Pulse Amplitude Modulation with a Femtojoule Silicon Microring Modulator at 80-Gb/s

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***Abstract*—We report 80-Gb/s pulse amplitude modulation (PAM)-4 operation with a microring modulator at 5-fJ/bit. To our knowledge, this is the highest bit rate achieved with a microring modulator. We also demonstrate the first PAM-8 operation at 45-Gb/s with 1-fJ/bit, and 64-Gb/s PAM-4 transmission over 5-km.**

***Index Terms*—Silicon-on-insulator, Electro-optic modulation, Ring resonators, Optical interconnects**

I. Introduction

SILICON photonics may provide powerful solutions for ultrahigh-speed computer and data center communications at 400 Gb/s and beyond. Microring modulators (MRMs) are among the most promising technologies since they combine multiple desirable features [1], especially their compactness and low power consumption down to fJ/bit [2]. Silicon MRMs have been used to demonstrate 60 Gb/s on-off keying (OOK) [3] and wavelength division multiplexing links. Advanced modulation formats using MRMs have been demonstrated for coherent, e.g. 56 Gb/s quadrature phase-shift keying [4], and non-coherent, e.g. 24 Gb/s PAM-4 [5], applications. In addition, digital signal processing can further increase the transmission capacity and is being actively examined for 400 Gb/s Ethernet [6].

In this work, we demonstrate an error-free capable MRM operating at 80 Gb/s with PAM-4 modulation format and a power consumption of 5 fJ/bit. In addition, we demonstrate the first PAM-8 operation at 45 Gb/s with 1 fJ/bit. These results show the ability to simultaneously achieve ultra-high speed (toward 100 Gb/s) and ultralow power consumption (femtojoule) in silicon photonic modulators.

II. Design, Fabrication & Results

We designed and optimized the modulator using the dynamical model presented in [7]. The modulator makes use of the plasma dispersion effect through carrier depletion in a lateral p-n junction. The MRM has a radius of 8 μm, a coupling gap of 230 nm, and a centered p-n junction phase shifter spanning roughly 70% of the circumference. The light is guided on chip through 500-nm-wide waveguides with a 220-nm-thick rib and a 60-nm-thick slab. A semiconductor resistor heater is implemented in the coupler region for wavelength tuning to compensate for fabrication errors and thermal fluctuations. The modulator was fabricated at IMEC, Belgium, using 193-nm lithography.

We measured an extinction ratio (ER) of 35 dB and a quality factor $Q \sim 17000$. The 3 dB electro-optic (OE) bandwidth is found to be 27 GHz at -11 GHz of frequency detuning, as per Fig. 1. Note that the strong modulation resonance, associated with the relatively high Q, effectively increases the OE bandwidth, enabling high-speed operation well beyond the optical bandwidth ($<$ 12 GHz) of the resonator.

In the transmission experiment, the modulator is biased at -5 V. A 14 dBm tunable laser is used and light is coupled in/out of the chip using a fiber array and on-chip grating couplers. The modulated light is amplified using an erbium-doped fiber amplifier to compensate for the 16 dB fiber-to-fiber insertion loss (IL). The received optical signal is detected with a 70 GHz photo-detector and is collected with a 80 GSa/s real-time oscilloscope (RTO) of 30 GHz analog bandwidth. Off-line processing is done to retrieve the bit error rate (BER) and equalize the signal with a minimum mean square error (MMSE) filter. The MMSE filter is designed using 100 taps and 2000 training symbols. We used a 2^{15}-1 pseudo-random bit sequence (PRBS) as the transmitted data.

Figure 2 presents examples of eye diagrams for PAM-4 and PAM-8 operations. It also presents the measured BERs for both raw and equalized signals. The driving voltage is 3.8 V_{pp} and 2.2 V_{pp} for PAM-4 and PAM-8, respectively. The capacitance of the modulator is calculated to be 5 fF under the operating conditions [7], which yields a power

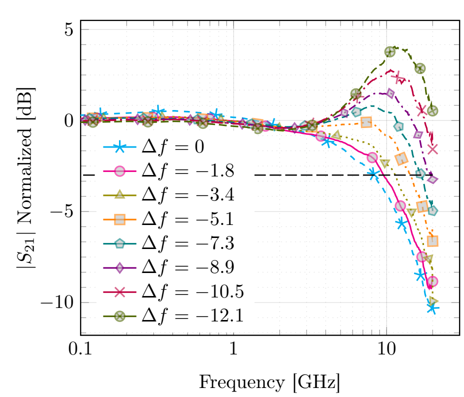

Figure 1: Measured electro-optic response at various frequency detuning. The frequency detuning is measured from the resonance center at equilibrium.

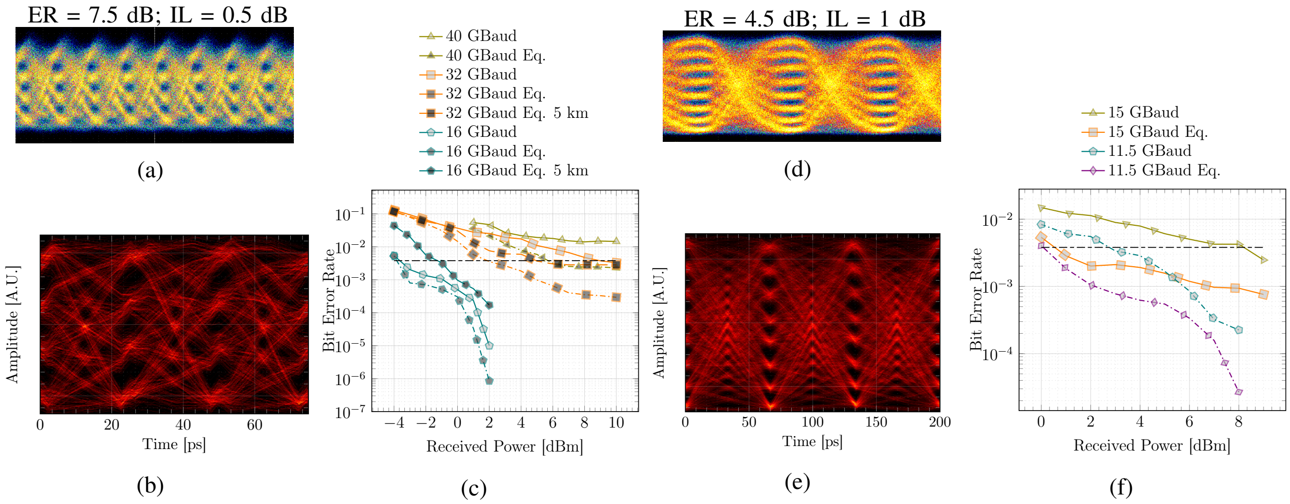

Figure 2: a) 32 GBaud eye diagram after 5 km of SSMF with 9 dBm received power; b) Equalized eye diagram at 80 Gb/s PAM-4, 9 dBm of received power. c) Raw and equalized BERs for PAM-4 in back-to-back and after 5 km transmission; d),e) Raw and equalized eye diagrams at 45 Gb/s PAM-8 with 9 dBm of received power; f) Raw and equalized BER for PAM-8 in a back-to-back configuration. We assume that Gray coding is used and that errors happen between adjacent levels [8]. The forward error correction (FEC) threshold of 3.8x10^{-3} with a 6.7% overhead, based on the OT4U standard [9], is indicated by the black horizonthal line.

consumption of 5 fJ/bit and 1 fJ/bit for 80 Gb/s PAM-4 and 45 Gb/s PAM-8 [2], respectively. It is noteworthy that the 80 Gb/s operation at 5 fJ/bit represents, to our best knowledge, the highest bit rate ever demonstrated with a single MRM, as well as the lowest power consumption at such a high speed. The 1 fJ/bit PAM-8 operation also represents a record in power consumption at a speed beyond 40 Gb/s.

We also measured raw BERs below the FEC threshold for OOK modulation up to 66 Gb/s in a back-to-back configuration (not shown in the figure), where 3.5 V_{pp} was used for a power consumption of 15 fJ/bit, i.e., about 3 times that of PAM-4 and 15 times that of PAM-8. This is due to the quick degradation of electrical driving signal at high baud rates, and clearly shows the benefits of PAM formats. Apparently, more advanced modulation formats typically require more power on signal processing on the receiver side, for which the trade-off needs to be carefully investigated for the optimal link power budget.

Finally, we report a 5 km transmission over a standard single mode fiber (SSMF) of the PAM-4 signal up to 32 GBaud (64 Gb/s) with a BER below the FEC threshold, as shown in Fig. 2c.

III. Conclusion

We have demonstrated PAM transmissions up to 80 Gb/s using a single silicon MRM with an ultralow modulation power at the level of fJ/bit. The resonance-enhanced OE bandwidth and the equalization technique were the key to this record breaking performance. Improved performance is expected as the post-processing technique is refined and optimized. These results are promising for the development of integrated high-speed transceivers addressing 400 Gb/s (e.g., $5\lambda \times 80$ Gb/s PAM-4) and beyond as many compact MRM can be integrated in an energy efficient way on a single chip, even on a single bus carrying all wavelengths.

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References

[1] G. L. *et al.*, "Ring resonator modulators in silicon for interchip photonic links," *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 19, no. 6, p. 3401819, 2013.

[2] E. T. *et al.*, "An ultralow power athermal silicon modulator," *Nature Communications*, vol. 5, no. 4008, pp. 1 – 11, 2014.

[3] X. Xiao *et al.*, "60-Gb/s silicon modulators with enhanced electro-optical efficiency," in *Optical Fiber Communication Conference (OFC 2013, OW4J.3)*, 2013.

[4] P. Dong *et al.*, "Silicon microring modulators for advanced modulation formats," in *Optical Fiber Communication Conference (OFC 2013, OW4J.2)*, 2013.

[5] L. Wang *et al.*, "Transmission of 24-Gb/s PAM-4 over 150-km SSMF using a driverless silicon microring modulator," in *Asia Communications and Photonics Conference (ACPC 2014, ATh4D)*, 2014.

[6] Y. Kai *et al.*, "Experimental comparison of pulse amplitude modulation PAM and discrete multi-tone DMT for short-reach 400-Gb/s data communication," in *European Conference on Optical Communications (ECOC 2013, Th1F3)*, 2013.

[7] R. D.-D. *et al.*, "Analytical modeling of silicon micoring and microdisk modulators with electrical and optical dynamics," *Journal of Lightwave Technology*, vol. PP, no. 99, 2015.

[8] M. C. *et al.*, "Experimental study of 112 Gb/s short reach transmission employing PAM formats and SiP intensity modulator at 1.3 μm," *Optics Express*, vol. 22, no. 17, pp. 21 018 – 21 036, 2014.

[9] IEEE Std. 802.3ba. (Approved by IEEE and ANSI on Jun. 17, 2010) Media access control parameters, physical layers, and management parameters for 40 Gb/s and 100 Gb/s operation. [Online]. Available: http://standards.ieee.org/findstds/standard/802.3ba-2010.html