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Wavelength Conversion of a 640 Gbit/s DPSK Nyquist Channel Using a Low-Loss Silicon Nanowire

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Abstract: 640 Gbit/s N-OTDM DPSK wavelength conversion is demonstrated in a Si-nanowire. All 64 tributaries are converted within an average power penalty of 1 dB at the FEC BER-limit 3E-3. Only 22-fJ/bit switching energy is required.
OCIS codes: (230.7405) Wavelength conversion devices; (060.4510) Optical communications

1. Introduction

There has been great interest in increasing the spectral efficiency (SE) in order to achieve a large capacity within the telecom C&L band [1]. Recently, Nyquist optical time division multiplexing (N-OTDM) has been proposed to achieve very high spectral efficiency optical transmission [2-4]. In contrast to Gaussian-shaped pulses for RZ-OTDM signals, Nyquist pulses have sinc-shapes with zero crossing at the center of each neighbouring tributary bit slot. Therefore, inter-symbol interference (ISI) can be avoided even if the neighboring pulses are strongly overlapped.

Wavelength conversion is a desirable functionality for a dynamic wavelength-routed network and can offer flexible and efficient interconnects based on wavelength routing. Silicon based wavelength conversion has attracted a lot of research interest due to its complementary metal-oxide-semiconductor (CMOS) compatibility, ultra-compactness, broad bandwidth and high-speed operation [5-6]. However, linear losses due to sidewall roughness of the Si waveguides, in combination with nonlinear losses due to two-photon and free carrier absorption (TPA, FCA), limit the four-wave mixing (FWM) efficiency in silicon, which ultimately limits the obtainable OSNR of the wavelength converted signal. Since an N-OTDM signal requires higher OSNR than an RZ-OTDM signal, it is quite challenging to wavelength convert an N-OTDM signal in silicon.

In this paper, we report the first demonstration of silicon based all-optical wavelength conversion (AOWC) of a 640 Gbit/s DPSK N-OTDM signal, enabled by the fabrication of a low-linear-loss Si nanowire resulting in improved conversion efficiency. The successful wavelength conversion is validated by BER measurements and the result is below the FEC limit for all 64 OTDM tributaries. The AOWC is based on FWM in a 1.5 cm long silicon nanowire. The switching energy can be as low as 22 fJ/bit, which is 5 fold lower than previous silicon based 640 Gbit/s RZ AOWC [6], even if the N-OTDM requires higher OSNR.

2. The Si-nanowire

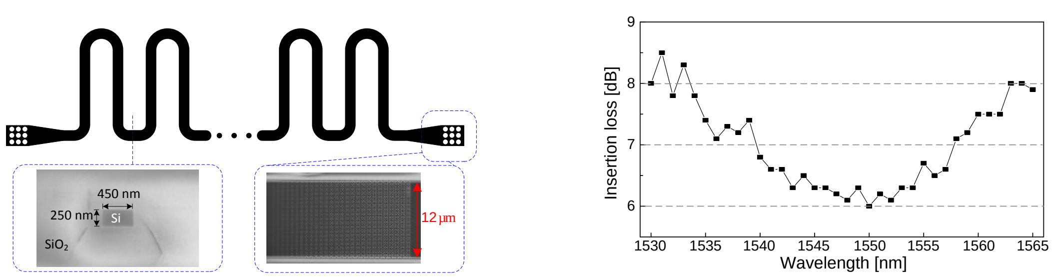

Fig. 1 Left: Schematic of the Si-nanowire with grating couplers. The insets show a scanning electron microscopy (SEM) image of the cross-section of the Si-nanowire and the apodized PhC grating coupler. Right: Insertion loss of the grating coupled Si-nanowire including coupling loss and propagation loss.

Fig. 1 (left) shows the schematic of the Si-nanowire used in the experiment. The length of the Si-nanowire is 1.5 cm. The width and height of the Si-nanowire was designed to be 450 nm and 250 nm, respectively, with SiO_2 as upper and lower cladding. Fully etched apodized photonic crystal (PhC) grating couplers [7] are designed for coupling between Si-nanowire and standard single mode fiber (SSMF). In order to improve the coupling efficiency, an aluminum (Al) mirror is introduced below the grating coupler [8]. The device is fabricated on a commercial SOI sample with top silicon thickness of 250 nm and buried silicon dioxide (BOX) of 3 μm. A single step of standard SOI processing, including e-beam lithography and inductively coupled plasma (ICP) etching is first used to fabricate the grating couplers and the Si-nanowire simultaneously. In order to introduce the Al mirror, a bonding method is used [8]. In general, a 1600 nm thick layer of SiO_2 (800 nm SiO_2 and 800 nm boro-phosphosilicate (BPSG) glass) is deposited on the chip. Afterwards, a 100 nm thick Al layer is deposited on top of the SiO_2, followed by another 1 μm SiO_2 deposition. Then, an about 2 μm thick BCB layer is spun on both the sample and silicon carrier wafer. The sample is then flip-bonded on the silicon carrier wafer and thermally cured in an oven. After that, the substrate of the chip is removed by ICP fast etching, and the BOX layer is finally thinned to an optimized thickness of 1 μm by buffered hydrofluoric acid (BHF) etching. The propagation loss of the Si-nanowire is measured to be 2 dB/cm by the cut-back method. In [6] the propagation loss was 4.3 dB/cm, so this device should give a better conversion efficiency than previous devices. To optimize the coupling central wavelength and bandwidth, the angles between the SSMF and the grating coupler of the Si-nanowire are selected to be 71^o and 73^o at the input and output, respectively. Fig. 1 (right) shows the insertion loss of the Si-nanowire measured at input CW power of 0 dBm. The minimum insertion loss is 6 dB at around 1550 nm and the 3 dB bandwidth covers the entire c-band.

3. Experimental procedure for 640 Gbit/s wavelength conversion

The experimental setup is shown in Fig. 2. It includes a 640 Gbit/s N-OTDM DPSK signal transmitter, the Si-nanowire based wavelength converter and a time-domain Optical Fourier Transformation (TD-OFT) based receiver. In the N-OTDM DPSK transmitter, a 10 GHz pulse train with central wavelength of 1542 nm is generated by an erbium glass oscillator pulse generating laser (ERGO-PGL). Based on self-phase modulation, the pulses are compressed and wavelength converted to the central wavelength of 1557 nm using a high power EDFA and a 400-m dispersion-flattened HNLF (DF-HNLF). A part of the 10 GHz pulse train is used as the pump pulse for the OFT

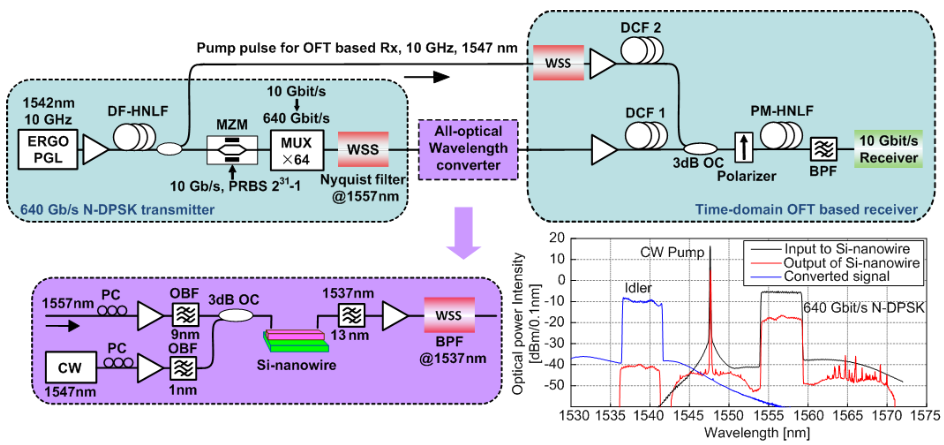

Fig. 2, Experimental setup and the optical spectra before and after the Si-nanowire

based receiver. The other part of the pulse train is DPSK encoded in a Mach-Zehnder modulator (MZM) by a 10 Gbit/s PRBS of 2^{31}-1. The generated 10 Gbit/s DPSK signal is multiplexed to 640 Gbit/s in time using a passive fiber-delay multiplexer. Then the 640 Gbit/s DPSK data signal is Nyquist filtered (rectangular filtering with a bandwidth equal to the symbol rate) using a wavelength selective switch (WSS), resulting in a 640 Gbit/s N-OTDM DPSK data signal.

In the wavelength converter, the 640 Gbit/s N-OTDM DPSK signal is amplified, filtered and finally launched into the Si-nanowire in combination with a CW pump for the FWM processing. The CW pump is at 1547 nm. Polarization controllers are used to align the input polarizations of the pump and data signal to the TE mode for the grating coupler. Through a 3-dB optical coupler (OC) and the grating coupler, the data signal and the CW pump are together launched into the Si-nanowire. At the output of the Si-nanowire, the wavelength converted signal at 1537 nm together with the residual pump and original signal is coupled out from the second grating coupler. The residual pump and original signal are filtered out by an optical bandpass filter and a WSS. The average optical power of the data signal coupled into the Si-nanowire is 14 dBm. Two coupled pump powers of 16.5 dBm and 11.5 dBm are used in the experiment to investigate the cases with different switching energy. As shown in Fig.2, optical spectra before and after the Si-nanowire are measured for the pump power of 16.5 dBm, and the conversion efficiency in the Si-nanowire is -23 dB, which is about 6 dB better than previously obtained in [6].

After the wavelength conversion, a TD-OFT based receiver is used to receive the converted signal. By applying dispersion and quadratic phase modulation on optical pulses, the optical waveform of the signal in the time domain can be Fourier transformed to the frequency domain [2]. The input 640 Gbit/s signal is dispersed by a dispersion compensating fiber (DCF 1) with dispersion $\beta_2 L_{DCF1}$=1.243 ps^2, and quadraticly phase modulated by the chirped pump during a FWM process in a 100 m polarization-maintaining highly nonlinear fiber (PM-HNLF). The pump pulses with a super-Gaussian spectrum (FWHM of 1.6 THz) centered at 1545 nm are linearly chirped by a DCF with dispersion $\beta_2 L_{DCF2}$=2.486 ps^2. As a result, the 640 Gbit/s signal with Δt=1.562 ps is converted to parallel channels with a frequency spacing of 200 GHz. A tunable BPF with bandwidth of 40 GHz is used to consecutively select each of the N-OTDM tributaries.

4. Experimental results and discussion

Fig. 3 shows the measured BER performance of the converted 640 Gbit/s N-OTDM DPSK signal. Fig. 3 (left) shows the BER performance of one 10 Gbit/s tributary demultiplexed from the original 640 Gbit/s signal (B2B) and from the converted 640 Gbit/s signal using two different pump powers. The BER curve of the converted 640 Gbit/s N-OTDM DPSK signal shows an error floor at 1E-7 and 1E-4 for CW pump powers of 16.5 dBm and 11.5 dBm, respectively, limited by obtainable OSNR after the conversion. Compared to the back-to-back signal, the power penalties at the BER of 3E-3 (FEC limit) are 0.5 dB and 2.7 dB for the pump power of 16.5 dBm and 11.5 dBm, respectively. The switching energy of the Si-nanowire based wavelength converter is only 22 fJ/bit when the pump power is 11.5 dBm. This is 5 fold lower than previous silicon based 640 Gbit/s AOWC [6], and this is possible even for the more OSNR-demanding N-OTDM signal format. Fig. 3 (middle) shows that the BERs of all 64 converted channels are all below 1E-4 which is well below the FEC limit of 3E-3, when the pump power is 16.5 dBm. Fig. 3 (right) shows the measured receiver sensitivity of all 64 B2B channels and converted channels (pump power 16.5 dBm) at the FEC limit of 3E-3. The receiver sensitivity of the B2B channels shows that there is a 1.5 dB variation among all the 64 channels. This is caused by the fiber-delay multiplexer. After wavelength conversion, the 1.5 dB variation is increased to 2.7 dB and the average receiver power is increased from -46.2 dBm to -45.2 dBm, which means the wavelength converter induces only 1 dB average power penalty.

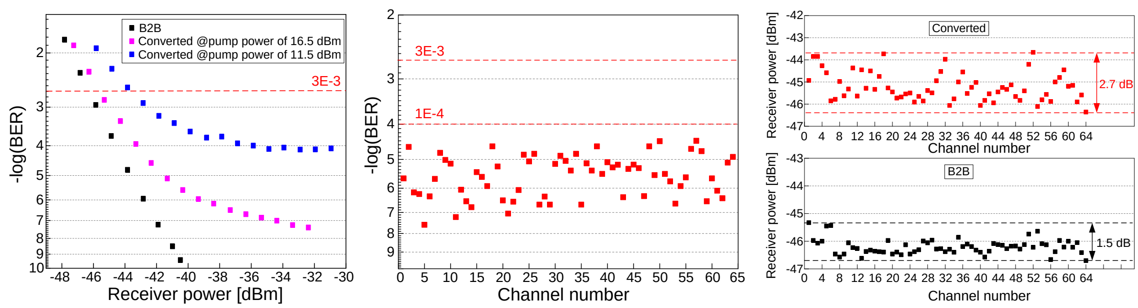

Fig. 3. Experimental results. Left: BER performance of one arbitrary tributary at pump power of 16.5 dBm and 11.5 dBm compared with B2B. Middle: BER performance of all 64 channels for pump power 16.5 dBm. Right: Receiver sensitivity at BER 3E-3 of all 64 converted channels (pump power 16.5 dBm) compared to B2B, yielding an average power penalty of 1 dB.

5. Conclusion

Wavelength conversion of a 640 Gbit/s N-OTDM DPSK data signal using a low-loss Si-nanowire is successfully demonstrated. All 64 N-OTDM tributaries are wavelength converted with BERs below 1E-4. Compared to B2B data at the BER of 3E-3, the average receiver power penalty is only 1 dB for the pump power of 16.5 dBm. With a strongly reduced pump power of only 11.5 dBm, corresponding to a switching energy of only 22 fJ/bit, the BER of the converted signal is still below the FEC limit.

6. Acknowledgement

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