Silicon Photonics for Signal Processing of Tbit/s Serial Data Signals

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(Invited Paper)

***Abstract*—In this paper, we describe our recent work on signal processing of terabit per second optical serial data signals using pure silicon waveguides. We employ nonlinear optical signal processing in nanoengineered silicon waveguides to perform demultiplexing and optical waveform sampling of 1.28-Tbit/s data signals as well as wavelength conversion of up to 320-Gbit/s data signals. We demonstrate that the silicon waveguides are equally useful for amplitude and phase-modulated data signals.**

***Index Terms*—Optical fiber communication, optical fiber filters, optical switches, silicon photonics.**

I. Introduction

THE Nobel Prize of 2009, given in parts to Charles Kao for his achievements concerning the development of the optical fiber [1] has put a welcome focus on a hot topic: fiber optics and the accompanying Internet traffic, and not least the fact that the Internet produces as much CO_2 as the aviation industry today. But unlike the aviation industry, the Internet continues to grow at dramatic rates (60% per year) [2], so power consumption must be reduced, while allowing for increased capacity. Optics looks like a good candidate to do just as in [2]–[4] by extending the use of optical technologies from pure transport of data to also include optics for signal processing and control. A commonly prospected benefit would come from avoiding numerous optical-to-electrical and vice versa conversions by staying in the optical domain—if proper optical solutions can be found.

Silicon has key optical properties, such as a high refractive index and an indirect bandgap, which makes it very attractive for passive waveguiding. For active signal processing, Si is more challenging with only a very few demonstrations of active components realized in the Si material. Active devices in Si present a challenge because of the indirect bandgap of Si inhibiting light emission, the absent electro-optic effect, impeding electro-optic modulation, and slow carrier dynamics associated with nonlinear absorption [21]. However, data modulators based on both Mach–Zehnder and ring-resonator structures have been demonstrated at data rates between 10 and 40 Gbit/s [6]–[8]. Another approach for making active devices based on the Si platform is bonding III–V semiconductor materials to Si waveguide structures. This has proven to be a promising approach [5], where a variety of well-known active components in III–V materials can be coupled to silicon waveguides [9]. This approach has resulted in e.g., a 25-Gbit/s data modulator [10], an optical triplexer chip [11] and the integration of up to four highly efficient microdisk lasers and Si structures [13]–[15]. Additionally, an optical frequency comb source, applicable to wavelength-division multiplexing or orthogonal frequency-division multiplexing has also been demonstrated based on this hybrid platform [12].

Another approach to do active signal processing in Si has been to use all-optical nonlinear effects in nanoengineered pure silicon waveguides. Basically, these waveguides are very narrow, on the order of 250–500 nm in cross section (here termed nanowires), which makes them very nonlinear, and thus data signals may be controlled by a pump pulse [16]. This all-optical approach is ultrafast and has resulted in 40- [17] and 160-Gbit/s all-optical signal processing [18] and signal processing of a 160-Gbit/s data signal [19], and very recently at DTU the record-breaking switching of a 1.28-Tbit/s data signal [20]. Adding other nonlinear materials to Si slot waveguides can induce a high nonlinearity but avoid the detrimental nonlinear absorption of silicon. Such materials could be organic molecules [21], [22]. Very recently, the use of organic molecules was demonstrated to enable the making of a 40-Gbit/s data modulator [23] and promising attempts at demultiplexing a 170-Gbit/s data signal [24].

In an optical time-division multiplexed (OTDM) system, relying on direct detection, the underlying idea is to try to carry on the trend of generating higher serial line rates, which has historically led to cost and power reductions, but doing so in the optical domain. The overall goal is to design ultrahigh symbol rate systems with reduced component counts, so as to ease management and reduce power consumption. The challenge is to find the right solutions that will allow this.

In this paper, we will revise our recent work on silicon nanowires for nonlinear signal processing of ultrahigh-speed serial data signals, such as switching of terabit per second data signals and wavelength conversion of 320-Gbit/s data.

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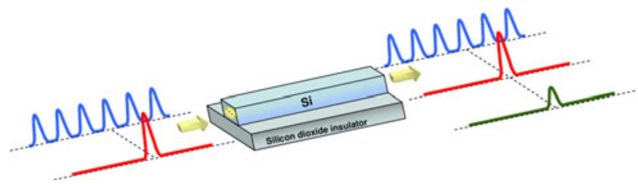

Fig. 1. Schematic of nonlinear effect exploited: four wave mixing.

We rely entirely on pure silicon waveguides and four-wave mixing in these to achieve the desired functionalities. All experiments are soundly backed up by solid bit error rate (BER) characterizations.

II. Experimental Setups

The underlying principle exploited for all the experiments covered in this paper is four-wave mixing (FWM) in the silicon nanowire, as sketched in Fig. 1. The experimental setup used for the experiments is mostly common to all experiments and shown in Figs. 2 and 3. Fig. 3 shows the 1.28-Tbaud transmitter [25] setup used to demonstrate back-to-back 1.28-Tbaud OOK 1.28-Tbit/s data generation and demultiplexing. The heart of an ultrahigh-speed serial data system is the short pulse generation. Here, dispersion-flattened highly nonlinear fibers (DF-HNLF: $D = -0.45$ ps/nm·km and slope $S = 0.006$ ps/nm^2·km at 1550 nm, nonlinear coefficient $\gamma = 10.5\,W^{-1}\cdot km^{-1}$) are used to chirp the pulses followed by subsequent linear compression in dispersive fiber. The compressed pulses are around 350-fs wide full-width at half-maximum (FWHM) out of the 1.28-Tbit/s transmitter. The generated supercontinuum output from DF-HNLF1 is split into two and filtered at separate wavelengths, one for the control and one for the data. In the data branch, the pulses are compressed further in a second compression stage with DF-HNLF2 followed by a 14-nm broad filter. The output from here is data modulated and multiplexed to a 1.28-Tbaud pulse train. In this paper, all data modulation will only be binary, so the 1.28 Tbaud will correspond to a 1.28-Tbit/s single-polarization, single-wavelength channel. To derive a control pulse for demultiplexing, in this back-to-back scenario, the second branch is fed to a third pulse compression stage (Compressor 3). The principle here is the same as before: chirping in a DF-HNLF and subsequent linear compression. The control pulse wavelength is chosen at 1574 nm, i.e., in the *L*-band. This means that the FWM product will be positioned even further up in the *L*-band. The control and data signals are coupled through a 3-dB coupler and sent into the Si-nanowire.

Fig. 3 shows a schematic of the full setup. The input powers to the silicon waveguide are monitored on the second output of the 3-dB coupler at the input to the waveguide. The port facing the waveguide is connected to a tapered fiber (3-μm spot diameter), allowing for good coupling efficiency to the waveguide. The Si waveguide is tapered down to 40 nm width in each end, coupling light into an overlaying polymer waveguide of 3.4-μm cross-sectional diameter, making the coupling loss about 2.6-dB per facet [26]. The 40-nm tip is achieved by e-beam lithography and dry thermal oxidation to create an inverse taper coupler. The overall fiber-to-fiber insertion loss is around 7.5 dB for a 5-mm long device, and the propagation loss for the fabricated devices used in these experiments is about 4.5 dB/cm. The nonlinear coefficient γ of the used silicon nanowire is measured using the continuous wave (CW) SPM method to be around $4 \times 10^5\ W^{-1}\cdot km^{-1}$.

The output of the Si waveguide is in the *L*-band and is filtered out through a bandpass (BP) *L*-band 1-nm wide filter and preamplified in an *L*-band erbium-doped fiber amplifiers. The amplified demultiplexed data are photodetected and BER is measured. As a baseline for the *L*-band receiver, a 10-to-10-Gbit/s demultiplexing is performed for comparison with the terabit per second demultiplexing. This is necessary, as the *C*- and *L*-band receivers are very different, so comparing a *C*-band back-to-back with the demultiplexed *L*-band FWM signal would not make sense.

Fig. 4 shows eye diagrams of the generated data signals at 640 Gbit/s and 1.28 Tbit/s using a commercial optical sampling oscilloscope. The eyes shown are in fact all 64 or 128 channels, respectively, overlaid on each other, revealing good signal quality. It appears as if the pulses are stretched and extend into neighboring time slots. In reality they do not, they are only 350 fs wide, and the appearance in Fig. 4 is due to limited resolution bandwidth of the sampling oscilloscope, which is based on HNLF with accompanying walkoff. As we will see later in this paper, the data pulses in the 1.28-Tbit/s data signal can be resolved using an Si-nanowire, and when doing so, clear eye diagrams are obtained revealing no pulse tail overlap in the 1.28-Tbit/s data signal.

III. Experimental Demonstrations

The spectra involved are shown in Fig. 5. The input to the silicon waveguide, the output of the silicon waveguide, and the filtered FWM product are all shown together. The effective FWM conversion efficiency of the silicon waveguide can be estimated from the spectra. The FWM conversion efficiency is calculated by integrating the optical spectra of the data and the FWM product, i.e., to obtain the average power of the output data signal and the FWM product, respectively. Then the duty cycle difference between the data signal and the pump (18 dB for 640 Gbit/s and 21 dB for 1.28 Tbit/s) is considered, as well as the insertion loss (7.5 dB). Thus, the effective fiber-to-fiber FWM conversion efficiency is estimated in decibel as

$$\eta = P_{\mathrm{FWM}}(\mathrm{out}) - [P_{\mathrm{signal}}(\mathrm{out}) + \mathrm{Loss}_{\mathrm{insertion}}] + \mathrm{dutycycle}.$$

Therefore, even if the FWM product in Fig. 5 appears quite modest, the actual conversion efficiency is really higher. In this case, the conversion efficiency is measured to -15.1 dB.

The relatively low conversion efficiency obtained here is partly due to the long wavelength used. The conversion bandwidth is only about 18 nm for this particular device [20], and with the wavelength allocation used here, the FWM product is on the edge of the conversion bandwidth.

A 5-mm long device is used here as a compromise between conversion efficiency and propagation loss. Its cross-sectional

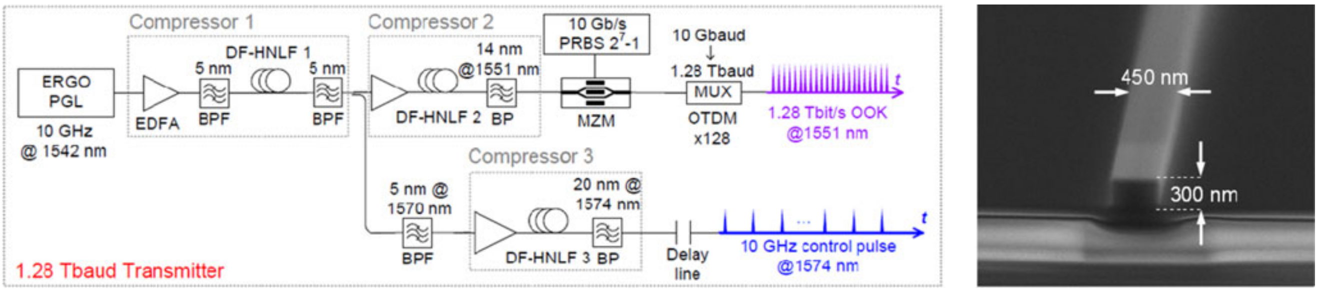

Fig. 2. Schematic of the 1.28 Tbaud transmitter and the derivation of the 10 GHz control pulse for back-to-back demultiplexing characterization. The data modulation can be either OOK, DPSK, or DQPSK in this setup. Right: a microscope image of the silicon nanowire.

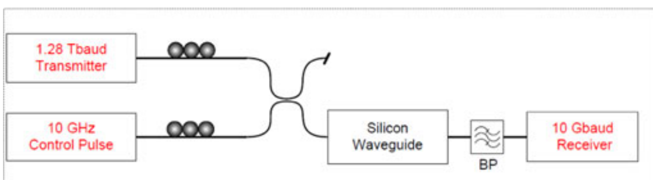

Fig. 3. Schematic setup. The receiver contains both a *C*-band and an *L*-band version, to accommodate for varying received wavelengths.

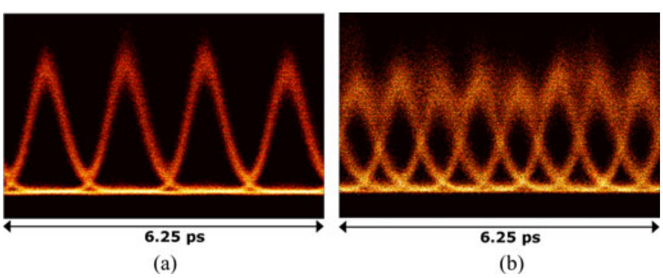

Fig. 4. Eye diagrams of 640 Gbit/s and 1.28 Tbit/s data signals as measured on a state-of-the-art sampling oscilloscope. (a) 640 Gbit/s, (b) 1.28 Tbit/s.

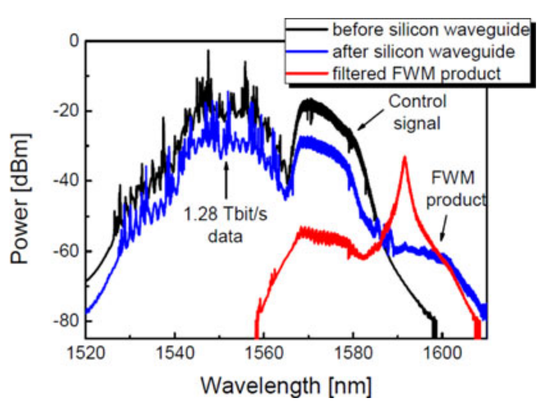

Fig. 5. I/O spectra to and from the silicon waveguide, showing a modest FWM product. 10-dB attenuation is used when measuring these spectra, in order to spare the spectrum analyzer from excess peak power.

dimensions are 250 nm × 450 nm. From waveguide simulations, for the TE mode, as used here, the zero dispersion wavelengths of this device are at 1275 and 1850 nm with positive dispersion in between, reaching 3421 ps/nm·km at 1550 nm and with a slope of 3.56 ps/nm^2·km from 1500–1600 nm. Higher conversion efficiency is obtained with a longer device; however, the propagation loss in these particular devices is too high to get a strong enough FWM signal out of the device for demultiplexing purposes. With a lower propagation loss, through lower roughness of waveguide sides, this is expected to improve in future experiments.

In the following, we describe the demultiplexing performance of 1.28-Tbit/s data signals carrying either OOK or differential phase-shift keying (DPSK) data formats.

A. 1.28-Tbit/s OOK Demultiplexing in an Si-Nanowire

The average power of the data and the control pulses entering the Si waveguide is about 20 dB·m (100 mW) and 14 dB·m (25 mW), respectively (0.24 W, 5.3-W data and pump peak power, resepctively). Since the pump is running at 10 GHz, bringing the multiplexed data down to 10 Gbit/s by demultiplexing, the switching energy for this process becomes $P_{\text{pump}}/B =$ 25 mW / 10 Gbit/s = 2.5 pJ/bit. This is a fairly average switching energy for this type of process and material as seen in [27]. This may be optimized by the aforementioned loss reduction allowing for longer waveguides.

Fig. 6 shows the OOK demultiplexing results. The pulsewidth of the data signal in this case is 330 fs and the control pulse is 470-fs wide FWHM. The BER curves in Fig. 6 reveal an error-free (BER $< 10^{-9}$) performance with no sign of an error floor below 10^{-9}. So the silicon nanowire really does work as a demultiplexer for these high bit rates. The baseline is 7 dB better than the terabit per second demux. This may partly be caused by timing jitter and some modest pulse overlap, but since both BER curves correspond to signals passed through the Si device, it is hard to conclude much on the Si device performance alone. In [20], we also present results on 640-Gbit/s operation and show very low penalty, 0.7 dB to the *L*-band back-to-back, and the *L*-band back-to-back has only a 0.7-dB penalty to the *C*-band back-to-back. All 64 OTDM tributaries are characterized and demonstrated error free, i.e., with BER $< 10^{-9}$.

B. 1.28-Tbit/s DPSK Demultiplexing in an Si-Nanowire

As FWM is ideally a phase-preserving effect, it is worthwhile confirming the ultrahigh-speed operation on a phase-modulated data signal. In the following, we describe the successful demultiplexing of a 1.28-Tbit/s DPSK data signal, i.e., still a serial binary format. The transmitter is the same as described

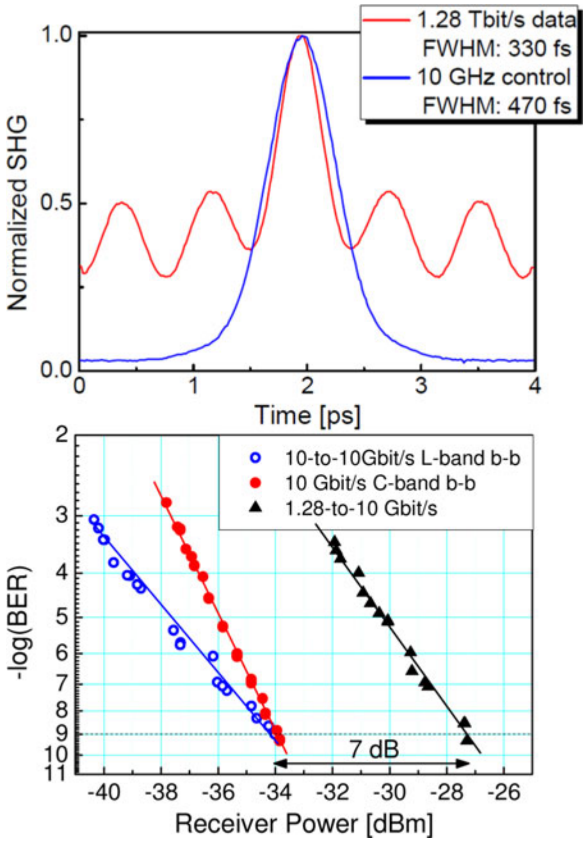

Fig. 6. 1.28-Tbit/s demultiplexing results. Top: Autocorrelation traces of the multiplexed data and the control pulse. Bottom: BER curves for 1.28-Tbit/s demultiplexing and as back-to-back a 10 Gbit/s to 10 Gbit/s demultiplexing. There is no error floor, but a 7-dB penalty. Also, the 10 Gbit/s *C*-band back-to-back is presented. The *L*-band and *C*-band preamplified receivers are different and, hence, the curves have different slopes, but almost identical sensitivity.

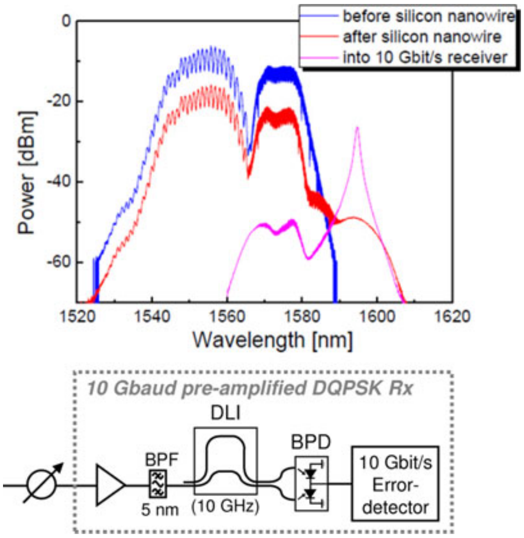

Fig. 7. 1.28-Tbit/s DPSK demultiplexing in an Si-nanowire and subsequent demodulation in a delay interferometer (DLI) and balanced photo detection (BPD) receiver. Top: I/O spectra to/from the Si-nanowire and the filtered demultiplexed FWM product to the receiver. Bottom: Schematic of receiver for DQPSK or DPSK data.

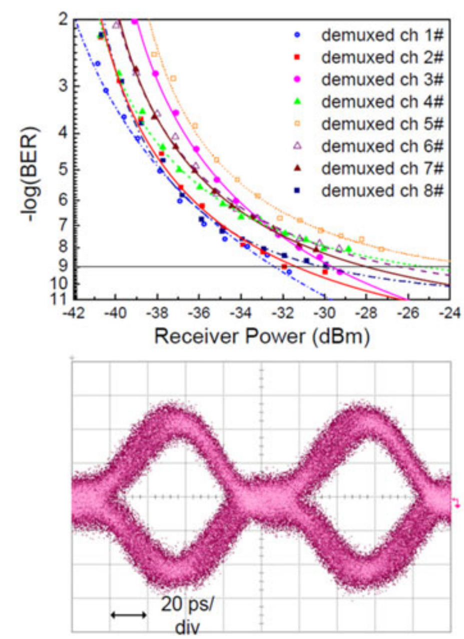

Fig. 8. 1.28-Tbit/s DPSK demultiplexing. Top: BER curves for eight consecutive channels. Bottom: Error-free (< BER 10^{-9}) demultiplexed eye diagram.

earlier, except that the data modulator is swapped for a $LiNbO_3$ phase modulator. The multiplexer is designed to preserve a 2^7–1 OOK data signal, and not designed for phase modulated signals, which simply turn into a pulse train with higher repetition rates. Therefore, we do not take particular care to keep the pseudo random binary sequence (PRBS) to the low 2^7–1 sequence, and instead a 2^{31}–1 is used. This way, we can more clearly see any pattern effects on the tributary rate, i.e., at 10 Gbit/s. The receiver is changed to a DPSK receiver with balanced detection, see Fig. 7, following the Si-nanowire demultiplexer.

The receiver may also be used for differential quadrature phase shift keying (DQPSK) data, but here we restrict ourselves to DPSK. The device used here is identical in dimensions to the one used earlier, i.e., 5 mm × 250 nm × 450 nm. The insertion loss is only 6 dB for this device, owing to better fabrication; however, there are some minor reflections giving some feedback to the waveguide.

Fig. 7 shows the spectra at the I/O of the Si-nanowire. As before, the control and FWM product is in the *L*-band. The data are at 1551 nm, the control at 1570 nm, and the FWM product at 1599 nm. The pulsewidths are 350 and 540 fs for the data and control, respectively, see Fig. 9 (top). The data and pump average input powers are 13.5 and 14 dB·m, respectively.

BER curves are presented in Fig. 8 for eight consecutive channels. There is a clear error floor appearing in these curves, and half of them get BER below 10^{-9} and the rest merely below 10^{-8}. When checking with OOK data, at 640 Gbit/s and 1.28 Tbit/s the same performance appears, and we conclude that the error floor must be isolated to the performance of the device, i.e., it is not due to the DPSK data format. At 640 Gbit/s, there is still an error floor, but all measured channels are below BER

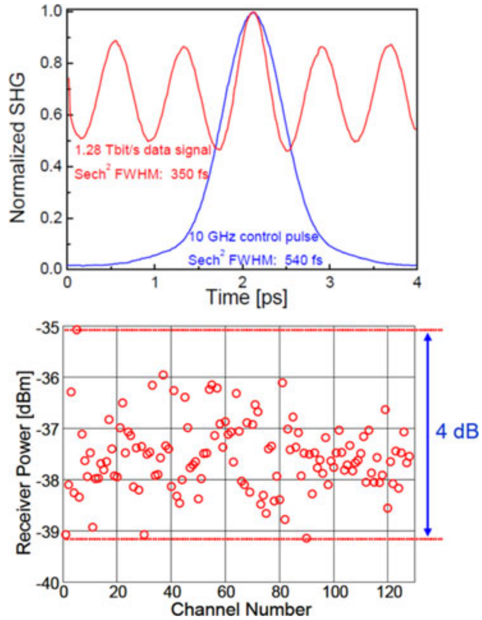

Fig. 9. 1.28-Tbit/s demultiplexing in an Si-nanowire. Characterisation of all 128 channels. Top: Autocorrelation of 1.28-Tbit/s data signal and 10 GHz control pulse. Bottom: Measured receiver sensitivities for all channels at BER $= 10^{-4}$.

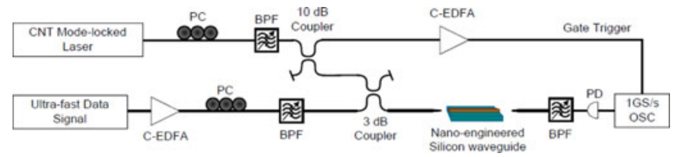

Fig. 10. Schematic set-up for all-optical sampling of 1.28-Tbit/s serial data signal.

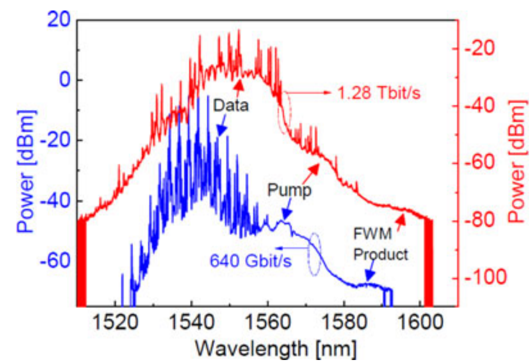

Fig. 11. Output spectra of the Si-nanowire at 640-Gbit/s and 1.28-Tbit/s sampling. The sampling pulse is at low repetition rate, and hence the pump and FWM product appear small in these averaged spectra.

of 10^{-9}. The demodulated, demultiplexed eye diagrams from 1.28 Tbit/s appear clear and open though, see Fig. 8 (bottom). We expect the error floor to be due to excessive reflections from this particular device.

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-Tbit/s data payload, i.e., a 1.19-Tbit/s error free DPSK data signal is, thus, processed in this silicon nanowire. The results are shown in Fig. 9 (bottom). 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.

C. 1.28-Tbit/s OOK All-Optical Sampling in an Si-Nanowire

The 1.28 Tbit/s eye diagrams presented earlier in Fig. 4 are measured using a commercially available ultrafast sampling oscilloscope based on HNLF as the nonlinear sampling medium. This particular HNLF-based scheme has many advantages such as offering parametric gain and, thus, high sensitivity, and quite high timing resolution and stable operation. However, with the silicon nanowires explored here, the small size may be an advantage, as it may offer lower walkoff than HNLF-based solutions, and hence higher timing resolution. This is investigated in this section.

Fig. 10 shows the schematic setup for using the silicon nanowire in a sampling system. A 1.28-Tbit/s OOK serial data signal is generated as described earlier, and this is fed to the Si-nanowire together with a short sampling pulse through a 3-dB coupler. The major difference to the setup described earlier is the sampling pulse source. It consists of a low-repetition rate mode-locked erbium-doped fiber ring laser using carbon nanotubes as saturable absorber [28]. The pulse repetition rate is 16.3 MHz, the central lasing wavelength is 1558 nm, and the pulse width is 710 fs. This low-rate pulse source will take slow sample points of the 1.28-Tbit/s data signal, and these may be stored directly in a 1-Gsample/s oscilloscope and the temporal waveforms of the data signal, such as eye diagrams may be constructed.

Fig. 11 shows the output spectra of the silicon waveguide for the 640 Gbit/s and 1.28-Tbit/s data cases. For 640 Gbit/s (and also for 320 Gbit/s), the data wavelength is set at 1545 nm, the sampling pulse at 1565 nm and the FWM product appears at 1586 nm. For 1.28 Tbit/s, the data are at 1551 nm, the sampling pulse at 1574 nm, and the FWM product appears at 1597 nm. The wavelength shifting of the sampling pulse is achieved by adding a 10-m DF-HNLF for supercontinuum generation and appropriate filtering, generating $\sim$700-fs pulses at the desired wavelength. The FWM products appear very small in these spectra; however, this is because of the low duty cycle of the pump pulse and, hence, of the FWM product. The pump power as averaged on the optical spectrum analyzer also appears very small. The average pump power is only -10 dB·m, and the data average power is 20 dB·m.

Fig. 12 show sampling results when measuring on 320 Gbit/s, 640 Gbit/s, and 1.28 Tbit/s. In all cases, clearly resolved data pulses are observed with clear and open eye diagrams. Comparing the sampled measured pulsewidth to an autocorrelation of the data pulse, the timing resolution may be derived [29] and in all cases a timing resolution of $\sim$365 fs is obtained. This is one of the highest timing resolutions ever demonstrated, and

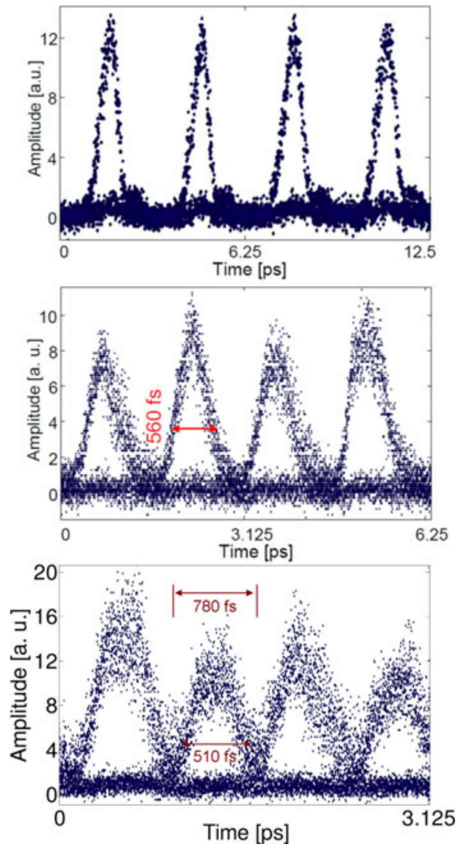

Fig. 12. Measured sampling traces for 320, 640 Gbit/s and 1.28 Tbit/s serial data signals. The corresponding timing resolution is in all cases ∼365 fs. Top: Sampling of 320 Gbit/s. Middle: Sampling of 640 Gbit/s. Bottom: Sampling of 1.28 Tbit/s data signal.

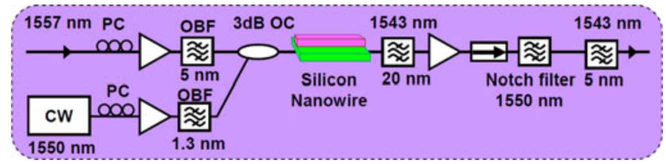

Fig. 13. Schematic setup for all-optical wavelength conversion in an Si-nanowire.

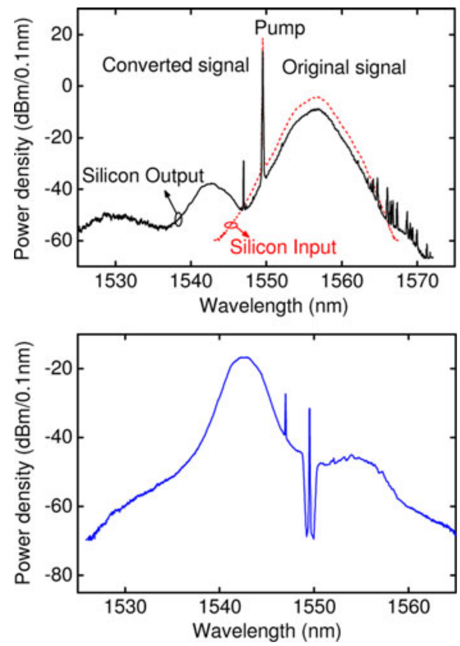

Fig. 14. Output spectrum from the Si nanowire top) and the filtered FWM product (bottom), i.e., the wavelength converted signal.

certainly 1.28 Tbit/s is the highest bit rate of a data signal that has ever been demonstrated. Comparing the 1.28-Tbit/s sampled waveform in Fig. 12 (bottom) to the eye diagram of Fig. 4, it is clearly observed that the silicon based sampling system offers a considerably higher timing resolution, where the individual data pulses are seen not to overlap, as Fig. 4 would otherwise suggest.

D. Si-Nanowire Based All-Optical Wavelength Conversion

One of the most promising features of serial communications is the prospect of reducing the energy consumption per bit for higher serial bit rates. This feature is most easily obtained in a wavelength conversion experiment, where all tributaries are switched simultaneously in the same device. As discussed in [27], this is exactly one of the functionalities where optical signal processing may offer power reductions, and the switching energy per bit scales inversely with the serial bit rate. This stems from the simple fact that narrower pulses result in higher peak powers for a given average power. But sharing the average power among more pulses leverages the peak power out. So double the bit rate requires half the pulse width and twice as many pulses, and hence the same net peak power for the same average power. We have previously demonstrated 640-Gbit/s wavelength conversion in 100-m HNLF with a switching energy of 95-fJ/bit [30]. If this is achievable in silicon waveguides, that would be very exciting. In this section, we describe our results on wavelength conversion in silicon nanowires, and present the first BER measurements. Fig. 13 shows the setup for these experiments.

We use FWM again, but this time the pump is a CW, and the data are 320-Gbit/s DPSK. The 320-Gbit/s data are generated as described earlier, but with a 5-nm filter centred at 1557 nm. The data are merged with the CW pump in the silicon waveguide, which is 3.6 mm long and has a cross-sectional dimension of 250 nm × 450 nm.

Fig. 14 shows the output spectrum from the Si-nanowire as well as the filtered output. As shown in Fig. 13, the FWM product at 1543 nm is filtered through with a series of filters, first a 20-nm BP filter, then a notch filter to suppress the CW pump, and finally a 5-nm BP filter to suppress amplified spontaneous emission and the original signal fully. The notch filter is essential for this operation to suppress the CW enough to avoid interference with the FWM product. The additional peak appearing in the spectrum is due to cross-phase modulation of the CW pump from the data signal, i.e., the 320-Gbit/s data creates sidebands on the CW, which are 320 GHz (2.56 nm) away from the CW. The higher sideband is not visible here, as it is buried in the data spectrum. The data power is 16.8 dB·m and the CW pump

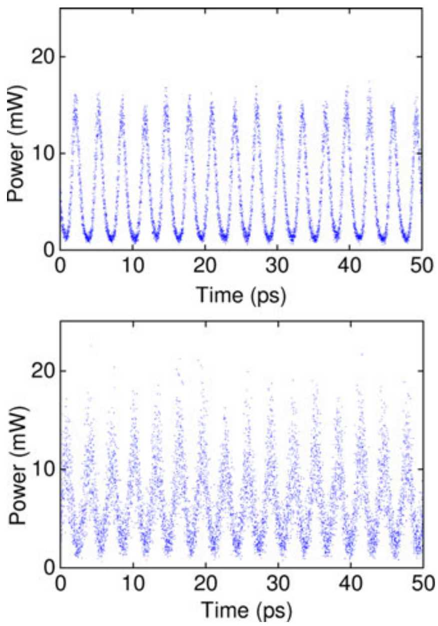

Fig. 15. Waveform traces of the original 320 Gbit/s DPSK (top) and the converted 320 Gbit/s (bottom).

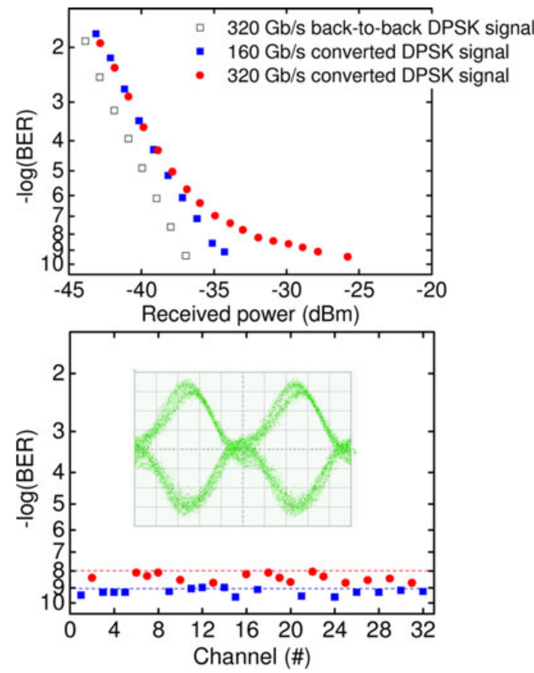

Fig. 16. Schematic setup for all-optical sampling of 1.28 Tbit/s serial data signal.

power is 20.8 dB·m at the input of the silicon nanowire. This corresponds to a switching energy of 375 fJ/bit. The conversion efficiency in this experiment is −29 dB.

Fig. 15 shows sampled waveform traces of the 320 Gbit/s original and converted DPSK data signal. The converted trace contains some noise, but as will be apparent the conversion is nonetheless with BER $\sim 10^{-9}$.

The converted signal is demultiplexed in a nonlinear optical loop mirror, and the BER measurements of the demultiplexed converted signals are shown in Fig. 16 (top) as a function of the received power. BER curves are shown for a 320-Gbit/s return to zero DPSK (RZ-DPSK) wavelength converted and demultiplexed signal, and for a wavelength converted and demultiplexed 160-Gbit/s RZ-DPSK signal. These curves are shown in comparison with the original 320 Gbit/s demultiplexed signal. The wavelength converted 160-Gbit/s RZ-DPSK signal shows clear error-free performance (BER$<10^{-9}$) with a 2.5-dB penalty in receiver power compared to the reference curve at a BER of 10^{-9}. The wavelength converted 320-Gbit/s RZ-DPSK signal also achieves a BER below 10^{-9} but with a significant error floor at $\sim 10^{-9}$, which is expected to be due to reduced optical signal-to-noise ratio (OSNR) after the wavelength conversion. Due to the relatively low conversion efficiency in this experiment, for a given input power, the power in each converted data channel will be smaller for higher bit rates, as more channels share the energy. Hence, the OSNR of the converted data scales inversely with bit rate in this experiment, and this causes the higher penalty when going from 160 to 320 Gbit/s. The error floor might be lowered if the FWM efficiency of the all-optical wavelength conversion (AOWC) is increased. The inset of Fig. 16 (bottom) shows the demodulated 10-Gbit/s eye diagram demultiplexed from the 320-Gbit/s wavelength converted DPSK signal. The eye is clear and open.

For wavelength conversion type of experiments where all channels are switched, it is absolutely imperative that all converted channels are characterized, and hence all 32 converted channels are measured on. Fig. 16 (bottom) shows the BER for all the 32 OTDM tributaries measured with a fixed receiver power of −22 dB·m. The performance varies among different tributaries due to the slightly different properties of the OTDM channels depending on their path through the optical multiplexer. All the tributaries show a BER below 10^{-8}, and 16 tributaries are better than a BER of 10^{-9}.

These experiments constitute the first BER characterisations of 320-Gbit/s wavelength conversion, or indeed above 80 Gbit/s. A previous result [31] showed great promise but insufficient support to claim a real demonstration of 320-Gbit/s wavelength conversion. The CW pump power used for this experiment only amounts to 375 fJ/bit in switching energy. As the same average pump power would be needed at 640 Gbit/s, or even 1.28 Tbit/s, we would expect it to be plausible to get below 100 fJ/bit with silicon switching. In fact, very recently we found it is possible to do 640-Gbit/s wavelength conversion in the same silicon nanowire [32].

IV. Conclusion

We have demonstrated signal processing of ultrahigh-speed data signals in silicon nanowires. We have described our recent progress in demultiplexing of a 1.28-Tbit/s serial data signal, both with amplitude and with phase modulation. We have described our use of nonlinear signal processing in the silicon nanowire for all-optical waveform sampling of a 1.28-Tbit/s data signal, and we have described our very recent progress in wavelength conversion and shown the first BER-based demonstration of 320-Gbit/s wavelength conversion. The switching energy used is down to 375-fJ/bit for the nonlinear process.

These results make us confident that silicon nonlinear signal processing has a key role to play in communication systems of the future.

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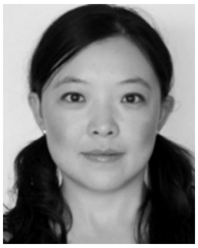

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