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1.28-Tb/s Demultiplexing of an OTDM DPSK Data Signal Using a Silicon Waveguide

Hua Ji, Michael Galili, Hao Hu, Minhao Pu, Leif K. Oxenløwe, Kresten Yvind, Jørn M. Hvam, and Palle Jeppesen

***Abstract*—This letter demonstrates optical demultiplexing of a 1.28-Tb/s serial differential phase-shift-keying data signal using a nano-engineered silicon waveguide. We first present error-free performance at 640 Gb/s and then at 1.28 Tb/s with characterization of all 128 channels. Bit-error rates below 10^{-9} are achieved for some channels and below forward-error-correction limit for all channels, corresponding to a 1.19-Tb/s error-free data signal.**

***Index Terms*—Nano-engineered silicon waveguide, optical communication, ultrafast optical signal processing.**

I. Introduction

With the required capacity of the Internet continuously increasing, terabits-per-second bit rates for Ethernet applications may well be needed soon. To enable this progress, optical time-division-multiplexing (OTDM) systems may be a viable route to explore. For instance, 1.28-Tbaud OTDM-OOK (on–off keying) data generation and demultiplexing have already been demonstrated [1], and using OTDM differential quadrature phase-shift keying (DQPSK) and polarization multiplexing, up to 5.1-Tb/s signal generation and error-free demodulation using direct detection has also been demonstrated [2]. For these high-speed serial data signals, ultrafast optical switching is necessary. Several materials for optical switching have successfully been demonstrated at 640–1280 Gb/s, materials such as highly nonlinear fiber (HNLF), periodically poled lithium niobate (PPLN), semiconductor optical amplifiers (SOAs), and chalcogenide waveguides [1], [3]–[5]. In recent years, silicon has been proposed for optical switching [6]. Silicon nanowires in particular are investigated to realize various functionalities for ultra-high-speed serial data, due to their fast response, compactness, robustness, and mature fabrication and processing technology. Four-wave mixing (FWM)-based 10-Gb/s signal regeneration has been demonstrated in a silicon nanowire [7], and very recently 160-Gb/s demultiplexing and wavelength conversion were also demonstrated in silicon nanowires [8], [9]. In [10], the highest signal processing speed in pure silicon was reported, and the paper demonstrated 1.28-Tb/s all-optical demultiplexing and waveform sampling of an OTDM-OOK data signal, i.e., using the simple amplitude modulation format on–off keying.

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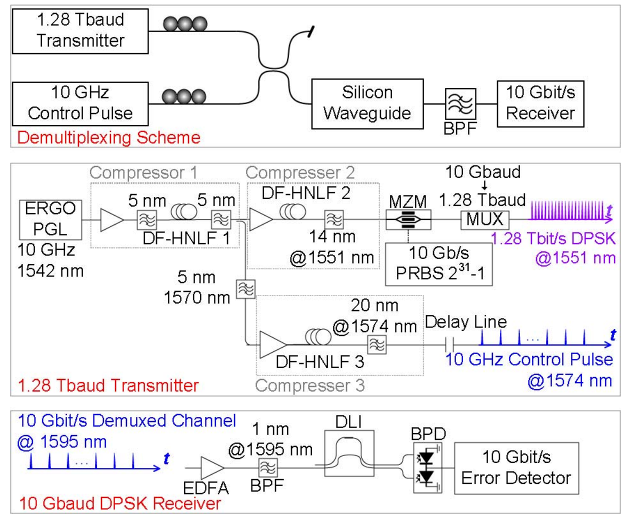

Fig. 1. (Top) Experimental scheme. (Middle) The 1.28-Tbaud transmitter. (Bottom) The 10-Gb/s receiver.

In this letter, we present experimental demonstrations of 640- to 10-Gb/s and 1.28-Tb/s to 10-Gb/s demultiplexing of OTDM differential phase-shift-keying (DPSK), i.e., phase modulated data signals. We utilize the phase-preserving effect of FWM for switching in a 5-mm-long silicon nanowire.

II. Experimental Setup and Procedure

The experimental scheme is shown in Fig. 1 (top). The 1.28-Tb/s OTDM DPSK data signal generated by the 1.28-Tbaud transmitter [1] is injected into the nano-engineered silicon waveguide together with the 10-GHz control pulse train. Polarization controllers are used to adjust the polarization states of the data signal and control pulse train into the nano-engineered silicon waveguide. This will ensure phase matching and optimize the FWM product in the nano-engineered silicon waveguide. The FWM product will be filtered out using a 5-nm bandpass filter centered at 1595 nm and then sent into a 10-Gb/s preamplified L-band receiver where the bit-error-rate (BER) performance is measured.

The nano-engineered silicon waveguide used in the experiment is 5 mm long and its cross-sectional dimensions are 250 nm $\times$ 450 nm. It is a silicon-on-insulator (SOI) structure, with the silicon waveguide placed on a SiO_2 substrate. The width at the end of the silicon waveguide is tapered from 450 nm to a tiny tip end of 40 nm so that the guided mode will be expanded into a polymer waveguide, surrounding the SOI waveguide and the taper. The 5-mm length of the waveguide includes the tapering sections, which are about 1 mm long each. The cross-sectional dimension of the polymer waveguide matches with the tapered access fibers, reducing the coupling

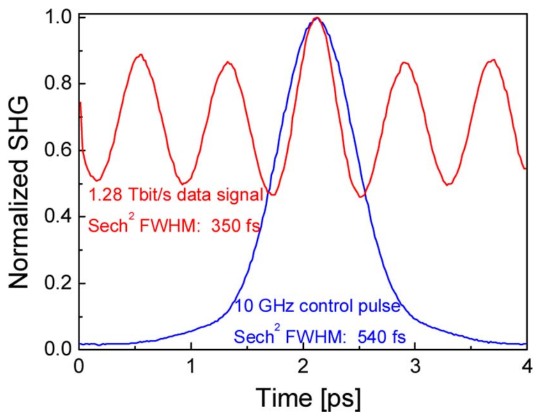

Fig. 2. Autocorrelation traces of the 1.28-Tb/s DPSK signal and 10-GHz control pulses. (The specified FWHMs are for a corresponding Sech^2 pulse shape.)

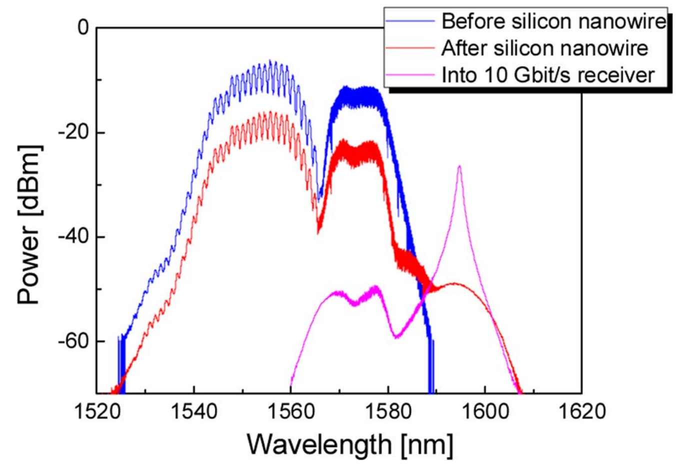

Fig. 3. Optical spectra, measured at input and output of the silicon waveguide, and also at input to the DLI.

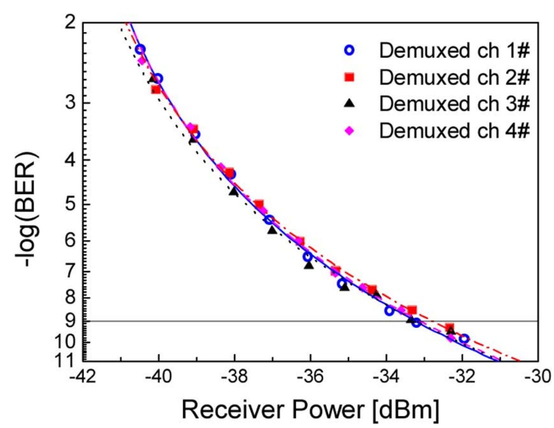

Fig. 4. BER curves of four neighboring 10-Gb/s DPSK channels demultiplexed from the 640-Gb/s OTDM DPSK data signal.

loss [11]. The measured propagation loss is 4.7 dB/cm and the device insertion loss is 7 dB.

Fig. 1 (middle) shows how the 1.28-Tbaud OTDM transmitter generates the 1.28-Tb/s OTDM DPSK data signal. The erbium glass oscillating pulse-generating laser (ERGO-PGL) produces 10-GHz pulses at 1542 nm with a 1.5-ps full-width at half-maximum (FWHM) pulsewidth. The spectrum of the pulses is broadened in the 400-m dispersion-flattened highly nonlinear fiber 1 (DF-HNLF 1) (dispersion coefficient $D = -0.45$ ps/nm/km and dispersion slope $S = 0.006$ ps/nm^2/km at 1550 nm, nonlinear coefficient $\gamma = 10.5$ W$^{-1}\cdot$ km^{-1}) due to self-phase modulation (SPM). The pulse train with broadened spectrum is split into two and filtered at 1551 nm with a 5-nm optical bandpass filter (BPF) to generate the 10-GHz pulses for the data signal, and using another 5-nm BPF at 1570 nm to obtain the 10-GHz control pulses. The 10-GHz pulses at 1551 nm are subjected to further spectral broadening by SPM in the 100-m DF-HNLF 2 ($D = -1.07$ ps/nm/km and $S = 0.004$ ps/nm^2/km at 1560 nm, $\gamma = 10.5$ W$^{-1}\cdot$ km^{-1}), and subsequently filtered with a 14-nm BPF at 1551 nm. The strongly chirped pulses are then linearly compressed in time by transmission through the standard single-mode fiber in the remainder of the transmitter. The compressed pulses have 350-fs FWHM width (as shown in Fig. 2) and are then encoded in the DPSK format with 10-Gb/s PRBS $(2^{31}-1)$ data using a Mach–Zehnder modulator. The modulated 10-Gb/s DPSK signal is multiplexed in time using a passive fiber-delay multiplexer (MUX $\times$128) to generate the 1.28-Tb/s signal. The other 10-GHz pulses at 1570 nm are further compressed to 540-fs FWHM (as shown in Fig. 2) in the DF-HNLF3 (200 m, $D = -0.27$ ps/nm/km and $S = 0.005$ ps/nm^2/km at 1560 nm, $\gamma = 10.5$ W$^{-1}\cdot$ km^{-1}). After the silicon waveguide, one demultiplexed channel is filtered out by a 5-nm BPF and detected by the 10-Gb/s receiver [shown in Fig. 1 (bottom)]. Here, the demultiplexed 10-Gb/s data signal is preamplified, filtered using a 1-nm BPF and then detected by a 1-symbol delay interferometer (DLI). The output from the DLI is detected using a balanced photodetector (BPD), followed by a 10-Gb/s error-detector for BER measurement.

III. Experimental Results and Discussion

Fig. 3 shows the spectra measured at the input and output of the nano-engineered silicon waveguide and also measured at the input of the 10-Gb/s receiver. By integrating the optical spectrum of the data and the FWM product at the output of the silicon waveguide, and considering the difference in duty cycle between the pump and data pulses ($\sim$18 dB), the peak fiber-to-fiber FWM conversion efficiency is estimated to -14 dB. These fiber-to-fiber conversion efficiencies include the 7-dB insertion loss.

The BER performance of the demultiplexing using the nano-engineered silicon waveguide is measured both for 640 Gb/s and 1.28 Tb/s. In the 640- to 10-Gb/s demultiplexing, the average power of the data and control signals sent into the silicon waveguide is 13.5 and 14 dBm, respectively. Fig. 4 shows the measured BER curves of four neighboring 10-Gb/s DPSK channels demultiplexed from the 640-Gb/s OTDM DPSK data signal. All four channels show error-free performance, i.e., with a BER $< 10^{-9}$. The receiver sensitivity is about -33 dBm, being similar for all channels. However, the BER curves all seem to flatten out, i.e., revealing an error-floor below 10^{-9}. This error-floor was not present in the OOK demonstration of 640 Gb/s and 1.28 Tb/s presented in [10] and is believed to be caused by reflections from the particular waveguide used in the experiments presented in the present letter. The reflections will result in interference between data pulses so as to decrease the BER performance.

The 1.28-Tb/s OTDM DPSK data signal is also demultiplexed to 10 Gb/s using the nano-engineered silicon waveguide.

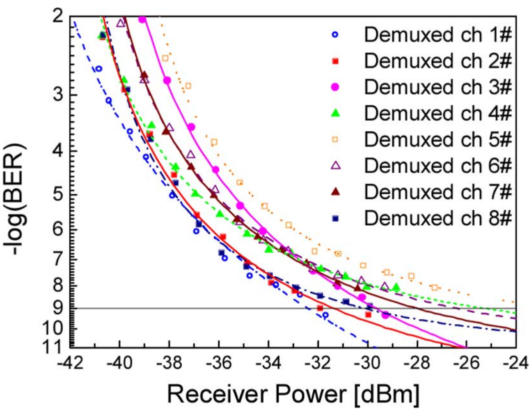

Fig. 5. BER curves of eight neighboring 10-Gb/s DPSK channels demultiplexed from the 1.28-Tb/s OTDM DPSK data signal.

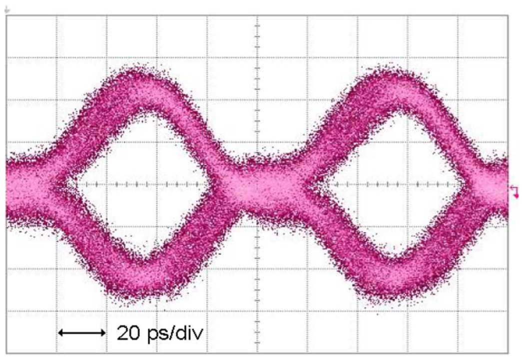

Fig. 6. Clear eye-diagram of a 1.28-Tb/s DPSK demultiplexed channel at error-free operation.

The average power of the data signal and control signal sent into the silicon waveguide is 16.5 and 14 dBm, respectively. Eight neighboring 10-Gb/s DPSK data signal channels are measured to evaluate the BER performance, shown in Fig. 5. Three of the tested channels obtain a BER below 10^{-9}, one is on the border, and the last four are merely below 10^{-8}. There is an error-floor between BER 10^{-8} and 10^{-9}. The error-floor cannot be suppressed down to 10^{-9} by increasing the power of the data signal or the control pulses. Again, a reflection in the particular silicon waveguide used in these experiments is believed to be the reason for the error-floor. Fig. 6 shows an eye-diagram of a demultiplexed channel at error-free operation. The eye is seen to be clear and open.

In order to characterize all 128 OTDM tributary channels in a practical way, the receiver power for each channel is measured at the relatively high BER of 10^{-4}. This BER allows for faster measurements, and is still below the standard forward-error-correction (FEC) limit of BER 10^{-3}. All 128 channels are scanned through and readily yield a BER of 10^{-4}, i.e., below the FEC limit. Assuming a 7% FEC redundancy would then lead to a 1.19-Tb/s data payload, i.e., a 1.19-Tb/s error-free DPSK data signal processed in this silicon nanowire. The results are shown in Fig. 7. There is about 4-dB variation in receiver sensitivity among all the channels. This variation stems from the slight difference among all the channels caused by the multiplexer.

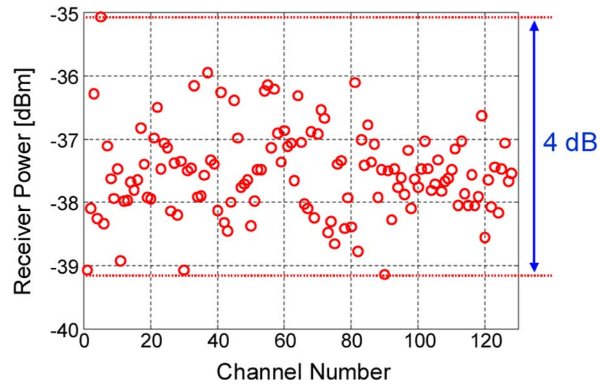

Fig. 7. Receiver sensitivities of all 128 channels at BER 10^{-4}. All channels are below the 10^{-3} FEC limit.

IV. Conclusion

We have experimentally demonstrated 1.28-Tb/s OTDM-DPSK data signal demultiplexing using a nano-engineered silicon waveguide. Error-free operation at BER 10^{-9} is achieved. However, an error-floor exists around the 10^{-9} level. All 128 channels are demultiplexed and receiver sensitivities are measured at BER 10^{-4}. There is about 4-dB variation among all the channels. The nano-engineered silicon waveguide shows promising potential for ultrafast optical signal processing.

References

[1] H. C. H. Mulvad, L. K. Oxenløwe, M. Galili, A. T. Clausen, L. Grüner-Nielsen, and P. Jeppesen, "1.28 Tbit/s single-polarisation OTDM-OOK data generation and demux," *Electron. Lett.*, vol. 45, no. 5, pp. 280–281, Feb. 2009.

[2] H. C. Hansen Mulvad *et al.*, "Demonstration of 5.1 Tbit/s data capacity on a single-wavelength channel," *Opt. Express*, vol. 18, no. 2, pp. 1438–1443, 2010.

[3] L. K. Oxenløwe *et al.*, "640 Gbit/s data transmission and clock recovery using an ultra-fast periodically poled lithium niobate device," in *Proc. OFC 2008*, San Diego, CA, Feb. 24–28, 2008, Paper PDP22.

[4] E. Tangdiongga *et al.*, "All-optical demultiplexing of 640 to 40 Gbits/s using filtered chirp of a semiconductor optical amplifier," *Opt. Lett.*, vol. 32, no. 7, pp. 835–837, 2007.

[5] T. D. Vo *et al.*, "Photonic chip based 1.28 Tbaud/s single-polarisation serial OOK transmitter optimization and receiver OTDM switching," in *Proc. OFC 2010*, San Diego, CA, Mar. 21–26, 2010, Paper PDPC5.

[6] V. R. Almeida, C. A. Barrios, R. R. Panepucci, and M. Lipson, "All-optical control of light on a silicon chip," *Nature*, vol. 431, pp. 1081–1084, 2004.

[7] R. Salem, M. A. Foster, A. C. Turner, D. F. Geraghty, M. Lipson, and A. L. Gaeta, "Signal regeneration using low power four-wave mixing on silicon chip," *Nature Photon.*, vol. 2, pp. 35–38, 2008.

[8] F. Li *et al.*, "Error-free all-optical demultiplexing at 160 Gb/s via FWM in a silicon nanowire," *Opt. Express*, vol. 18, no. 4, p. 3905, Feb. 2010.

[9] N. Ophir *et al.*, "First 80-Gb/s and 160-Gb/s wavelength converted data stream measurements in a silicon waveguide," in *Proc. OFC 2010*, San Diego, CA, Mar. 21–26, 2010, Paper OWP5.

[10] H. Ji *et al.*, "1.28 Tbit/s OTDM-OOK data waveform sampling and demultiplexing using silicon nano-wire," in *Proc. OFC 2010*, San Diego, CA, Mar. 21–26, 2010.

[11] M. Pu, L. Liu, H. Ou, K. Yvind, and J. M. Hvam, "Ultra-low-loss inverted taper coupler for silicon-on-insulator ridge waveguide," *Opt. Commun.*, vol. 283, pp. 3678–3682, Oct. 2010.