Pattern-Dependent Performance of Microring Modulators

Xiaoliang Zhu[1], Kishore Padmaraju[1], Long Chen[2], Dylan F. Logan[3, 4], Jason J. Ackert[3], Andrew P. Knights[3], Michal Lipson[2], Keren Bergman[1]

1: Department of Electrical Engineering, Columbia University, 500 West 120th Street, New York, New York 10027, USA
2: School of Electrical and Computer Engineering, Cornell University, 428 Phillips Hall, Ithaca, New York 14853, USA
3: Department of Engineering Physics, McMaster University, 1280 Main Street West, Hamilton, ON, L8S 4L8, Canada
4: Currently with the Edward S. Rogers Sr. Department of Electrical and Computer Engineering, University of Toronto, 10 King's College Rd., Toronto, ON, M5S 3G4, Canada
xz2237@columbia.edu

Abstract: We characterize microring modulators under consecutive data patterns and find significant power penalties when long sequences of zeros and ones are introduced. The penalty is greater for injection mode devices compared to depletion mode devices.
OCIS codes: (230.4110) Modulators; (230.4555) Coupled Resonators; (200.4650) Optical Interconnects.

1. Introduction

Optical interconnects have been proposed as a possible solution to the bandwidth and energy bottlenecks in next generation computer systems. Many proposed architectures envision silicon photonic components forming high performance interconnects for networks-on-chip (NoC), as well as serving as the high-bandwidth data link between processor and memory systems [1, 2]. A critical component in these proposed architectures is the microring modulator, which has the advantages of small footprint, low power consumption, and wavelength division multiplexing (WDM) capability [3]. In this paper we report on and characterize for the first time to our knowledge a data dependent sensitivity of microring modulators to long sequences of consecutive ones and zeros in the modulated data. This modulator sensitivity to pattern length is important to the above mentioned photonic interconnect architectures, where burst and random data traffic can contain a large number of consecutive data symbols.

Electro-optic microring modulators enable on-off-keyed (OOK) modulation through the free-plasma dispersion effect, where injection or removal of free carriers shifts the resonance of the microring [4]. In a carrier-injection mode modulator, a p-i-n diode is used to inject carriers into the microring under forward bias. The speed of carrier-injection devices are limited by carrier recombination dynamics at the junction, and to achieve high bitrates the pre-emphasis technique, where driving voltage is made larger at bit transitions, must be applied [4]. The optimal pre-emphasis condition is different for every device geometry and bitrate combination, and a different number of bit-transitions in a data sequence will mean different average driving voltages for the modulator.

In contrast, a depletion mode modulator uses a reverse biased pn-junction to sweep carriers out of the microring. There is no bias current flow during operation. Depletion mode modulators are not speed limited by carrier recombination, and thus they do not require pre-emphasis. The electrical driving condition for the depletion mode modulator does not fundamentally vary for different data sequences. The systematic characterization presented below explores how injection and depletion mode devices perform as we change the data pattern length.

2. Experiment and results

We experimentally evaluate two separate electro-optic microring modulator devices. The first is a 6-µm radius carrier-injection mode device fabricated at the Cornell Nanofabrication Facility, with further details found in [5]. The second is a 15-µm radius depletion mode device designed at McMaster University, details of whose fabrication will appear in a future publication [6].

In the experimental setup shown in Fig. 1, a tunable laser is passed through a polarization controller and coupled onto the chip, using lateral coupling for the injection mode device and holographic grating coupling for the depletion mode device. The fiber to fiber loss is approximately -32 dB for the injection mode device, and -17 dB for the

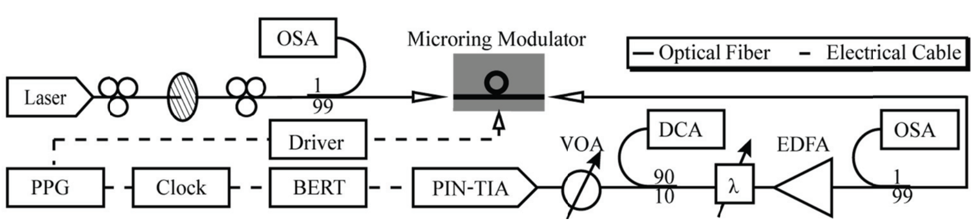

Fig. 1. Experimental Setup

depletion mode device. In both experiments -3 dBm of optical power reaches the modulator. High speed electrical probes contact the chip and a pulsed-pattern-generator (PPG) is used to generate a non-return-to-zero (NRZ) pseudo-random bit sequence. For the injection mode device we apply a 0.5 V forward bias and a 4 Vpp driving signal with pre-emphasis. For the depletion mode device we apply a -2.5 V bias and a 5 Vpp driving signal without pre-emphasis. The modulated signal is coupled off-chip, amplified, and filtered before being sent to a PIN-TIA photo detector followed by a limiting amplifier (LA). A bit-error-rate tester (BERT) and a variable optical attenuator (VOA) are used for the BER measurements and characterization.

The input data sequence is varied from PRBS 2^7-1 to 2^{31}-1, thus generating data streams where the max number of consecutive ones and zeros vary from 7 to 31. Each time the pattern length changes, attempts are made to optimize experimental parameters such as bias voltage and laser wavelength. The BER curves presented below represent the best modulated data at each bitrate, input laser power, and data pattern.

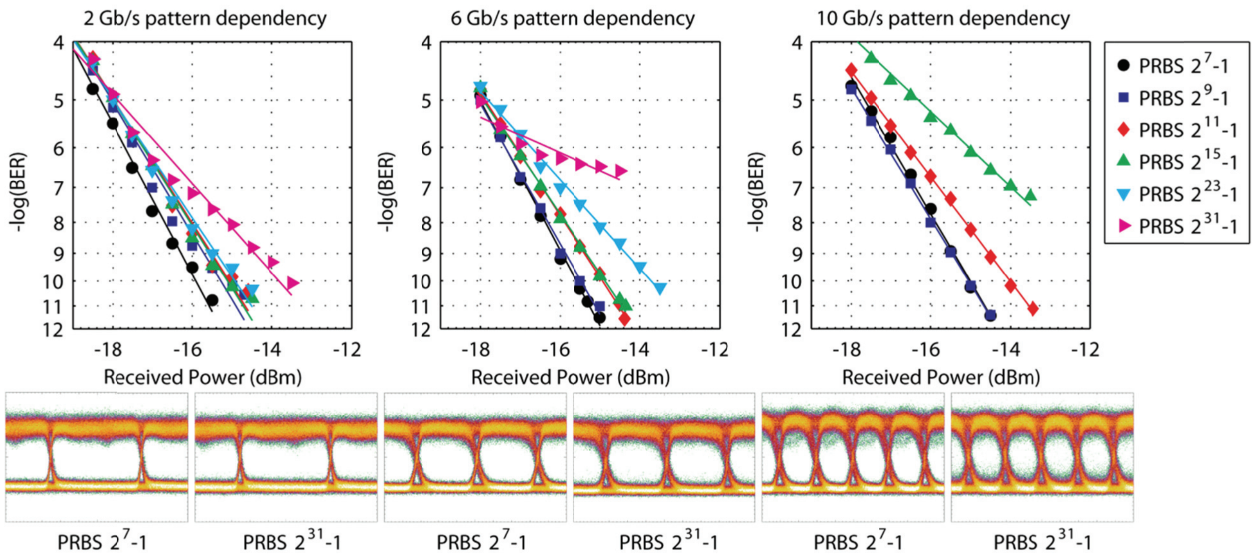

Fig. 2. Injection mode modulator BER curves and eye diagrams collected at various bitrates. Clear pattern dependent penalty can be seen. The input laser power is kept constant for all measurements. At 10 Gb/s the data encountered an error floor of 10^{-6} above 2^{15}-1 (not shown).

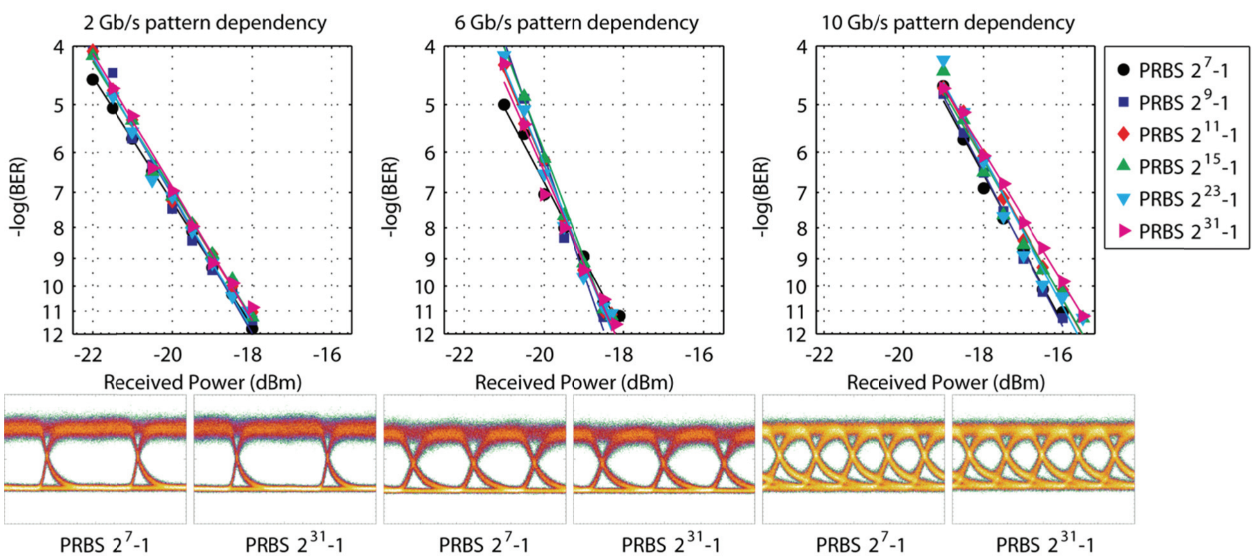

Fig. 3. BER curves and eye diagrams collected for the depletion mode modulator at various bitrates. There is no noticeable pattern dependent penalty. The horizontal scale covers the same span as in Fig. 2.

Fig. 2 shows the BER measurements and eye diagrams collected for the injection mode device as bitrate is increased from 2 Gb/s to 10 Gb/s. Increased power penalties clearly result when pattern length is increased. Higher bitrates are more sensitive to changes in the PRBS sequence, and at 10 Gb/s the modulated data is no longer meaningful after PRBS 2^{15}-1. The eye diagrams also show more noise as the pattern length is increased. Fig. 3

shows the same measurements collected for the depletion mode device, which in contrast demonstrates minimal pattern dependency.

We suspect transient thermal fluctuations as the source of the power penalty. A temperature change on the order of ~1 K is enough to significantly change the operating wavelength of the device [7], and thus degrade the modulation. While the resonance-shift time constant of these devices, when driven by external heaters, are on the order of microseconds [8], the localized heating to the microring from pattern dependency may be much faster. The source of the thermal fluctuation is likely the heat generated by forward current in the p-i-n diode. A long sequence of ones in the data will cause more current to flow, and a sequence of zeros much less. The pre-emphasis voltage that only occurs at bit-transitions also likely contributes to current variation as the pattern length change.

In contrast, negligible current flows in the reverse-biased depletion mode device in operation, meaning the electrical driving signal is not a source of heating. The depletion mode device used in this experiment is larger than the injection mode device, but we believe the lack of electrical heating is the principle cause for not observing pattern dependency in the depletion mode device. Evidence dismissing the importance of device size can be found in [8], where thermally isolated 4 and 10 μm radius microring devices experienced similar resonance tuning for the same heater power. Future measurements using devices with identical geometries can be used to confirm and further validate these results.

The modulated optical power can also change the temperature of the ring in a pattern dependent manner. To characterize the effect of optical power on pattern dependency, we repeated the experiment at a lower laser power for the injection mode device while keeping the identical electrical driving signal. Fig. 5 shows the power penalties at the 10^{-9} BER point for the when the original -3 dBm and then -5 dBm of optical power reach the modulator. Larger optical power leads to larger penalty, except the 10 Gb/s point which is affected by decreased OSNR at the lower power. This data lends additional support to thermal fluctuation as cause of pattern dependency.

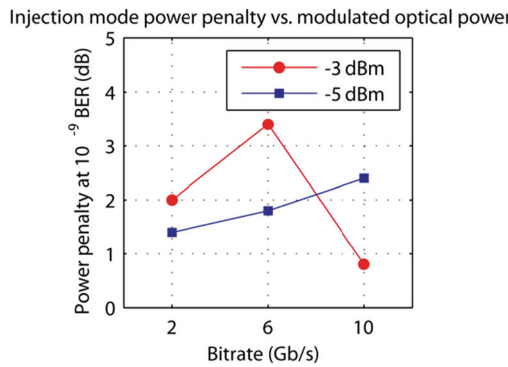

Fig. 5. The power penalties at the 10^{-9} BER point when two different optical powers reach the injection mode modulator. The points are for PRBS 2^{31}-1 at 2 Gb/s, PRBS 2^{23} -1 at 6 Gb/s, and PRBS 2^{11} – 1 at 10 Gb/s, which are the comparable points collected having the largest pattern difference at each wavelength.

3. Conclusion

We report significant power penalty in an injection mode microring modulator as data pattern length is increased from 7 to 31 consecutive symbols: as much as 2 dB at a 2 Gb/s bitrate, and the introduction of an error floor at 6 Gb/s and 10 Gb/s. Similar measurements for a depletion mode modulator yielded minimal power penalty.

In light of these observations, future optical interconnect systems leveraging microring modulators should consider the effect of data pattern length in their operation, and employ compensation methods. These results show that depletion mode devices offer near immunity to pattern dependency, and hence are more ideal devices to employ in silicon photonic interconnects.

This work was supported in part by the National Science Foundation and SRC under grant ECCS-0903406 SRC Task 2001, the Columbia Optics and Quantum Electronics IGERT under NSF grant DGE-1069420, the Samsung Corporation, and the Natural Sciences and Engineering Research Council of Canada. We are grateful to CMC Microsystems and IME Singapore for enabling work in the design and fabrication of the depletion modulation chips.

4. References

[1] A. Shacham, et al., “Photonic networks-on-chip for future generations of chip multiprocessors,” IEEE Trans. Comput. 57 (9) 1246-1260.
[2] D. Brunina et al, “10-Gb/s WDM Optically-Connected Memory System using Silicon Microring Modulators”, ECOC 2012 Mo.2.A.5, (2012)
[3] C. Batten, et al., “Building many-core processor-to-DRAM networks with monolithic CMOS silicon photonics,” IEEE Micro 29 (4) 8-21.
[4] Q. Xu, et al, “12.5 Gbit/s carrier injection-based silicon microring silicon modulators”, Optics Express, Vol. 15, No. 2, 430, 22 (2007)
[5] L. Chen et al., “Integrated GHz silicon photonic interconnect with μm-scale modulators and detectors,” Opt. Express. 17 (17). (2009).
[6] D. F. Logan, J. J. Ackert and A. P. Knights, to be published.
[7] K. Padmaraju, et. al., “Dynamic stabilization of a microring modulator under thermal perturbation”, OFC 2012 OW4F.2 (2012).
[8] P. Dong, et al., "Thermally tunable silicon racetrack resonators with ultralow tuning power," Opt. Express 18, 20298-20304 (2010).