A 240 Gb/s PAM4 Silicon Micro-Ring Optical Modulator

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Abstract: We report a micro-ring modulator with 0.53 V·cm phase efficiency, 54 GHz bandwidth, and 16.3 nm FSR. We have achieved 224 and 240 Gb/s PAM4 eye diagrams with 1.6 dB and 3.9 dB TDECQ, respectively.

1. Introduction

Silicon photonics has emerged as a key enabling technology for high-bandwidth data center optical interconnect [1,2], co-packaged optics and optical I/O [3-5], and is an attractive solution for future applications beyond 400GbE [6,7] to meet the ever-increasing data communication demands. High-speed optical modulation above 200Gb/s has been demonstrated using silicon Mach-Zehnder modulators and advanced modulation formats [8]. In comparison, silicon microring modulators (MRM's) have some unique advantages such as small footprint, simple driver configuration, low power consumption, and suitability for dense wavelength division multiplexing (DWDM) applications. They are therefore favorable for applications where space and power consumption are constrained such as co-packaged optics and optical I/O [3-5].

Silicon MRM's have been extensively researched over the past years and data rates up to 200 Gb/s have been demonstrated using four-level pulse-amplitude modulation (PAM4) [9, 10]. However, achieving >200 Gb/s data rate has remained a major challenge for MRMs due to their intrinsic trade-off between bandwidth and modulation efficiency. In this paper, we report, to the best of our knowledge, the first silicon photonic MRM operating at > 200 Gb/s. At 224 Gb/s (112 GBaud PAM4), we achieved a transmitter penalty (TDECQ) of 1.6 dB; and at 240 Gb/s (120 Gbaud PAM4), a TDECQ of 3.9 dB.

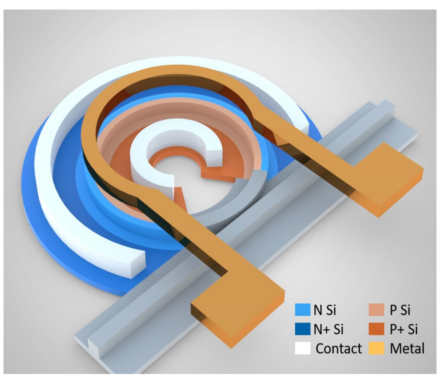

Fig. 1: A schematic of the silicon photonic microring modulator with a thermal phase tuner.

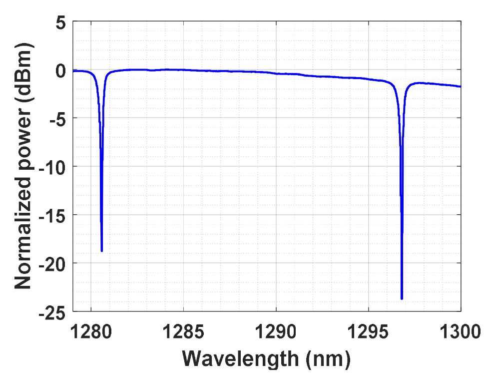

Fig. 2. Optical tranmission spectrum of the microring modulator, showing a FSR of 16.3 nm.

2. Modulator Design and Characterization

Figure 1 shows a schematic of the silicon photonic MRM design. The microring was formed by a silicon rib waveguide with height of 300 nm, width of 500 nm, and slab thickness of 100 nm. Compared to our previous work [10], we reduced the microring modulator radius from 6 µm to 4 µm, resulting in lower capacitance and larger free spectral range (FSR) of 16.3 nm (Fig. 2), capable of accommodating 12 DWDM channels with 200 GHz spacing. The loaded quality factor of the MRM was measured to be 4000, and the electro-optic (EO) phase efficiency ($V\pi \cdot L$) of the PN junction was measured to be 0.42 V·cm and 0.53 V·cm at a reverse bias voltage of 0 V and 3 V, respectively. The electrical S11 parameter of the MRM was measured at a reverse bias voltage of 3 V using a vector network analyzer. The responses of the cables and the probe were de-embedded using a calibration substrate. The measured S11 results are presented in Fig 3. We extracted the resistance R = 58 Ω and capacitance C = 25 fF, resulting in an intrinsic RC bandwidth of 110 GHz.

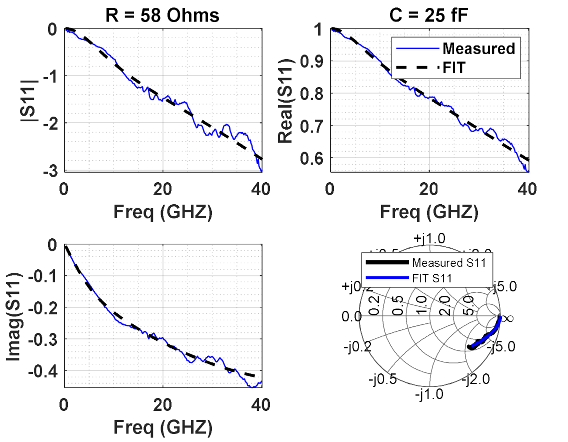

Fig. 3. Measured S11 and extracted RC characteristics.

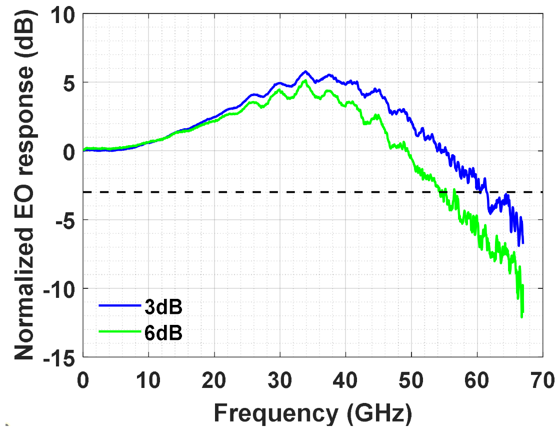

Fig. 4. Measured EO response (S21) for wavelength detuning levels of 3 and 6 dB.

The EO response (S21) was measured using a Lightwave Component Analyzer (LCA) at a reverse bias of 3V for laser wavelength detuning corresponding to 3 and 6 dB down from the off-resonance transmission maximum power level. As shown in Fig. 4, the measured 3-dB RF modulation bandwidths are 62 and 54 GHz, correspondingly. The MRM was driven using a 128 GS/s arbitrary waveform generator (AWG), followed by an RF amplifier, a bias-tee, and a 50-Ω terminated probe. The response of the RF driver link, including the AWG frontend, the RF amplifier, the bias tee, and the RF cables was de-embedded through signal de-emphasis function of the AWG, which mitigates the high-frequency loss of the RF driver link up to 50 GHz. The light from a tunable laser was coupled in and out of the MRM chip through on-chip optical mode convertors. The modulated optical signal was amplified by a fiber optical amplifier and detected by the optical sampling head of a digital communication analyzer (DCA).

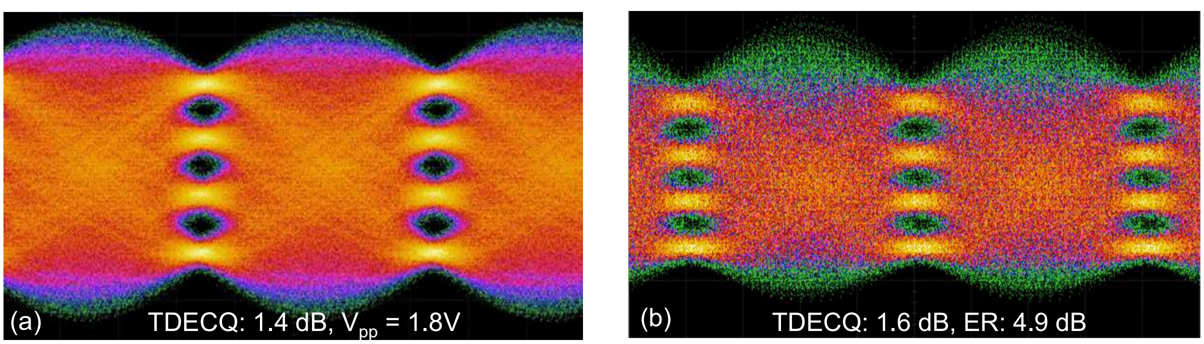

Fig. 5: PAM-4 Eye diagrams at 112 Gbaud or 224 Gb/s (a) electrical input; (b) optical modulator output.

Figures 5 and 6 show the measured eye diagrams of the electrical driving signals and the received optical signals when the MRM was driven by a PAM4 PRBS data pattern at 112 GBaud (224 Gb/s), and 120 GBaud (240 Gb/s), respectively. For optimum OMA and linearity, we operated the MRM at a wavelength detuning corresponding to 6 dB insertion loss point. The peak-to-peak RF swing was Vpp=1.8 V. The outer ER, namely the extinction ratio between the top level and the bottom level of the PAM4 eyes, was measured to be 4.9 and 4.8 dB, respectively. To measure the Transmitter Dispersion Eye Closure Quaternary (TDECQ) penalty of the MRM transmitter we used a half baud rate filter and 21-tap FFE equalizer at the receiver. The TDECQ was measured at a soft-decision forward error correction (FEC) threshold of 1.8E-2 [11]. As shown in Fig. 5 and 6 the measured TDECQ of the MRM was 1.6 dB, and 3.9 dB at symbol rates of 224 Gb/s (112 Gbaud) and 240 Gb/s (120 Gbaud), respectively.

We also measured the TDECQ of the electrical drive signals. The degradation from the electrical transmitter was 0.2 dB and 0.8 dB at 224 Gb/s and 240 Gb/s, respectively, without using any optical transmitter pre-equalization. We believe these results can be further improved by using a dedicated MRM driver with matched impedance and higher bandwidth.

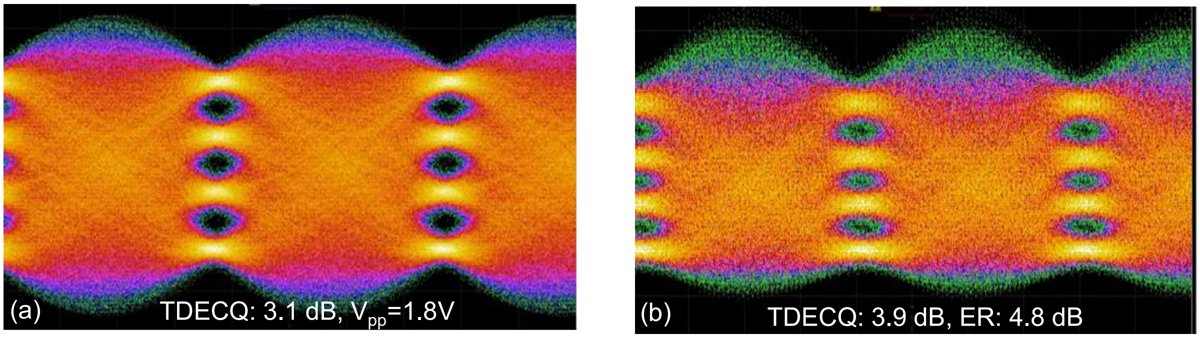

Fig. 6: PAM-4 Eye diagrams at 120 Gbaud or 240 Gb/s (a) electrical input; (b) optical modulator output.

3. Conclusions

We have demonstrated, to the best of our knowledge, the first silicon microring modulator operating at >200 Gb/s with <2.0 Vpp drive voltage swing and without any optical transmitter pre-equalization. The transmitter TDECQ of the PAM4 modulation at 224 Gb/s and 240 Gb/s was measured to be 1.6 dB and 3.9 dB, corresponding to 0.2-dB and 0.8-dB additional penalty with respect to the electrical signal source, respectively. This demonstration opens up the possibility of using compact, low power, silicon microring modulators for future high-speed optical interconnects and optical I/O.

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