A high-speed micro-ring modulator for next generation energy-efficient optical networks beyond 100 Gbaud

9 authors, including:

Meer Nazmus Sakib
University of California, Berkeley
48 PUBLICATIONS **363** CITATIONS

Chaoxuan Ma
University of California, San Diego
16 PUBLICATIONS **206** CITATIONS

Guan-Lin Su
University of California, Berkeley
17 PUBLICATIONS **48** CITATIONS

Saeed Fathololoumi
Kotura
53 PUBLICATIONS **1,609** CITATIONS

A high-speed micro-ring modulator for next generation energy-efficient optical networks beyond 100 Gbaud

Meer Sakib, Peicheng Liao, Chaoxuan Ma, Ranjeet Kumar, Duanni Huang, Guan-Lin Su, Xinru Wu, Saeed Fathololoumi, and Haisheng Rong
Intel Corporation, 3600 Juliette Ln, Santa Clara, CA 95054
meer.nazmus.sakib@intel.com

Abstract: We demonstrate a silicon micro-ring modulator supporting 128 Gb/s NRZ modulation with SNR=5.2, ER=3.8 dB, 0.8 V_{pp} drive swing, and 5.3 fJ/bit power consumption. We have also achieved 192 Gb/s PAM-4 modulation with TDECQ of 2.5 dB.

1. Introduction

Silicon optical modulators provide low-cost solutions for high-speed optical communications and interconnects. Such modulators are generally based on Mach-Zehnder interferometers that can support high baud rate applications [1]. However, high-speed silicon micro-ring modulators (MRMs) have recently emerged as an attractive alternative to MZMs due to their compact size and low power consumption [2-4]. In a 2020 demonstration, a silicon micro-ring modulator based 1.6 Tb/s optical engine was co-packaged with a 12.8Tb/s Ethernet switch and shown to interoperate with a standard DR4 pluggable module [5]. A photonic chip with such high bandwidth density was only achievable by using compact micro-ring modulators. In this paper, we report a high-speed silicon micro-ring modulator with a record-breaking speed of 128 Gbaud on-off keying (OOK) modulation. We have achieved a clear open eye diagram with signal to noise ratio (SNR) of 5.2 and extinction ratio (ER) of 3.8 dB measured directly with a digital communication analyzer (DCA) without any offline digital signal processing (DSP). The drive voltage swing was 0.8 Vpp and the MRM consumed less than 5.3 fJ/bit power. This is a significant milestone for next generation energy-efficient high-speed optical communication networks beyond 100 Gbaud with low-cost silicon optical modulators.

2. Modulator Design and Characterization

Figure 1 shows a schematic of the silicon photonic MRM design. The micro-ring was formed by a silicon rib waveguide with height of 300 nm, width of 400 nm, and slab thickness of 100 nm. The MRM has a radius of 6 µm, resulting in a Free Spectral Range (FSR) of 11.3 nm at 1310 nm. The loaded quality factor of the MRM was measured to be 4200. The electro-optic (EO) phase efficiency ($V_\pi \cdot L_\pi$) of the PN junction of the MRM as a function of the reverse bias is shown in Fig. 2. The measured $V_\pi \cdot L_\pi$ is 0.53 V·cm at a reverse bias voltage of 3 V and 0.42 V·cm at 0 V bias. Compared to our previous work [2], the junction was redesigned to support higher data rate of >100 Gbaud and lower heater voltage of V_π < 1.5V for thermo-optic phase tuning.

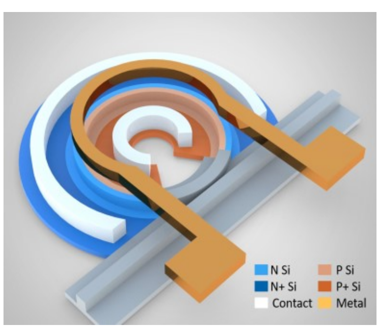

Fig. 1. A schematic of the silicon photonic MRM with metal heater.

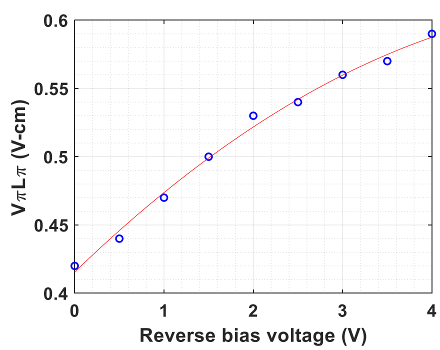

Fig. 2. Modulation efficiency as a function of reverse bias.

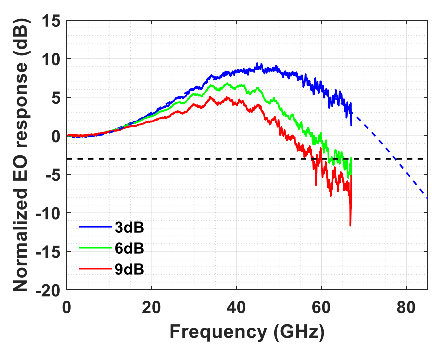

Fig. 3. Measured EO response (S21) at reverse bias of 3V for 3 wavelength detuning levels of 3, 6 and 9 dB.

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 through standard calibration. The extracted resistance and capacitance of the PN junction were 26 Ω and 33 fF, respectively. The EO response (S21) was measured using a Lightwave Component Analyzer (LCA) at reverse bias of 3V for three laser wavelength detuning points corresponding to 3, 6 and 9 dB down from the off-resonance transmission maximum power level. As shown in Fig. 3, the measured 3-dB RF modulation bandwidths were 77, 63, and 58 GHz, correspondingly.

Figures 4 and 5 show the measured electrical and optical eye diagrams. We used an arbitrary waveform generator followed by a RF amplifier and a 50-Ω terminated probe to drive the MRM. The optical input was provided by an O-band tunable laser and the optical output from the MRM was amplified by an optical amplifier and sent to the DCA. Fig. 4(a) shows the 128 Gb/s electrical driving signal with SNR of 4.6 and RF swing of 0.8 V_{pp}. We obtained an open eye with SNR of 2.7 and ER of 3.9 dB at a wavelength detuning point of -9 dB, as shown in Fig. 4(b), without any equalization. By applying a 7-tap feed forward equalization (FFE), the SNR can be improved to 5.2, Fig. 4(c). Based on the eye SNR (Q-factor), we estimated the bit error ratio (BER) would be 3.4×10^{-3} at the receiver without any equalization [6]. The power consumption of the MRM was calculated to be 5.3 fJ/bit based on the drive voltage and its capacitance. We also drove the MRM with a 96 Gbaud or 192 Gb/s PAM-4 electrical signal with a voltage swing of 1.6 Vpp, Fig. 5(a). The directly measured PAM-4 optical eye diagram showed ER of 3.5 with no FFE. For better linearity we operated the MRM at a wavelength detuning point of -6 dB. By applying a 5-tap FFE, we obtained an improved PAM-4 eye with a TDECQ of 2.5 dB and an outer ER of 3.4 dB, as shown in Fig. 5(c). We believe the obtained results can be further improved by using a dedicated modulator driver with matched impedance and higher bandwidth.

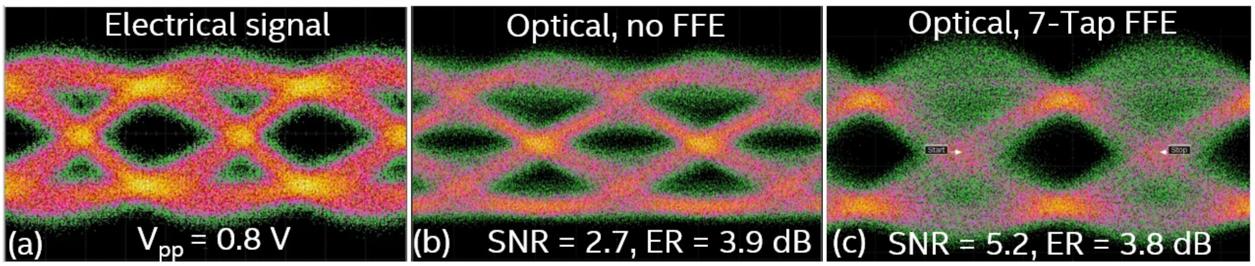

Fig. 4 NRZ Eye diagrams at 128 Gbaud. (a) electrical input; (b) optical eye without FFE; and (c) optical eye with 7-tap FFE.

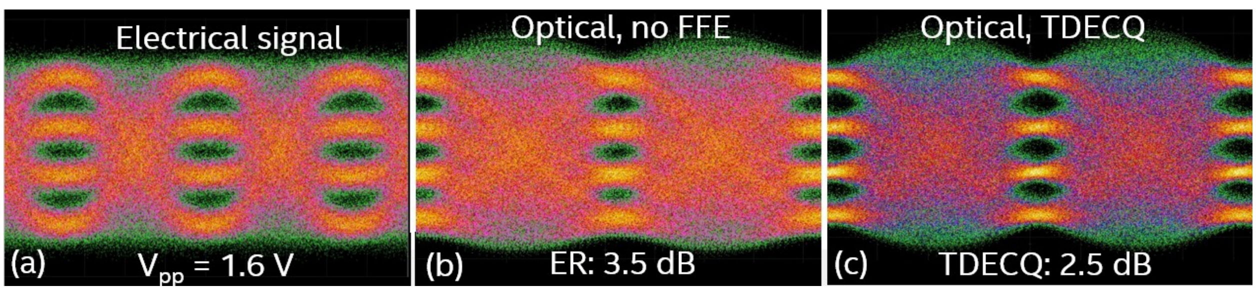

Fig. 5 PAM-4 Eye diagrams at 96 Gbaud or 192 Gb/s (a) electrical input; (b) optical w/o equalizer; and (c) optical eye with 5-tap FFE.

4. Conclusion

We demonstrated, to the best of our knowledge, the first silicon modulator operating at 128 Gb/s NRZ modulation consuming 5.3 fJ/bit without any DSP. We obtained eye SNR of 5.2 with a 7-tap receiver FFE, supporting hard-decision forward error correction with a threshold of BER<3.8×10^{-3} [7]. We also demonstrated 192 Gb/s PAM-4 modulation with a TDECQ of 2.5 dB without any transmitter pre-equalization. We believe that the silicon MRM is a promising candidate for next generation short-reach optical networks beyond 100 Gbaud per channel with compact size and low power consumption [8].

Acknowledgements

We would like to thank James Jaussi, Ling Liao, Yuliya Akulova, Robert Blum, Ali Eftekhar, Siamak Amiralizadeh for their support and technical discussions, Gregory Lovell and Jordan Davis for test equipment support, and our process engineers in Fab11x for device fabrication.

4. References

[1] F. Zhang, *et al.*, "High baud rate transmission with silicon photonic modulators," IEEE JSTQE, 27(3), (2021).
[2] J. Sun, *et al.*, "A 128 Gb/s PAM4 silicon microring modulator with integrated thermo-optic resonance tuning," JLT, 37(1), (2019).
[3] H. Li *et al.*, "A 112 Gb/s PAM4 silicon photonics transmitter with microring modulator and CMOS driver," JLT 38 (1), (2020).
[4] Y. Zhang, *et al.*, "200 Gbit/s optical PAM4 modulation based on silicon microring modulator," ECOC, Th3A-1 (2020).
[5] S. Fathololoumi, *et al.*, "1.6 Tbps Silicon Photonics Integrated Circuit and 800 Gbps Photonic Engine for Switch Co-Packaging Demonstration," JLT, 39(4), 2021.
[6] G. Agrawal, "Fiber-Optic Communication Systems," Chap 4, pp. 164, Wiley 1992.
[7] J. Wei *et al.*, "Experimental comparison of modulation formats for 200 G/λ IMDD data centre networks," ECOC, Tu3D.2 (2019).
[8] "IEEE launches 802.3™ Beyond 400Gb/s Ethernet Study Group to Define Next High-Speed Threshold for Ethernet Data Rate," IEEE press release (2021). https://standards.ieee.org/news/2020/802_3-ethernet-study-group-high-speed-threshold.html