Single Lane 330 Gb/s Silicon Photonic Microring Modulator with sub 2 V_{pp} Driving Voltage

David W.U Chan[1], Xiong Wu[2], Alan Pak Tao Lau[3], Chao Lu[2] and Hon Ki Tsang[1]
[1]Dept. of Electronic Engineering, The Chinese University of Hong Kong, Hong Kong
[2]Photonics Research Institute, Dept. of Electronic and Information Engineering, The Hong Kong Polytechnic University, Hong Kong
[3]Photonics Research Institute, Dept. of Electrical Engineering, The Hong Kong Polytechnic University, Hong Kong
Author e-mail address: hktsang@ee.cuhk.edu.hk

Abstract: We present the first silicon photonic microring modulator operating at up to 330 Gb/s. The modulator can support PAM-8 with driving voltage under 2 V_{pp} in C-band using a polynomial nonlinear equalizer. © 2022 The Author(s)

1. Introduction

Silicon photonics (SiPh) is one of the most promising technologies to enable low-cost and high-performance optical transceivers. The development of SiPh modulators in the recent years reveals a pathway for achieving datarates beyond 800 GbE in short-reach intensity modulation-direct detection (IM-DD) transceivers. Transmission experiments have previously achieved single lane rates of over 300 Gb/s using silicon Mach-Zehnder modulators (MZM) [1]. More compact and possibly more energy-efficient transmitters based on the microring modulator (MRM) or the use of GeSi electro-absorption modulator (GeSi-EAM) have also attracted much attention for dense integration of transceivers supporting many lanes of data in next-generation transceivers using SiPh [2,3]. The MRM in particular has previously been shown to be suitable for IM-DD formats with data rates of 240 Gb/s using PAM-8 and PAM-4 [4-6].

In this paper, we present a silicon MRM with 50 GHz EO bandwidth optimized for high order modulation formats. PAM-8 IM-DD is demonstrated at up to 110 Gbaud with a driving voltage below 2 V_{pp}. Ultra-high baud rate operation using PAM-4 was also tested for up to 130 Gbaud with BER under 2.4 E-2.

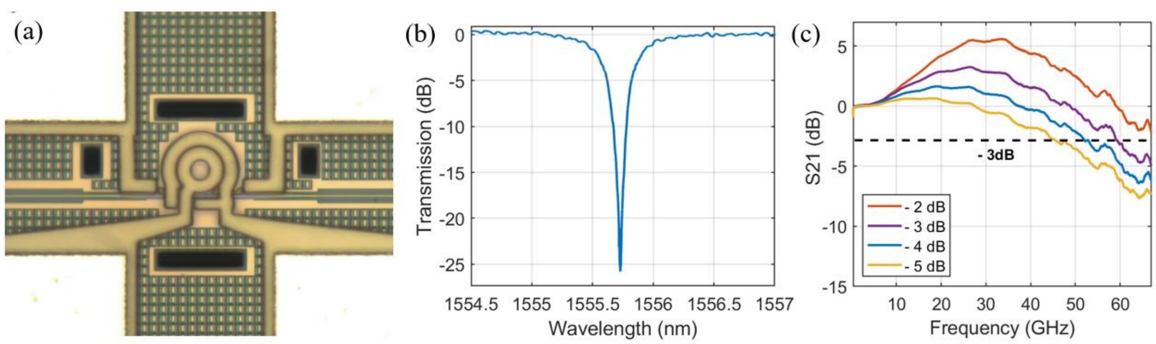

Fig. 1. (a) Fabricated MRM under microscope, (b) static transmission spectrum of the MRM at 0 V bias, (c) electro-optic (EO) S21 response of the MRM for the input wavelength detuned to differ levels of transmission loss near the resonance.

2. Device design and characterization

The MRM was fabricated in a commercial foundry using a SiPh multi-project wafer (MPW) platform. The buried oxide has a thickness of 2 um and the silicon layer has a thickness of 220 nm. The fabricated MRM is shown in Fig. 1 (a). The MRM radius was chosen to be 7.5 μm and designed to have a loaded Q factor of around 5000 for possible use with higher order pulse amplitude modulation (PAM) formats. The modulator uses a lateral PN junction in the ring waveguide to provide varying carrier-depletion at different reverse voltages. A TiN heater is integrated which is embedded in the oxide above the Si MRM for thermo-optic resonance tuning. The heater can shift the resonance over the full free-spectral range (FSR) of the MRM. Deep trenches were etched around the MRM for thermal isolation and the metal pads were designed for the high-speed data signal and control of the heater, with pitch matched multi-contact RF probes. The transmission spectrum of the MRM is shown is Fig. 1 (b). An extinction ration (ER) of 25 dB and a loaded Q factor of ~5200 is measured. The electro-optic (EO) S21 response of the MRM, measured using a 67 GHz lightwave component analyzer (LCA), is shown in Fig. 1 (c). The EO S21 parameter is measured with a reverse bias of – 3 V and thermally tuning the MRM to enter the resonance at the different levels of insertion loss, indicated in the plot. The insertion loss levels between – 2dB to – 5dB are equivalent to wavelength detuning values that can be estimated from Fig. 1 (b). For the detuning levels between – 2 dB to – 4 dB, the MRM has a bandwidth of >50 GHz. The MRM bandwidth benefits from the optical peaking effect which enhances the bandwidth of the MRM beyond the photon lifetime limitation [7]. The optical peaking effect is stronger when the laser is detuned further away from the resonance. At a large detuning to the relatively high level of – 2 dB, the MRM shows a peak at 5 dB and a 3-dB bandwidth of 67 GHz. Fig. 2 (a) shows the EO S21 response under different biasing voltages. Under a resonance detuning of – 4 dB, bandwidth of > 50 GHz is measured for – 3 V and – 4 V.

3. High-speed testing

The high-speed testing was performed using an arbitrary waveform generator (AWG) (Keysight 8199A) operating at interleaving mode with a sampling rate of 256 GSa/s. The RF signal is amplified using a 60 GHz wideband RF amplifier to produce a signal level of 1.8 V_{pp} at the modulator. The signal is applied to the chip using a terminated RF probe. PAM-8 and PAM-4 modulation formats were tested from 70 to 120 Gbaud (210 Gb/s to 360 Gb/s) and from 100 to 160 Gbaud (200 Gb/s to 320 Gb/s) respectively. In addition to back-to-back (B2B) testing, performance on transmission over 1 km standard single mode fiber (SSMF) was also assessed. The signal was amplified using an erbium doped fiber amplifier (EDFA) and received using a 70 GHz photodiode connected directly to a real-time oscilloscope (RTO) (Keysight UXR0802A) with 80 GHz analog bandwidth and 256 GSa/s sampling rate. The received signal is processed offline. Digital signal processing (DSP) at the transmitter side uses pre-distortion which re-map the PAM-4 levels (not used in PAM-8) to compensate for the non-linear transmission curve of the MRM [8]. Digital pre-emphasis was also applied to compensate for high-frequency loss. At the receiver side, different equalizers were evaluated including feed-forward equalizer combined with decision feedback equalizer (FFE-DFE) and polynomial non-linear equalizer (PNLE).

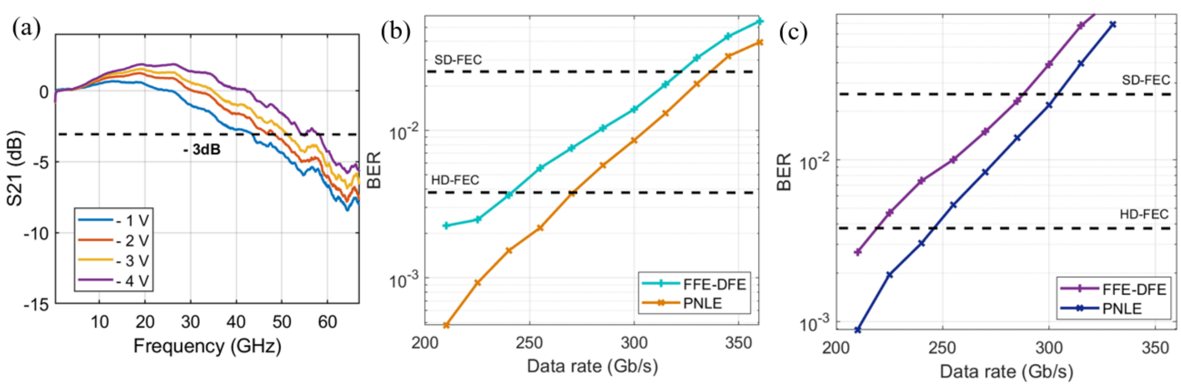

Fig. 2. (a) Electro-optic (EO) S21 response of the MRM under different biasing voltages, (b) PAM-8 B2B BER results, (c) PAM-8 1km SSMF transmission BER results.

Fig. 2 (b) shows the PAM-8 B2B results. Using the linear FFE-DFE, 240 Gb/s and 315 Gb/s are achieved under the general 7 % hard-decision forward-error correction (HD-FEC) threshold of 3.8 E-3 and the 20 % soft-decision forward-error correction threshold (SD-FEC) of 2.4 E-2 respectively. Using PNLE, the performance is improved, since the non-linear equalizer can compensate for transmitter, fiber, and receiver non-linearities. Up to 270 Gb/s and 330 Gb/s are achieved using PNLE under HD-FEC and SD-FEC respectively. The test is repeated by transmitting through 1 km SSMF, which is commonly used for short reach data center interconnects (DCI). Using FFE-DFE, 210 Gb/s and 285 Gb/s are reached for HD-FEC and SD-FEC respectively. For PNLE, 240 Gb/s and 300 Gb/s are reached for HD-FEC and SD-FEC respectively. The difference in performance compared with B2B is due to the presence of fiber dispersion in C-band, which causes severe inter-symbol interference (ISI), limiting the transmission distance and signal bandwidth. Performance for PAM-4 is shown in Fig 3. Fig. 3 (a) shows for B2B, using FFE-DFE, 250 Gb/s and 270 Gb/s are achieved under HD-FEC and SD-FEC respectively. For PNLE, 260 Gb/s and 280 Gb/s are achieved under HD-FEC and SD-FEC respectively. The results show PAM-4 can also benefit from the designed high modulation depth of the modulator and can operate at very high baud rates. Fig. 3 (b) shows the results for PAM-4 after transmission through 1 km SSMF. For FFE-DFE, 220 Gb/s and 240 Gb/s are achieved for HD-FEC and SD-FEC respectively. Using PNLE, 230 Gb/s and 260 Gb/s are achieved for HD-FEC and SD-FEC respectively. Since the baudrates of PAM-4 are higher than for PAM-8, PAM-4 occupies a wider bandwidth, and the PAM-4 fiber transmission results are more degraded by fiber dispersion than the PAM-8 signals, enlarging the penalty between B2B and 1-km transmission. Comparing the B2B results of PAM-8 and PAM-4, PAM-4 can operate at a higher baud

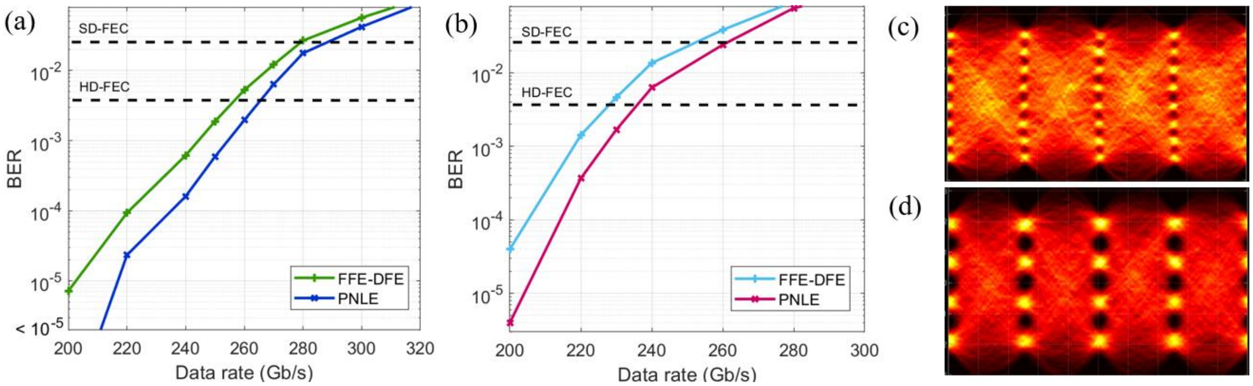

Fig. 3. (a) PAM-4 B2B BER results, (b) PAM-4 1km SSMF transmission BER results, (c) B2B 100 Gbaud PAM-8 eye-diagram, (d) B2B 130 Gbaud PAM-4 eye-diagram.

rate because of its fewer number of amplitude levels, which gives more amplitude margin, and wider inner optical modulation amplitude (OMA) before the signal is heavily degraded by ISI as shown in Fig. 3 (c) and (d). However for the 1 km SSMF transmission in C-band, the first fiber dispersion notch is at 63 GHz and the 6-dB bandwidth is 51 GHz, which puts a limit to the maximum bandwidth of the IM-DD setup. For this fiber bandwidth limitation, PAM-8 can transmit at a higher data rate using a smaller signal bandwidth, which enabled a net rate improvement of 35 Gb/s (16 %) compared with PAM-4. When the electronic amplifiers/signal sources bandwidth is limited to 50GHz, and the fiber also limits the bandwidth to about 51GHz, PAM-8 is a better solution than PAM-4 for the 300 Gb/s single lane rate transmitters. Table 1 shows recent state-of-the-art demonstrations using MRMs.

Table 1. Recent state-of-the-art demonstrations using silicon MRM

Ref.	BW	Reach	Baudrate (Gross rate) (Format)	FEC	Net rate	λ	Remarks
[5]	54 GHz	B2B	120 Gbaud (240 Gb/s) (PAM-4)	20% SD-FEC	200 Gb/s	O-band	-
[4]	> 67 GHz	2 km	110 Gbaud (220 Gb/s) (PAM-4) 80 Gbaud (240 Gb/s) (PAM-8)	20% SD-FEC	183 Gb/s 200 Gb/s	O-band	MRM optical peaking, DSP: neural network, MLSE.
[6]	> 67 GHz	B2B 2 km	110 Gbaud (220 Gb/s) (PAM-4) 100 Gbaud (200 Gb/s) (PAM-4)	7% HD-FEC	205 Gb/s 187 Gb/s	C-band	MRM optical peaking.
This work	50 GHz	B2B 1 km	130 Gbaud (260 Gb/s) (PAM-4) 115 Gbaud (230 Gb/s) (PAM-4)	7% HD-FEC	243 Gb/s 215 Gb/s	C-band	MRM optical peaking, DSP: PNLE.
		B2B 1 km	110 Gbaud (330 Gb/s) (PAM-8) 100 Gbaud (300 Gb/s) (PAM-8)	20% SD-FEC	275 Gb/s 250 Gb/s		

4. Conclusion

We optimized the design of a silicon MRM for PAM-8 modulation and demonstrated its use for 330 Gb/s single lane data rate. It is a compact solution for dense integration of arrays of modulators for multilane transmitters.

Acknowledgements

We thank Keysight Technologies for providing the AWG. This project is supported by RGC GRF 14207021.

5. References

[1] M. S. Alam, "Net 300 Gbps/λ Transmission Over 2 km of SMF With a Silicon Photonic Mach-Zehnder Modulator," *IEEE Photonics Technol. Lett.* **33**, 1391–1394 (2021).
[2] D. W. U. Chan, "A Compact 112-Gbaud PAM-4 Silicon Photonics Transceiver for Short-Reach Interconnects," *J. Lightwave Technol.* **40**, 2265-2273 (2022).
[3] D. W. U. Chan, "Ultra-wide Free-spectral-range Silicon Microring Modulator for high capacity WDM," *J. Lightwave Technol*, doi: 10.1109/JLT.2022.3208745. (2022).
[4] Y. Zhang, "240 Gb/s optical transmission based on an ultrafast silicon microring modulator," *Phot. Res.* **10**, 1127 (2022).
[5] M. Sakib, "A 240 Gb/s PAM4 Silicon Micro-Ring Optical Modulator," in *OFC* (2022), pp. 01-03.
[6] D. W. U. Chan, "C-band 67 GHz silicon photonic microring modulator for dispersion-uncompensated 100 Gbaud PAM-4," *Opt.Lett.* **47**, 2935–2938 (2022).
[7] J. Müller, "Optical Peaking Enhancement in High-Speed Ring Modulators," *Sci Rep* **4**, 6310 (2014).
[8] X. Wu, "C-band 120-Gb/s PAM-4 transmissions over a 100-km dispersion-uncompensated SSMF using joint combined pulse shaping and low-complexity nonlinear equalization," *Opt.Lett.* ***47***, 5144 (2022).