Breakthrough switching speed with an all-optical chalcogenide glass chip: 640 Gbit/s demultiplexing

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Abstract: We report the first demonstration of error-free 640 Gbit/s demultiplexing using the Kerr non-linearity of an only 5 cm long chalcogenide glass waveguide chip. Our approach exploits four-wave mixing by the instantaneous nonlinear response of chalcogenide. Excellent performance is achieved with only 2 dB average power penalty and no indication of error-floor. Characterisation of the FWM efficiency for the chalcogenide waveguide is given and confirms the good performance of the device.

OCIS codes: (070.4340) Nonlinear optical signal processing; (230.7390) Waveguides, planar.

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1. Introduction

The last year has seen the birth of the concept of 1 Tbit/s Ethernet [1] to carry the future Internet traffic. This is spurred on by the continuous Internet traffic growth, with an annual traffic percentage growth remaining double-digits (~ 60%). More people get a fibre-to-the-home (FTTH) and more bandwidth hungry applications such as video-on-demand and HD-TV broadcasting and social platforms as Facebook are widely used. With the introduction of the 1 Tbit/s Ethernet concept in [1], it was also stated that how to actually implement it is an open question, as current technologies cannot carry the burden. Therefore new fundamental approaches are needed. To this end, optical TDM may prove to be an attractive solution. At ultra-high bit rates approaching 1 Tbit/s, such as 640 Gbit/s, it is only possible to perform switching with all-optical means, but several platforms for high-speed optical signal processing have already been identified and demonstrated over the years including non-linear optical glass fibres [2, 12], semiconductor devices [3] and lithium niobate devices [4]. The pros and cons of these material platforms include the following: Fibres are very efficient, yet bulky due to required lengths of several tens of metres, semiconductor devices are compact, but suffer from competing response times associated with free-carriers, and lithium niobate is very efficient, but usually relies on strict resonance mixing of wavelengths from several wavelength regions, i.e. not all in the telecom band. Recently chalcogenide (As2S3) waveguides have been proposed as a new platform for optical signal processing offering good performance at ultra-high bit-rates in a small device [5]. These structures combine several desirable features for ultra-fast signal processing. In particular, the femtosecond response time associated with the third order non-linearity allows for flexible ultra-fast signal processing in and beyond the telecom C-band. Furthermore, the Kerr non-linearity does not rely on any free-carrier recovery, thus eliminating competing time scales intrinsic to semiconductor devices. Most importantly, the high non-linearity enables compact components with the potential for monolithic integration of multiple functionalities on a single-chip [6].

In this paper we report on a breakthrough with the first demonstration of error-free demultiplexing of a 640 Gbit/s data signal into its 10 Gbit/s tributaries in a 5 cm long As_2S_3 planar waveguide. These results are achieved using a simple four wave mixing (FWM) based scheme. Demultiplexing is performed with only 2 dB penalty, clearly demonstrating the potential of As_2S_3 waveguide devices for ultra-high-speed signal processing. The size reduction to the cm range is the critical step that will allow the fabrication of complex multi-channel devices with a high degree of functionality on a single chip operating at Tbit/s rates at practical power levels.

2. Experimental setup and results

Figure 1(a) shows the geometry of the As_2S_3 waveguide used for 640 Gbit/s demultiplexing. A 2.2 μm thick As_2S_3 layer is deposited by ultrafast pulsed laser deposition [7] onto a silica-on-silicon substrate. A 2 μm wide rib waveguide is formed by etching 1.0 μm into the As_2S_3 surface using the reactive ion etching techniques described in [8]. The sample is then coated with a polymer glass film and cleaved to yield a low loss waveguide device as per Fig. 1(a). The high refractive index of As_2S_3 yields a 2.9 μm^2 effective mode area, which combined with the high n_2 of As_2S_3 delivers a non-linear coefficient γ of ~4100 $W^{-1}\cdot km^{-1}$ and a second order dispersion coefficient β_2 of ~375 ps^2/km. The dispersion parameter D is ~-294 ps/nm/km and a typical slope is on the order of -1.4 ps/nm^2km for As_2S_3, and since the device is only 5 cm long, the residual slope and dispersion is very small. The pulse broadening is negligible – a 600 fs pulse is broadened to 630 fs. The walk-off between the control and data wavelengths is about 300 fs, which is acceptable for 640 Gbit/s and with the narrow pulses used here – in fact, it results in a more flat switching window and helps to reduce the influence of timing jitter. In order to generate the $\chi^{(3)}$-mediated non-linear process of four wave mixing (FWM),

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good phase matching is crucial, and hence the seemingly high dispersion can limit the result. However with such a high non-linear coefficient that these materials offer, it is possible to reduce the device length to only 5 cm, allowing for sufficient phase matching even for the broad spectra involved at such high bit rates as 640 Gbit/s. And the short length itself is what really makes this device attractive in terms of stability and integration.

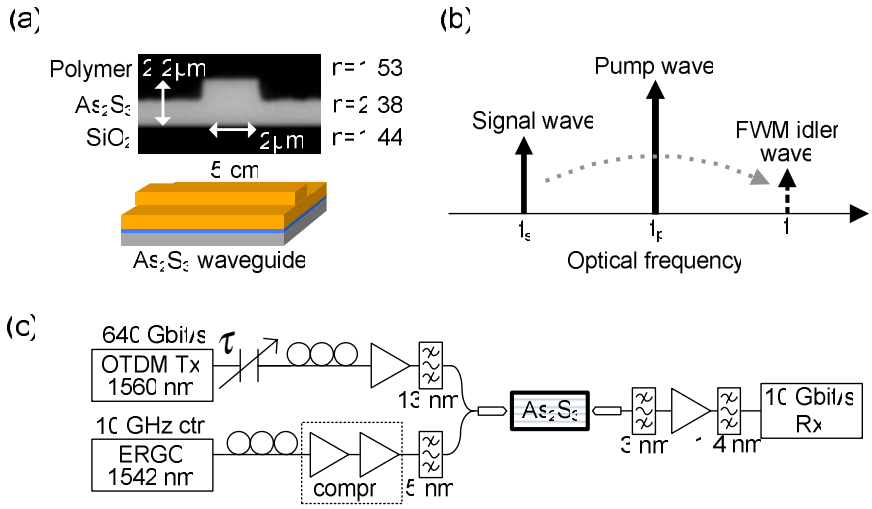

Fig. 1. The As_2S_3 device and the scheme used for the experiment. (a) (top) Scanning electron micrograph image of As_2S_3 planar waveguide cross-section and (lower) device schematic. (b) Principle of FWM generating an idler wave at a new frequency. (c) Experimental set-up for 640 Gbit/s demultiplexing.

This experiment utilises degenerate (single-pump) FWM as illustrated in Fig. 1(b) where an intense pump wave at frequency, f_p interacts with a co-propagating wave at frequency f_s. By the optical Kerr effect, the mixing of the two waves in the non-linear waveguide generates an idler at the frequency $f_i = 2f_p - f_s$ [9]. For time-division demultiplexing operation with a pulsed pump and signal, the idler is generated only when the pump (here at 10 GHz), coincides with a signal pulse in the 640 Gbit/s data signal.

Figure 1(c) outlines the experimental setup. The 640 Gbit/s data signal is generated in an optical time division multiplexing (OTDM) transmitter at 1560 nm as described in [4] with a PRBS sequence of 2^7-1. This PRBS length cannot be changed in this set-up, as the multiplexer is fixed and build to preserve that and only that sequence. However, in this experiment, relying on the ultra-fast Kerr effect, it is not expected that there will be any dependence on the used patterns. 1 ps FWHM narrow 10 GHz pump pulses at 1542 nm for demultiplexing are generated by adiabatic soliton compression of the pulses from an erbium glass oscillator (ERGO) laser in a cascade of two EDFAs. In the demultiplexer, the signal and pump pulses are combined and launched into the As_2S_3 waveguide. After the coupler the 640 Gbit/s data signal has a pulse peak power of ~0.5 W while the pump pulse peak power is ~17 W. Transmission through the waveguide and the associated fibre couplings cause a total loss of ~10 dB measured from the input fibre to the output fibre. It should be emphasised that due to the low duty cycle of the pump, the associated average power is only ~170 mW, which is well below the photodarkening threshold of this material [7].

The FWM performance in the chalcogenide waveguide is characterised in Fig. 2. The pump pulse at 1542 nm is injected into the device together with a continuous wave (CW) probe signal, which has a wavelength that is tuned. To avoid spectral overlap of the FWM product with the pump, the probe signal, i.e. the CW is tuned from 1555 nm to 1565 nm, i.e. 10 nm around the data signal wavelength centred at 1560 nm. Figure 2 (left) shows the spectra of the pump, the CW probe signal and the idler for various positions of the CW wavelength. Fig. 2 (right) shows the FWM efficiency as a function of the wavelength of the CW probe

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signal. The efficiency is derived from the spectra by integrating the power in the FWM product, and taking into account that the pump only appears in 1 ps once every 100 ps at the 10 GHz repetition rate, so the CW signal only uses 1% of its average power in the FWM process. So comparing the FWM power to 1% of the CW input power yields the FWM efficiency in this measurement where a mix of pulsed and CW lasers are used. As seen in Fig. 2 (right), there is a non-negligible FWM efficiency covering the whole central 10 nm of the data spectrum,

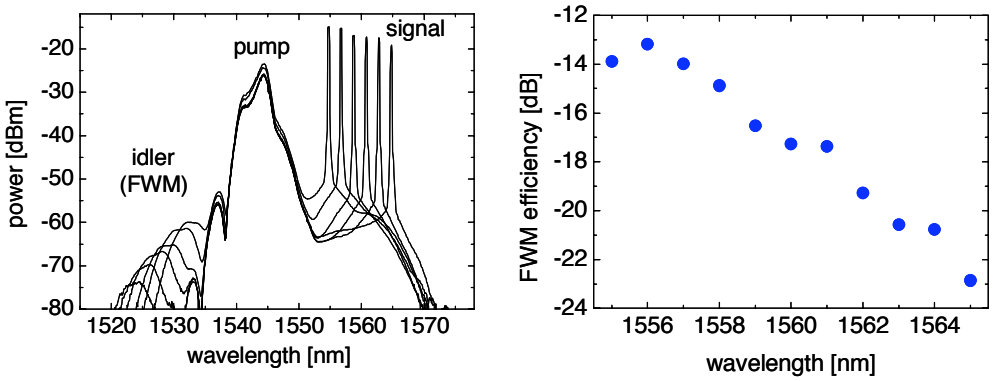

Fig. 2. FWM efficiency and bandwidth. Left: Optical spectra for various CW probe signal wavelengths. Right: FWm efficiency as a function of CW probe signal wavelength.

which is promising for a switching experiment. On the other hand, we also see a strong decay of the FWM efficiency when moving away from the pump wavelength, which is expected to be due to the dispersion of the device. For a demultiplexing experiment, the effect of this skewed efficiency will be small, as the demultiplexed pulses will be far apart in time. For more advanced functionalities such as wavelength conversion, additional tailoring of the waveguide dispersion would probably be needed. FWM is inherently polarisation dependent, so this scheme will be polarisation dependent, but this can be alleviated by some sort of polarisation diversity scheme. There has already been demonstrated various polarisation diversity schemes for other polarisation dependent switches, and we would speculate that these would also be applicable here. For instance, one could add a polarisation beam-splitter (PBS) in front of the chip, and then apply a half-wave plate in one arm before merging the two PBS outputs and injecting the signals into the chip.

Figure 3 shows the spectra when a pulsed probe signal is used, i.e. the real 640 Gbit/s data is mixed with the pump. The spectrum at the waveguide output is shown in Fig. 3 (solid line). A pump pulse and a data pulse co-propagate through the waveguide, and generate a FWM idler pulse at ~1530 nm representing the data content of one of the 64 tributary 10 Gbit/s channels. The pump pulse spectrum at the output is seen to be deformed. Since the accumulated dispersion is quite small, it is expected that the spectral deformation is primarily owing to SPM. The broadening of the spectrum will influence the demux performance if there is too great a spectral overlap. This also means that the two wavelengths must be placed at sufficient distance from each other, and this will reduce the FWM efficiency. The idler pulses are extracted by optical filtering and amplification to allow detection of the demultiplexed channel, Fig. 3 (dashed line). A 40 dB spectral contrast is obtained between the demultiplexed pulses and the pump pulses. A FWM conversion efficiency of -14 dB is estimated from the spectra taking into consideration that only one out of 64 data pulses takes part in the FWM process and coupling losses. -14 dB is the same order of magnitude as what is obtained with e.g. a standard semiconductor optical amplifier (SOA). The signal to idler energy conversion efficiency is determined by the phase matching between the three waves.

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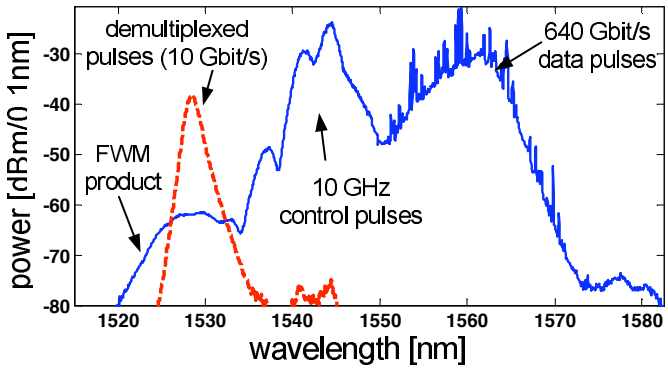

Fig. 3. Optical spectrum at the output of the waveguide (solid) and before the 10 Gbit/s receiver (dashed). Power is reduced 20 dB by tap couplers.

Dispersion is the dominant phase mismatch contributor in the As_2S_3 waveguide and can be expressed as a coherence length *(L_{coh})* of the phase matching between pump and signal, where $L_{coh} = 2\pi/|\Delta\beta| = 2\pi/\{|\beta_2|(2\pi(f_p-f_s))^2\}$ [8]. For an 18 nm pump to signal wavelength separation, L_{coh} is estimated at ~8 cm, comparable to the waveguide length. Hence significant scope exists for FWM efficiency increases by reduction of the dispersion [10] or the wavelength separation.

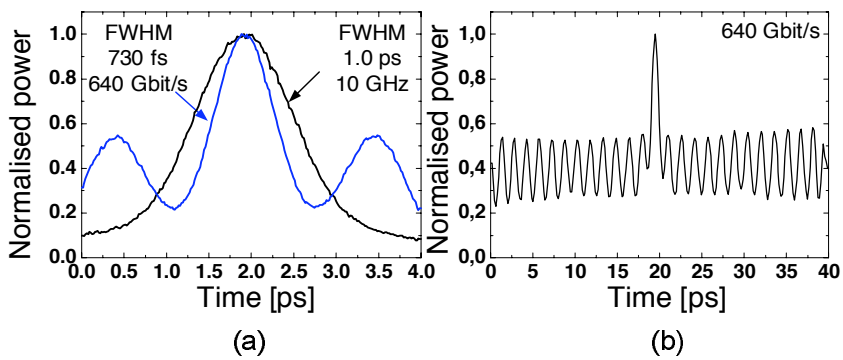

Fig. 4. Data and pump autocorrelations. (a) Autocorrelations of 640 Gbit/s data and 10 GHz pump pulses into the waveguide. (b) Zoom out of 640 Gbit/s data pulses.

Figure 4(a) shows autocorrelations of the data and pump pulses at the input of the waveguide. The data and pump pulse widths are 730 fs and 1.0 ps, respectively. Transmission through the waveguide and the necessary tapered input and output coupling fibres further broadens the output data pulses to 940 fs. The two autocorrelations in Fig. 4(a) indicate the operating condition of the demultiplexer, with the pump pulses only overlapping with one data channel at a time. The graph in Fig. 4(b) shows the good quality of both the amplitude equalisation and the temporal multiplexing of the 640 Gbit/s OTDM data signal.

In order to evaluate the performance of the chalcogenide demultiplexer in terms of data quality, the bit-error-rate (BER) is measured on the demultiplexed channel. The result is shown in Fig. 5.

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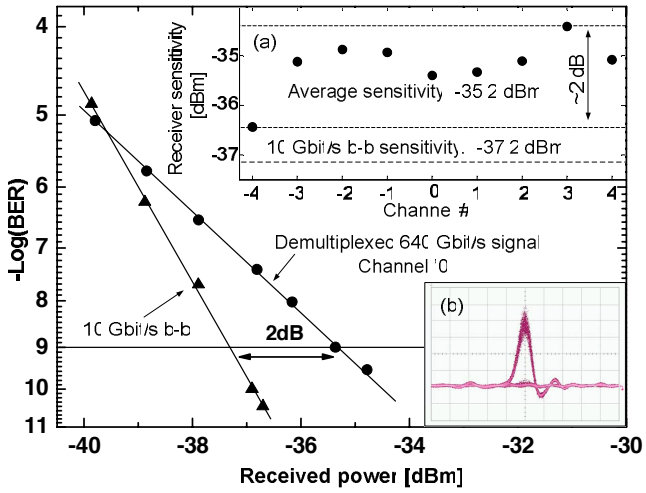

Fig. 5. BER performance of the 640-to-10 Gbit/s demultiplexing. (a) Receiver sensitivities for demultiplexing of nine adjacent data channels (b) Eye diagram of a demultiplexed error-free channel (10 ps/div).

Error free operation with no indication of an error-floor down to a BER of 10^{-10} is achieved with an average power penalty at BER 10^{-9} of only 2 dB compared to the 10 Gbit/s back-to-back baseline. Inset (a) shows the receiver sensitivity at 10^{-9} BER for nine consecutive channels. Error free operation is achieved for all channels with -35.2 dBm average sensitivity. The best measured channel achieved a -36.5 dBm sensitivity giving a power penalty of only 0.7 dB while the worst channel suffered a 2.8 dB penalty. This gives a variation in receiver sensitivities of only ~2 dB. Inset (b) shows a clear and open eye diagram for the demultiplexed signal at 10^{-9} BER.

The average 2 dB penalty includes the effects from all parts of the system, i.e., multiplexing, pulse compression, additional amplifications and filtering. The sensitivity spread of about 2 dB is not expected to be an inherent limitation in the demultiplexer but rather a manifestation of small inaccuracies in the generated 640 Gbit/s data signal. From reference measurements presented elsewhere [13], it is established that the generated OTDM data signal is of high quality and well-equalised with a sensitivity spread of a few dB, so the 9 channels presented here are representative of that. The aim here is not to characterise the full OTDM signal, but to focus on the performance of the demultiplexer, but to be sure that a representative estimate of the penalty is measured, 9 channels are characterised. The demultiplexer-unit, i.e., the 5 cm-long As_2S_3 waveguide, is thus considered to have excellent performance in demultiplexing a 640 Gbit/s data signal with minimal signal quality degradation.

3. Conclusion

This paper has reported on the breakthrough demonstration of the use of a non-linear chalcogenide glass wavguide as a demultiplexer for ultra-high bit rate data signals. We have demonstrated, error-free 640-to-10 Gbit/s optical time-division demultiplexing with a 5 cm long chalcogenide waveguide. Excellent performance is achieved with only 2 dB average power penalty. When combined with recent achievements in low-loss, long-length serpentine waveguides [11] and dispersion engineering [10], these results confirm the enormous potential of chalcogenide-based waveguides for ultrafast optical signal processing.

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