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

Jing Xu¹,², Michael Galili¹, Hans C.H. Mulvad¹, Leif K. Oxenløwe¹, Anders T. Clausen¹, Palle Jeppesen¹, Barry Luther-Davis³, Steve Madden², Andrei Rode³, Duk-Yong Choi², Mark Pelusi³, Feng Luan² and Benjamin J. Eggleton³

¹DTU Fotonik, Technical University of Denmark, DK-2800 Kgs. Lyngby, Denmark, Jing.Xu@fotonik.dtu.dk
²CUDOS, Laser Physics Centre, The Australian National University, Canberra, ACT 0200, Australia
³CUDOS, School of Physics, University of Sydney, NSW 2006, Australia
⁴Wuhan 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 5 cm 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 (As₂S₃) 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 As₂S₃ 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 As₂S₃ 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 As₂S₃ waveguide devices for ultra-high-speed signal processing.

Experimental set-up and procedure
Fig. 1(a) shows the geometry of the As₂S₃ waveguide used for 640 Gbit/s demultiplexing. A 2.2 μm thick As₂S₃ 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 As₂S₃ 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 As₂S₃ yields a 2.9 μm² effective mode area, which combined with the high n₂ of As₂S₃ delivers a nonlinear coefficient γ of ~4100 W⁻¹·km⁻¹ and a second order dispersion coefficient β₂ of ~375 ps²/km.

This experiment utilizes degenerate (single-pump) FWM as illustrated in Fig. 1(b) where an intense pump wave at frequency, fp, interacts with a co-propagating wave at frequency fs. By the optical Kerr effect, the mixing of the two waves in the nonlinear waveguide generates an idler at the frequency fi = 2fp - fs [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(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 As₂S₃ 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.

![Image of optical spectrum](image)

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 As₂S₃ waveguide and can be expressed
as a coherence length ($L_{coh}$) of the phase matching
between pump and signal, where $L_{coh} = 2\pi/|\Delta\beta| =
2\pi/(|\beta_2|/(2\pi f_p f_s))^1/2$ [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)
demonstrates the good quality of both the amplitude
equalisation and the temporal multiplexing of the
640 Gbit/s OTDM data signal.

![Image of autocorrelations](image)

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.

![Image of BER performance](image)

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 As₂S₃ 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
chalcosilicate waveguide. Excellent performance is
achieved with only 2 dB average power penalty. These
results confirm the enormous potential of chalcosilicate-
based waveguides for ultrafast optical signal processing.

**References**