40-Gb/s BPSK Modulation using a Silicon Modulator

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***Abstract* - We demonstrate BPSK modulation using a silicon traveling-wave modulator at a data rate of 40 Gb/s with record 10.5 pJ/bit energy efficiency, and compare its performance with a commercial Lithium Niobate phase modulator.**

I. Introduction

High-speed silicon modulators have attracted considerable research interests for advanced modulation formats in recent years [1]. Due to its advantage as a powerful integrated platform, silicon photonics is poised to enable low-cost and high yield device manufacturing with potentially large impact on applications ranging from optical communication [2-3] to high-performance computing [4-5]. Binary phase-shift keying (BPSK) modulation, as a basic building block for modulation formats such as quadrature phase-shift keying (QPSK), has been demonstrated up to data rate of 10-Gb/s using a silicon microring modulator [6] and 25-Gb/s in a silicon Mach-Zehnder modulator [7-9]. In this work we demonstrate for the first time BPSK modulation using a silicon traveling-wave modulator at a data rate of 40-Gb/s with 7.4 V_{pp} differential driving voltage and 4 V bias voltage. We, compare the modulator performance to a commercial 40-Gb/s phase modulator.

II. Device

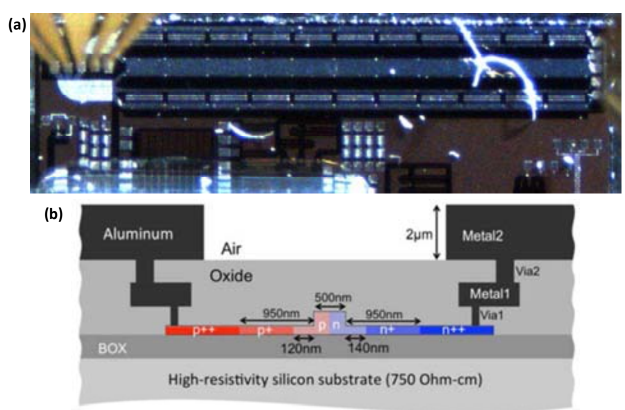

Figure 1. (a) Image of the silicon travelin-wave modulator showing GSGSG probe on the right for driving , GSGSG on the top for 50-Ω termination and PM fiber array on the bottom for coupling. (b) Cross sectional diagram of the phase shifter.

Fig. 1(a) shows an image of the silicon traveling-wave modulator used in the experiment. The details of the device design, fabrication and characterization can be found in [10]. The silicon modulator has a length of 3.5-mm, bandwidth of 27 GHz at -1V bias. Each arm of the modulator is a p-n junction in depletion mode with fully independent differential drive. A polarization-maintaining (PM) fiber array is attached to the chip to obtain stable coupling through grating couplers. Fig. 1(b) shows the cross sectional diagram of the p-n junction. The device V_{π} is measured to be ~ 5.5 V for each arm.

III. Experiment

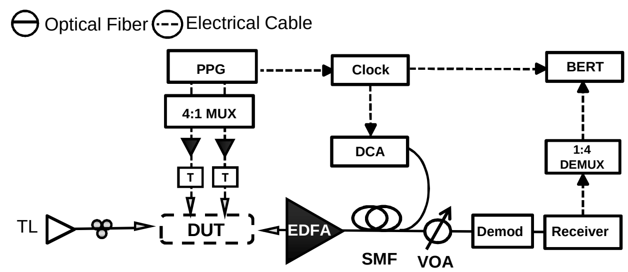

Figure 2. Experiment setup.

The experimental setup is shown in Fig. 2. A continuous-wave (CW) signal from a tunable laser (TL) is sent into the device-under-test (DUT). A pulsed-pattern generator (PPG) generates a non-return-to-zero (NRZ) 2^{31}-1 pseudo-random bit-sequence (PRBS) signal. The differential PRBS signal is 4:1 multiplexed, amplified, biased with a bias tee (T) and drives the silicon modulator through an RF GSGSG probe. The output light from the chip is then amplified with an erbium-doped fiber amplifier (EDFA). The amplified signal passes through a variable optical attenuator (VOA), a commercial BPSK demodulator with 50 GHz free spectral range (FSR) before being received on a PIN-TIA photodetector with limiting output buffer. The receiver output is connected to a 1:4 demultiplexer. The demultiplexed and selected tributary is then fed into a bit-error-rate tester (BERT) for BER measurements. A digital communications analyzer (DCA) was used to record eye diagrams throughout the experiment. The PPG, DCA and BERT are synchronized with the same clock signal.

In our experiment, the tunable laser wavelength is set at 1554.788 nm. The differential driving voltage applied to each arm of the silicon modulator is measured to be 7.4 V_{pp} biased at 4 V. The same driving voltage is applied to a commercial 40-Gb/s Lithium Niobate ($LiNbO_3$) phase modulator (Covega Mach-40) for comparison with the other parameters kept the same.

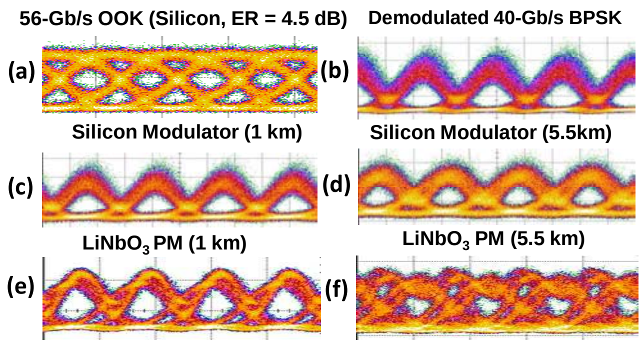

Figure 3. (a) 56-Gb/s OOK signal generated by silicon modulator. (20ps/div) (b) Demodulated 40-Gb/s BPSK by silicon modulator. Demodulated 40-Gb/s BPSK after (c) 1km (d) 5.5km SMF transmission. Demodulation 40-Gb/s BPSK by $LiNbO_3$ phase modulator after (e) 1km (f) 5.5km SMF transmission(10 ps/div).

The recorded eye diagrams are shown in Fig. 3. We first measure the OOK signal generated by the silicon modulator, showing up to 56 Gb/s operation (Fig. 3(a)). The wavelength is then tuned to the right wavelength for BPSK modulation [11]. After demodulation, clean and open eyes are observed (Fig. 3(b)). The demodulated eye diagrams are still open with 1km and 5.5 km SMF transmission. Due to the nature of BPSK generation in a phase modulator, chirp is introduced across each bit transition, causing the bits to interference with each other, evident at longer SMF lengths (Fig. 3(f)). The power consumption of the silicon modulator is estimated to be ~ 0.42 W ($P = 2 \times \left(\frac{1}{4} \cdot \frac{V_{pp}{}^2}{R}\right)$ [7], achieving energy efficiency of 10.5 pJ/bit at 40-Gb/s.

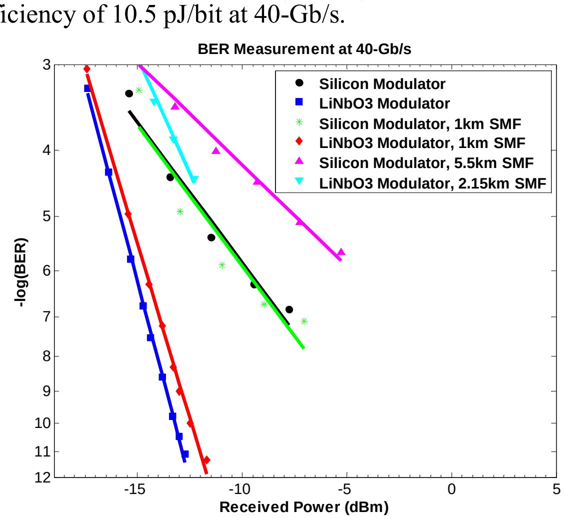

Figure 4. Measured BER curves of silicon and $LiNbO_3$ phase modulator.

With 1km SMF transmission, silicon modulator shows no power penalty while the $LiNbO_3$ phase modulator has ~ 0.8 dB power penalty (Fig. 4). With 2.15 km SMF transmission, the $LiNbO_3$ phase modulator has a BER error floor at 10^{-5} level, and with 5.5 km SMF transmission, BER measurement cannot be performed. In contrast, the silicon modulator shows BER of 10^{-6} level at 5.5 km SMF transmission, confirming the better dispersion tolerance of the silicon modulator.

IV. CONCLUSIONS

We demonstrate for the first time 40-Gb/s BPSK modulation using a silicon traveling-wave modulator. 7.4 V_{pp} differential driving voltage and 4 V bias voltage are used to drive the silicon modulator. 10.5 pJ/bit energy efficiency is achieved, lower than the previous record of 11.8 pJ/bti [7]. The silicon modulator is compared to a commercial 40-Gb/s $LiNbO_3$ phase modulator, showing better dispersion tolerance. The demonstrated silicon BPSK modulator could be used to as a basic building block for PDM-QPSK silicon modulator at unprecedented data rate.

ACKNOWLEDGMENT

The authors would like to thank Gernot Pomrenke, of AFOSR, for his support of the OpSIS effort, through both a PECASE award (FA9550-13-1-0027) and funding for OpSIS (FA9550-10-l-0439). We gratefully acknowledge the support from AFOSR STTR grants FA9550-12-C-0079.

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