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160 Gb/s Silicon All-Optical Data Modulator based on Cross Phase Modulation

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Abstract: We have demonstrated 160 Gb/s all-optical data modulation with an extinction ratio of 18.5 dB based on XPM in a silicon nanowire. Error free performance is achieved for the optically modulated 160 Gb/s signal.

OCIS codes: (060.2330) Fiber optics communications; (130.4110) Modulators; (190.4390) Nonlinear optics, integrated optics.

1. Introduction

The optical modulator that encodes data onto an optical carrier will be a key device also in future optical interconnect systems ranging from chip-to-chip to fiber-to-the-home interconnections. The silicon optical modulator has attracted considerable attention due to its unique combination of low fabrication costs, integration potential and complementary metal-oxide-semiconductor (CMOS) compatibility [1]. In the past few years, there have been significant advances in the development of silicon electro-optic (E/O) modulators based on either electro-refractive or electro-absorptive effects, such as carrier injection, carrier depletion and free-carrier plasma dispersion effects [2-6]. However, owing to weak electro-optic effects in silicon and long carrier lifetime, E/O data modulation in silicon is still challenging and most silicon E/O modulators suffer from limited modulation speed or low extinction ratio. The state-of-the-art silicon E/O modulator has a modulation speed of around 40 Gb/s and an extinction ratio of a few dB [7].

On the other hand, the all-optical modulator, where light is controlled by light, enables ultrafast signal processing by overcoming the limitation of E/O or O/E conversion. Based on the ultrafast Kerr effect, several functionalities and applications have been demonstrated, including signal regeneration, wavelength conversion, optical sampling and demultiplexing [7-11]. However, silicon based all-optical processing suffers from the slow dynamics of two-photon absorption (TPA) induced free carrier absorption (FCA). The long lifetime of the free carriers may limit the operation speed and introduce patterning effects.

In this paper, we experimentally demonstrate 160 Gb/s all-optical data modulation with an extinction ratio of 18.5 dB based on cross phase modulation (XPM) in a silicon nanowire. The optically modulated on-off keying (OOK) 160 Gb/s signal is subsequently off-center filtered and the input carrier is suppressed in order to reduce the carrier induced effects. Error free performance is achieved for the optically modulated 160 Gb/s signal.

2. Operation principle

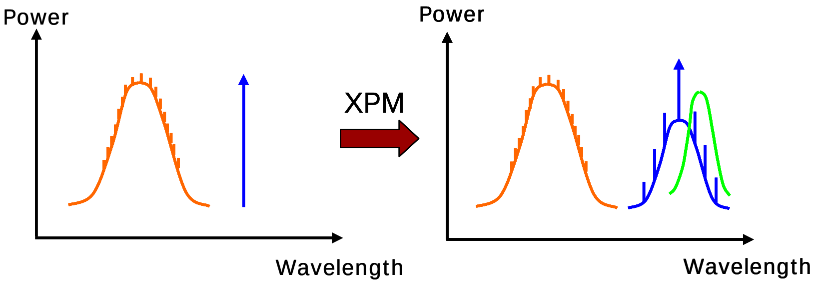

Fig. 1. Schematic of the XPM based all optical modulation with subsequent off-center filtering.

Low speed optical signals with a small duty cycle can be optically time-division multiplexed (OTDM) into a high speed signal based on bit interleaving. The OTDM signal is co-propagated with a continuous wave (CW) at a flexible wavelength in a silicon nanowire. The refractive index of the waveguide is modulated by the OTDM signal, which results in a phase modulation of the CW light. If an off-center filter (green, Fig. 1) is implemented, the phase modulation can be transferred into amplitude modulation. In addition, the original carrier is suppressed by a notch filter. Therefore, we can fully take advantage of the ultrafast Kerr effect to obtain the high speed modulated signal and reduce the slow carrier induced effects. It should be noted that although every tributary in the OTDM signal has no fixed phase relation between each other, the amplitude modulated high speed signal based on the XPM has coherent phase.

3. Experimental setup

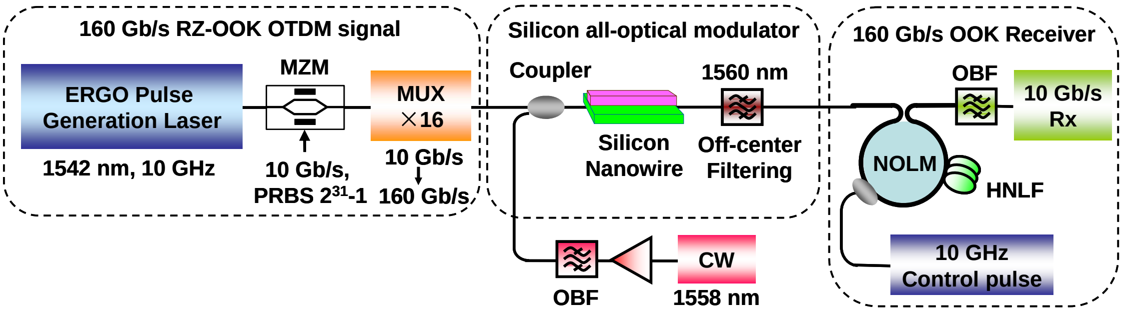

Fig. 2. Experimental setup of 160 Gb/s all-optical data modulation using a silicon nanowire.

The key device in the all-optical modulator is a nano-engineered silicon nanowire, which is 3.6 mm long and has cross-sectional dimensions of 240 nm × 450 nm. The device has a silicon-on-insulator (SOI) structure, with the silicon nanowire placed on a SiO_2/Si substrate. The width at the end of the silicon nanowire is tapered from 450 nm to a tiny tip of 40 nm so that the guided mode will expand into a polymer waveguide, surrounding the SOI waveguide and the taper. The 3.6-mm length of the nanowire includes the tapering sections, which are about 0.3 mm long each. The cross-sectional dimensions of the polymer waveguide matche the tapered access fibers, reducing the coupling loss [12]. The measured propagation loss is 4.3 dB/cm and the device insertion loss is 5.5 dB.

The experimental setup for the 160 Gb/s all-optical data modulation using a silicon nanowire is shown in Fig. 2. It includes a 160 Gb/s RZ-OOK OTDM signal generation, a silicon nanowire based all-optical modulator and a 160 Gb/s OOK receiver. 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) pulse width. A part of the pulses is on-off keying modulated by a 10 Gbit/s PRBS (2^{31}-1) signal in a Mach-Zehnder modulator (MZM). The other part of the pulses is used as 10 GHz control pulses for the demultiplexing in the 160 Gb/s receiver. The modulated 10 Gbit/s RZ-OOK signal is multiplexed in time to 160 Gb/s using a passive fiber-delay multiplexer (MUX × 16).

In the silicon all-optical modulator, CW light at 1558 nm is amplified by an EDFA, then filtered by a 1 nm optical bandpass filter (OBF) and finally launched into the silicon nanowire through a 3 dB optical coupler (OC). The 160 Gb/s RZ-OOK OTDM signal is also amplified and then filtered, and launched into the silicon nanowire through the second input of the 3 dB coupler. The launched power of the CW light and the OTDM signal are 16.4 dBm and 18.3 dBm, respectively. The polarizations of the CW light and the OTDM signal are both aligned to the TE mode of the waveguide. At the output of the silicon nanowire, the original signal and the modulated signal are launched into an off-center filtering subsystem which consists of a fiber Bragg grating (FBG) based notch filter, two 5 nm OBFs and an EDFA in between. The notch filter is used to suppress the original CW light and the OBFs are used to separate the modulated signal at 1560 nm from the OTDM signal.

The optically modulated 160 Gb/s RZ-OOK signal is detected by a 160 Gb/s OOK receiver which consists of a non-linear optical loop mirror (NOLM) based OTDM demutiplexer, a 1.3 nm filter, a preamplifier, a photodetector (PD) and an error analyzer. The NOLM is used to OTDM demultiplex the 160 Gb/s high speed data signal to a 10 Gb/s data signal based on cross-phase modulation in a 50 m HNLF. Finally, the demultiplexed 10 Gb/s RZ-OOK signal is detected by the PD and sent to an error analyzer for bit-error rate (BER) evaluation.

4. Experimental results

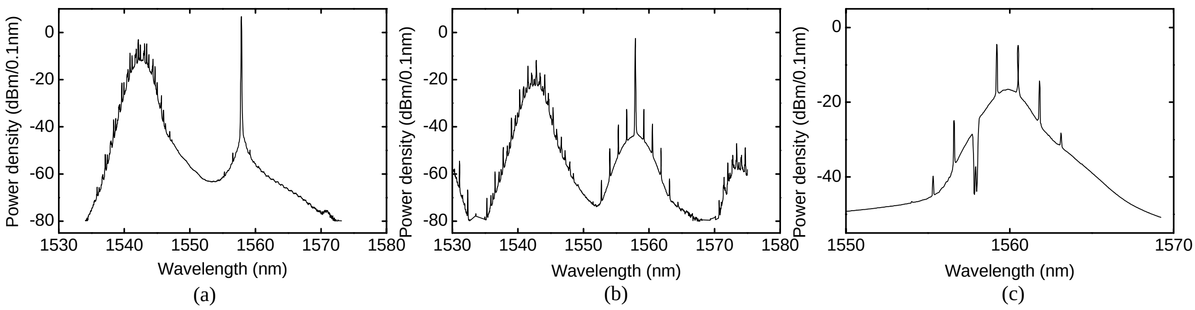

Fig. 3. (a) Spectrum at the input of the silicon nanowire; (b) Spectrum at the output of the silicon nanowire; (c) Spectrum of the modulated 160 Gb/s RZ-OOK signal after the off-center filtering and the carrier suppression.

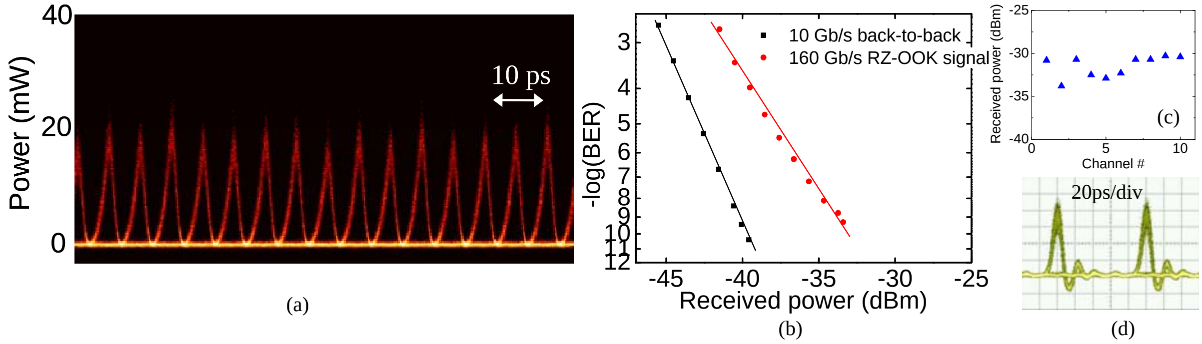

Fig. 4. (a) Optical sampling oscilloscope (OSO) eyediagram of the optically modulated 160 Gb/s RZ-OOK signal; (b) BER measurements for the 10 Gb/s back-to-back RZ-OOK signal and for the optically modulated 160 Gb/s RZ-OOK signal; (c) Receiver sensitivity at the BER of 10^{-9} for the adjacent channels; (d) Eyediagram of the demultiplexed 10 Gb/s RZ-OOK signal from the 160 Gb/s RZ-OOK signal.

The spectra at the input and output of the silicon nanowire are shown in Fig. 3 (a) and (b). We can see strong cross phase modulation on the CW light at the output of the silicon nanowire. The blue and red part of the phase modulated spectrum are generated from the rising and falling edge of the OTDM signal, respectively. We can off-center (blue shift or red shift) filter the phase modulated spectrum to obtain amplitude modulated 160 Gb/s signal. The spectrum at ~ 1574 nm is the four wave mixing product generated in the silicon nanowire. The original CW light at 1558 nm is suppressed by a notch filter and the spectrum of the modulated 160 Gb/s RZ-OOK signal after the off-center filtering and the carrier suppression is shown in Fig. 3 (c).

Fig. 4 (a) shows the eyediagram of the optically modulated 160 Gb/s RZ-OOK signal, measured by an optical sampling oscilloscope (OSO), and the extinction ratio of the 160 Gb/s signal is measured to be 18.5 dB. Bit error rate (BER) measurements are shown in Fig. 4 (b) as a function of the received power. BER curves are plotted for the 10 Gb/s RZ-OOK signal back-to-back and for the optically modulated 160 Gb/s RZ-OOK signal after demultiplexing. The 160 Gb/s RZ-OOK signal shows a clear error-free performance with 6.3 dB penalty in received power compared to the 10 Gb/s reference curve at a BER of 10^{-9}. The receiver sensitivities of 10 adjacent channels at the BER of 10^{-9} are measured, as shown in Fig. 4 (c). All these channels are error free with a receiver sensitivity variation of 3.5 dB. Fig. 4 (d) shows the 10 Gb/s eyediagram demultiplexed from the 160 Gb/s RZ-OOK signal.

4. Conclusion

We have demonstrated 160 Gb/s all-optical data modulation with an extinction ratio of 18.5 dB based on cross phase modulation (XPM) in a silicon nanowire. The modulated signal is obtained by off-center filtering and suppression of the original carrier. Error-free performance is achieved for the optically modulated 160 Gb/s RZ-OOK signal. In addition, the wide operation bandwidth of the silicon nanowire could allow for 160 Gbit/s all-optical modulation across the whole telecommunication C-band, if the OTDM signal was generated in the L band. We believe this is an important confirmation of the potential of the silicon all-optical modulator.

5. References

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