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Error-free 640 Gbit/s demultiplexing using a chalcogenide planar waveguide chip

Jing Xu[1,4], Michael Galili[1], Hans C.H. Mulvad[1], Leif K. Oxenløwe[1], Anders T. Clausen[1], Palle Jeppesen[1], Barry Luther-Davis[2], Steve Madden[2], Andrei Rode[2], Duk-Yong Choi[2], Mark Pelusi[3], Feng Luan[3] and Benjamin J. Eggleton[3]

[1] DTU Fotonik, Technical University of Denmark, DK-2800 Kgs. Lyngby, Denmark, Jing.Xu@fotonik.dtu.dk
[2]CUDOS, Laser Physics Centre, The Australian National University, Canberra, ACT 0200, Australia
[3]CUDOS, School of Physics, University of Sydney, NSW 2006, Australia
[4]Wuhan National Laboratory for Optoelectronics, Huazhong University of Science and Technology, China

Abstract *We demonstrate error free, low-penalty demultiplexing of a 640 Gbit/s OTDM signal to 10 Gbit/s using a 5cm long chalcogenide planar waveguide chip. Our approach exploits four-wave mixing by the instantaneous nonlinear response of chalcogenide.*

Introduction

Several platforms for high-speed optical signal processing have been identified and demonstrated over the years including optical fibres [1], semiconductor devices [2] and lithium niobate devices [3]. Recently chalcogenide (As_2S_3) waveguides have been proposed as a new platform for optical signal processing offering superior performance at ultrahigh bit-rates [4]. These structures combine several desirable features for ultrafast signal processing. In particular, the fast response time associated with the near-instantaneous third order nonlinearity allows flexible ultrafast signal processing in and beyond the telecom C-band. Additionally the high nonlinearity enables compact components with the potential for monolithic integration. Recently, such an As_2S_3 waveguide chip was used to demultiplex a 160 Gbit/s data signal down to 10 Gbit/s [5].

In this paper we report the first demonstration of error-free demultiplexing of a 640 Gbit/s data signal 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.

Experimental set-up and procedure

Fig. 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 [6] 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 [7]. 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 nonlinear coefficient γ of ~4100 W^{-1}·km^{-1} and a second order dispersion coefficient β_2 of ~375 ps^2/km.

This experiment utilizes 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 nonlinear waveguide generates an idler at the frequency $f_i = 2f_p - f_s$ [8]. 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.

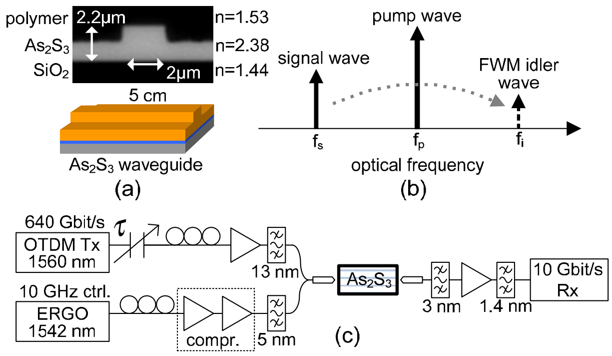

Fig.1 (a) (top) Scanning electron micrograph image of As_2S_3 planar waveguide cross-section and (lower) device schematic. (b) Principle of FWM generating an idler wave at new frequency. (c) Experimental set-up for 640 Gbit/s demultiplexing.

Fig. 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 [3]. 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 peak pump pulse 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.

The optical spectrum at the waveguide output is shown in Fig. 2 (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 10 Gbit/s channels. The idler pulses are extracted by optical filtering and amplification to allow detection of the demultiplexed channel, Fig. 2 (dashed line). A 40 dB spectral contrast is obtained between the demultiplexed pulses and the pump pulses.

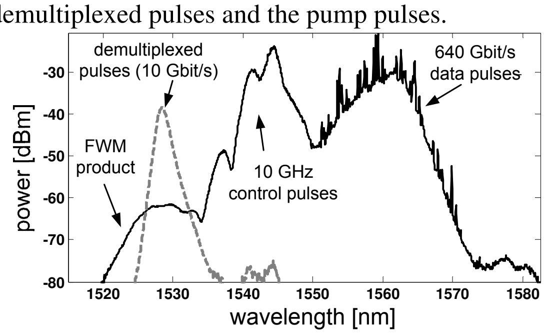

Fig.2 Optical spectrum at the output of the waveguide (solid) and before the 10 Gbit/s receiver (dashed). (Power is reduced 20 dB by tap couplers.)

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. The signal to idler energy conversion efficiency is determined by the phase matching between the three waves. 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 [9] or the wavelength separation.

Dynamic characterisation

Fig.3(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. 3(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. 3(b) shows the good quality of both the amplitude equalization and the temporal multiplexing of the 640 Gbit/s OTDM data signal.

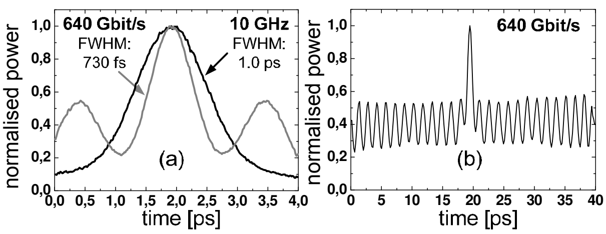

Fig.3. (a) Autocorrelations of 640 Gbit/s data and 10 GHz pump pulses into the waveguide. (b) Zoom out of 640 Gbit/s data pulses.

The bit-error-rate (BER) performance of the 640-to-10 Gbit/s demultiplexing is shown in Fig. 4. Error free operation with no indication of an error-floor down to a BER of 10^{-10} is achieved with an average power penalty 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.

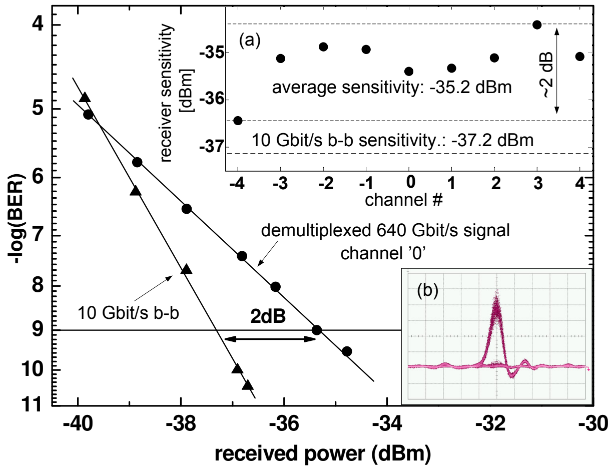

Fig.4 BER performance of the 640-to-10 Gbit/s demultiplexing. (a) Receiver sensitivities for demultiplexing of nine adjacent data channels (b) Eye diagram of a demultiplexed error-free channel.

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. The demux-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.

Conclusions

We have demonstrated, for the first time, error-free 640-to-10 Gbit/s optical time-division demultiplexing with a chalcogenide waveguide. Excellent performance is achieved with only 2 dB average power penalty. These results confirm the enormous potential of chalcogenide-based waveguides for ultrafast optical signal processing.

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