

High-Speed BPSK Modulation using a Silicon Modulator

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Abstract - We demonstrate BPSK modulation using a silicon traveling-wave modulator at data rate up to 48 Gb/s, with 7.4 V_{pp} differential RF driving voltage. The performance of the silicon BPSK modulator is compared with a commercial Lithium Niobate phase modulator, showing better dispersion tolerance.

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 BPSK modulation using a silicon traveling-wave modulator at record data rate. The silicon BPSK modulator is designed with slow-wave transmission line electrodes and is driven by 7.4 V_{pp} differential and 4 V bias voltage. Up to 56-Gb/s OOK modulation with open eye and 48-Gb/s BPSK modulation is shown. The silicon modulator is estimated to achieve 8.75 pJ/bit record dynamic energy efficiency at 48-Gb/s. The silicon modulator is compared with a commercial 35GHz LiNbO₃ phase modulator in the same experimental setup, and is shown to have better dispersion tolerance.

II. DEVICE

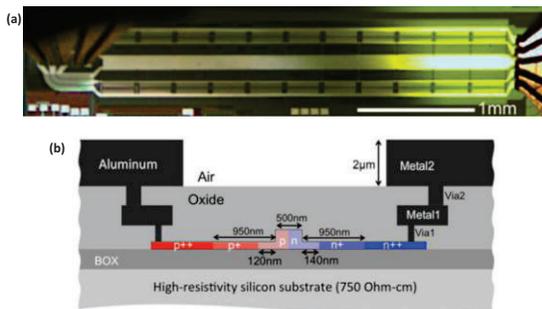


Figure 1. (a) Image of the silicon modulator showing GSGSG probe on the right for driving, GSGSG on the top for 50-Ω termination and PM fiber array on the bottom for coupling. (b) Cross sectional diagram of the phase shifter.

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

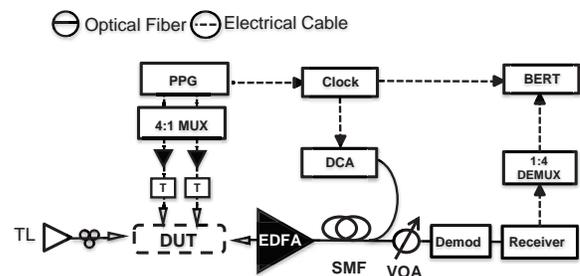


Figure 2. Experiment setup.

In the experiment (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) 2³¹-1 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.

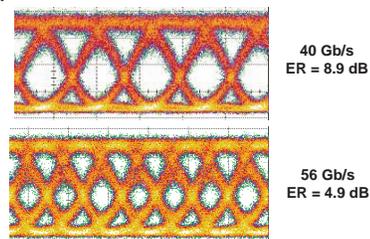


Figure 3. 40-Gb/s and 56-Gb/s OOK signal. (20ps/div).

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.

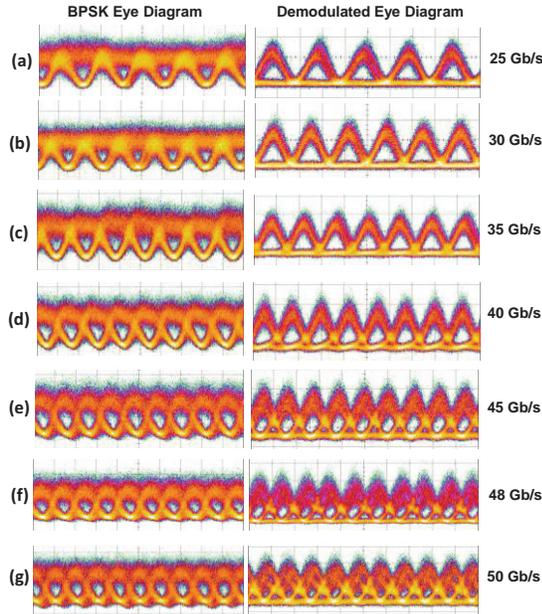


Figure 4. BPSK and the demodulated eye diagrams. (20ps/div).

We first measure the OOK signal generated by the silicon modulator, showing up to 56 Gb/s operation (Fig. 3). The wavelength is then tuned to the right wavelength for BPSK modulation [11]. After demodulation, clean and open eyes are observed up to 48 Gb/s (Fig. 4).

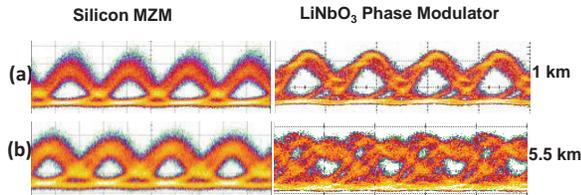


Figure 5. Demodulated BPSK eye diagram of silicon modulator and $LiNbO_3$ phase modulator at 40 Gb/s after (a) 1 km (b) 5.5 km SMF transmission.

The demodulated eye diagrams are still open with 1 km 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 interfere with each other, evident at longer SMF lengths (Fig. 5). The power consumption of the silicon modulator is estimated to be $\sim 0.42 W$ ($P = 2 \times \left(\frac{1}{4} \cdot \frac{V_{pp}^2}{R}\right)$ [7]), achieving energy efficiency of 8.75 pJ/bit at 48-Gb/s.

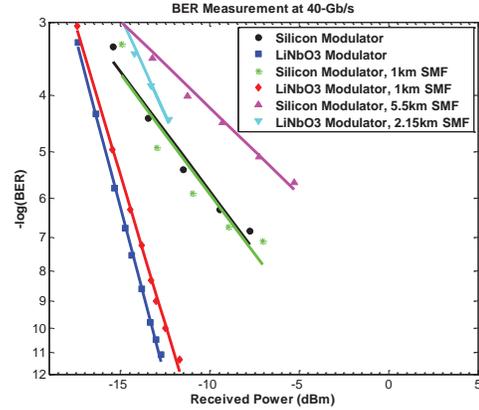


Figure 6. Measured BER curves of silicon and $LiNbO_3$ phase modulator.

With 1km SMF transmission, silicon modulator shows no power penalty while the $LiNbO_3$ phase modulator has ~ 0.8 dB power penalty (Fig. 6). 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.

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REFERENCES

- [1] P. Dong et al. "112-Gb/s monolithic PDM-QPSK modulator in silicon." *Optics Express* 20.26 (2012): B624-B629.
- [2] Y. Liu et al., "Ultra-compact 320 Gb/s and 160 Gb/s WDM transmitters based on silicon microrings," *Optical Fiber Conference (OFC) Th4G.6*. (2014).
- [3] Q. Li et al., "Scaling Star-Coupler-Based Optical Networks for Avionics Applications," *Journal of Optical Communications and Networking* 5 (9) (2013).
- [4] S. Rumley et al., "Silicon Photonics for Exascale Systems," *Journal of Lightwave Technology* 33 (4).
- [5] A. Krishnamoorthy et al., "Computer systems based on silicon photonic interconnects." *Proceedings of the IEEE* 97.7 (2009): 1337-1361.
- [6] Q. Li et al., "A 10-Gb/s Silicon Microring Resonator-Based BPSK Link," *IEEE Photonics Technology Letters* 26 (18) (2014).
- [7] T. Li et al. "Low-voltage, high speed, compact silicon modulator for BPSK modulation." *Optics Express* 21.20 (2013).
- [8] K. Goi et al. "20-Gbps BPSK silicon Mach-Zehnder modulator with excellent chirp-free performance." *Opto-Electronics and Communications Conference (OECC)*, 2012.
- [9] J. Wang et al. "Silicon high-speed BPSK modulator: design and optimization." *Asia Communications and Photonics Conference*. 2014.
- [10] R. Ding et al. "High-Speed Silicon Modulator With Slow-Wave Electrodes and Fully Independent Differential Drive," *Journal of Lightwave Technology* 32 (12) (2014).
- [11] A. Gnauck et al.. "Optical phase-shift-keyed transmission." *Journal of lightwave technology* 23.1 (2005): 115.