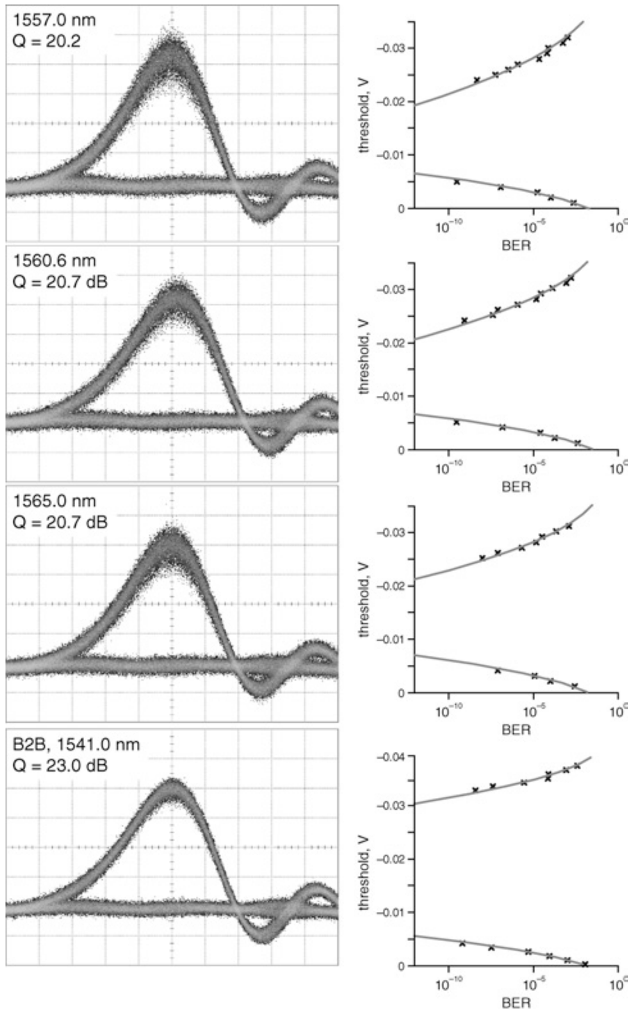

Fig. 4 *Eye diagrams of data converted to three different wavelengths and back-to-back pulse for comparison*

Experiment: As shown in Fig. 2, the input pump was provided by a 10 GHz clock signal with a full-width at half-maximum (FWHM) of 2.1 ps, which was modulated with a $2^{29}-1$ long PRBS, amplified and filtered to remove out-of-band ASE noise. This is combined through a 50/50 coupler with a CW probe which is also amplified and filtered for out-of-band ASE. The polarisations of both the pump and probe are controlled to allow alignment to the lower loss TE-mode of the waveguide and to maximise XPM. The combined signals are coupled into, and out of, the waveguide by butt-coupling SMF fibre pigtails with a short length of UHNA-4 spliced onto the end to better modefield diameter matching. Index matching fluid is applied to the butt-couple to minimise reflections, resulting in a coupling loss of ~2.2 dB per facet. The waveguide used in this experiment was fabricated using pulsed-laser deposition and dry etching, resulting in low propagation loss of ~0.3 dB/cm [10]. The pump was centred at 1541 nm with an average power of 115 mW (~5.8 W peak powers in the waveguide). The CW probe was 25 mW coupled in and set to three different wavelengths: 1555.4, 1559.5 and 1563.6 nm.

Results: Fig. 3 shows the XPM spectral broadening of the probe at the output of the waveguide. A significant portion of the CW probe remains owing to the low signal duty cycle. The amount of XPM spectral broadening is independent of the signal-probe wavelength offset. This is due to the short device length that ensures the dispersive pulse walk-off between the signal and probe is negligible. The bit error rates (BER) of the converted pulses were measured at all three probe wavelengths and the corresponding Q-factors were calculated [11], as shown in Fig. 4. The converted pulses were centred at 1557.0, 1560.6 and 1565.0 nm with Q-factors of 20.2, 20.7 and 20.7 dB, respectively. Comparing these Q-factors to that of the back-to-back signal at 1541 nm, the Q-factor penalty for wavelength conversion is 2.3 dB. While error-free wavelength conversion at telecommunication bit rates (10 Gbit/s and above) has been demonstrated in highly nonlinear fibre [7–9], this is the first demonstration based on pure Kerr (n_2) nonlinearities in an integrated planar waveguide device.

Conclusion: We have reported the first wavelength conversion in a 5 cm chalcogenide planar waveguide at telecommunication data rates, over 25 nm. Bit error rate measurements were taken, giving a Q-factor penalty of 2.3 dB. Owing to the short device length, group velocity mismatch will allow for conversion range of up to ±45 nm.

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M.R.E. Lamont, V.G. Ta'eed, M.A.F. Roelens and B.J. Eggleton (*Centre for Ultrahigh-bandwidth Devices for Optical Systems (CUDOS), School of Physics, University of Sydney, Sydney, NSW 2006, Australia*)

E-mail: mlamont@physics.usyd.edu.au

D.J. Moss (*Institut National de la Recherche Scientifique (INRS), Énergie, Matériaux et Télécommunications, Université du Québec, 1650 Boulevard Lionel-Boulet, Varennes, Québec J3X-1S2, Canada*)

D.-Y. Choi, S. Madden and B. Luther-Davies (*Centre for Ultrahigh-bandwidth Devices for Optical Systems (CUDOS), Laser Physics Centre, Australian National University, Canberra, ACT 0200, Australia*)

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