Experimental Characterization of the Optical-Power Upper Bound in a Silicon Microring Modulator

Qi Li[1], Noam Ophir[1], Lin Xu[1], Kishore Padmaraju[1], Long Chen[2], Michal Lipson[2], Keren Bergman[1]
1: Department of Electrical Engineering, Columbia University, 500 W. 120th Street, New York, NY 10027, USA
2: School of Electrical and Computer Engineering, Cornell University, Ithaca, NY 14853, USA
ql2163@columbia.edu

***Abstract*—We characterize the optical-power upper bound of CW light in a microring modulator. Heating due to absorption of light introduces instability which results in power penalty and ultimately limits optical power. The upper limit for a 2.5-μm radius, Q~3000 microring is found to be ~7dBm.**

Introduction

Silicon photonics is emerging as a leading candidate for addressing the power and bandwidth challenges of next generation on- and off-chip interconnects due to its compatibility with complementary-metal-oxide-semiconductor (CMOS) process, ultra-small device footprint, low power consumption and high bandwidth. Among the silicon photonics devices demonstrated so far, the microring modulator is a key building block [1, 2].

A key parameter for optical interconnects' design is the optical power budget, which is defined as the difference between the maximal power that can be injected into the network and the receiver sensitivity. The power budget, as well as considerations such as power efficiency, ultimately limits the size and scalability of chip-scale photonic interconnection networks [3, 4]. As such, it is important to understand what are the limiting factors on the optical power one can inject into such an optical interconnect.

As the modulator is one of the first elements in the lightpath, the optical power level (per wavelength channel) at the modulator is expected to be relatively high compared to subsequent components (switches, filters, etc.). Microring modulators in particular are susceptible to performance degradation from nonlinear effects because of the intensity enhancement in the cavity as well as the resonance shift which can result from two-photon absorption in the cavity (both from heating as well as plasma dispersion effect [5]).

Recent studies have predicted that nonlinearities will limit optical power to milliwatt levels for optical interconnects [4], but this important parameter has not been characterized experimentally before. In this work, we characterize a carrier-injection based 2.5-μm radius Q-factor ~3000 microring modulator performance as the optical power is gradually increased using eye-diagrams and bit-error-rate (BER) measurements at 1 Gb/s modulation rate. We first characterize the performance degradation caused by the resonance shift with wavelength and modulation bias fixed. We then observe the dominant resonance red shift induced by two-photon-absorption generated heat by characterizing the optimal modulation wavelength at various incident optical powers (with fixed bias); finally we characterize the performance as function of incident optical power with dynamic tuning of the modulation bias enabled and estimate the maximum optical power at microring modulator at which stable modulation can be achieved.

Device and Experiments

The microring modulator used in this experiment (Fig. 1a), fabricated at the Cornell Nanofabrication Facility, has a 2.5-μm radius, optical quality factor of ~ 3000, and is coupled to a waveguide with dimensions of 450nm × 260nm. The waveguide has a 50-nm slab that is doped to form a PIN diode structure which is used to shift the resonance of the microring modulator by carrier injection and extraction.

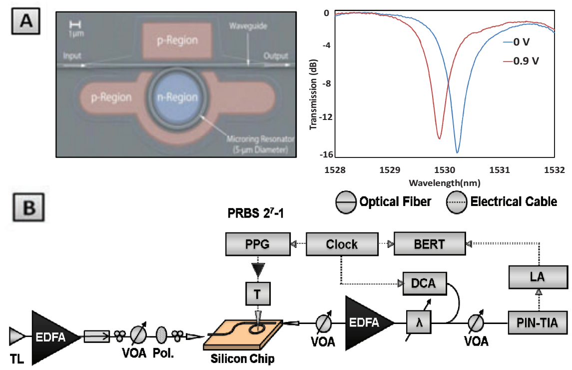

Fig. 1: (a) Scanning-electron-microscope (SEM) image and spectrum of the microring modulator. (b) Experimental Setup.

A continuous-wave (CW) light from a tunable laser (TL) is set at a wavelength slightly longer than the microring modulator resonance to achieve optimal modulation (the microring resonance is blue shifted by carrier injection). It is amplified by an erbium-doped fiber amplifier (EDFA), passes through an isolator and is attenuated by a variable optical attenuator (VOA) before going through a polarizer (Pol) and being launched on-chip using a tapered fiber at quasi-TE polarization. The modulator is driven using a high speed RF probe by a 2^7-1 pseudo-random bit sequence (PRBS) signal which is generated by a pulse pattern generator (PPG) and goes through a pre-emphasis circuit to improve modulator response. A bias-tee (T) is used to add DC modulation bias to the driving signal. The optical signal egressing the chip passes through a VOA, an EDFA, a band-pass filter (λ) and a second attenuator before being received by a PIN photodiode with a transimpedance amplifier (PIN-TIA) followed by a limiting amplifier (LA). The received electrical signal is evaluated using a BER tester (BERT). A digital communication analyzer (DCA) is used to record eye-diagrams and extinction ratios of the modulated signal. The PPG, DCA and BERT are synchronized to the same clock source which is set at 1-GHz. The optical power before entering the second EDFA is attenuated to a predetermined level to keep a constant optical signal noise ratio.

The first set of BER measurements consists of increasing the optical power launched into the chip while keeping the modulation bias and signal wavelength fixed. In order to determine how much power actually reaches the microring we perform the BER measurements twice – interchanging the input and output roles of chip facets. Since the relative power penalty introduced is only a function of the power reaching the microring, we can compare the BER curve sets taken from launching from the two sides of the chip to estimate ~ 4.9dB/cm waveguide propagation loss based on the 1-mm path difference from the microring modulator to the two

978-1-4577-1619-5/12/$26.00

sides of the chip. The fiber-to-fiber insertion loss of the chip is measured to be 20.1 dB off-resonance. Assuming equal coupling loss at both sides of the chip, we can estimate it to be ~8.5dB per facet. Using the above method we estimate the optical power reaching the microring modulator.

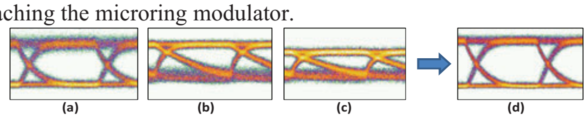

Fig. 2: (a, b, c) Eye diagrams of the microring modulator with increasing optical power from a to c at fixed wavelength. (d) Eye restoration by tuning to a longer wavelength (same optical power with c).

The open eye generated by microring modulator (Fig. 2a) degrades gradually with increasing optical power, which is mainly due to resonance shift induced by two-photon absorption. The eye diagram could be restored by tuning to a longer wavelength (Fig. 2d).

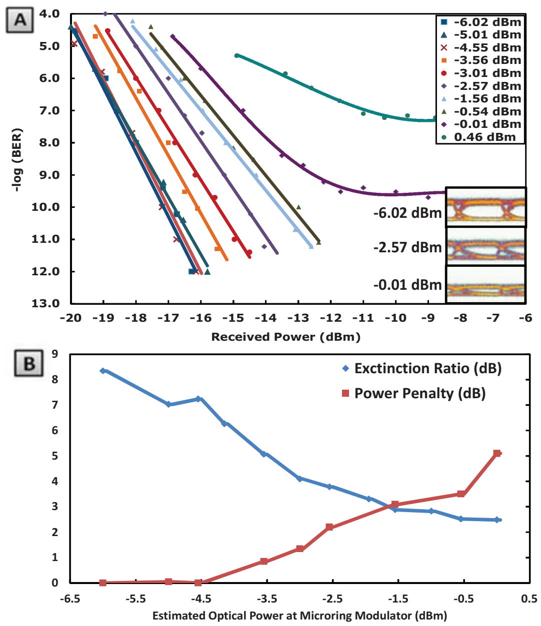

Fig. 3: (a) Recorded BER curves with increasing optical power at fixed wavelength, legend shows estimated optical power at microring modulator. (b) Extinction ratio and power penalty vs. estimated optical power.

Due to the resonance red shift, at increasing power the microring modulator exhibits decreasing extinction ratio and thus increasing power penalty (Fig. 3). We then measure the optimal operation wavelength with varied optical power and fit the experimental data with a parabolic curve (Fig. 4) as suggested in other study [6]. The resonance red shift indicates that thermal effects dominate over free plasma dispersion (which would cause a blue shift) in this microring in agreement with previous analysis [5].

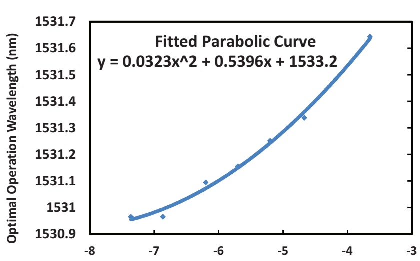

Fig. 4: Optimal operation wavelength with varied optical power.

For the second part of the experiment we proceed to characterize the optical-power upper-limit of the microring modulator by dynamically tuning modulation bias to compensate for the resonance shift (laser wavelength tuning is less feasible in a WDM-type optical interconnect). We observe constant performance up to 6-dBm power reaching the microring. Starting from 6 dBm, a power penalty shows up and increases dramatically as power increases to 7 dBm (Fig. 5). At this point the modulation point ceases to be stable as the resonance location becomes significantly dislocated from its initial (low optical power) state; a long string of 1 bits or a small thermal shift can cause significant enough resonance shift that the ring no longer sinks enough optical power and drifts back to its initial stable resonance location – away form the laser wavelength.

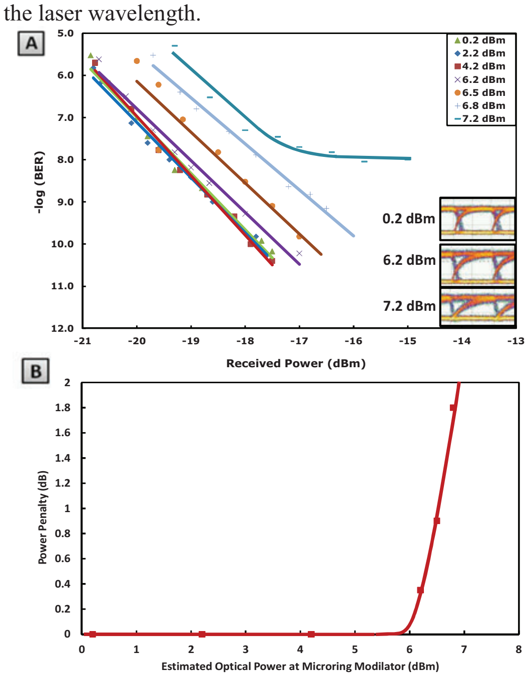

Fig. 5: (a) Recorded BER curves with increasing optical power at tuned modulation bias. (b) Power penalty vs. estimated optical power.

Conclusions

We have quantitatively characterized a carrier-injection based microring modulator with varied optical power, first at fixed wavelength and modulation bias, observing resonance shift mainly induced by optically generated heat at microring cavity. The resonance shift shows that some tuning needs to be implemented in order to avoid significant degradation even at fractions of mW powers. We proceed to implement the a tuning mechanism by shifting the modulation bias and show that even with such mechnisms, the maximal power modulated by a microring is limited. For a 2.5-µm radius, Q ~ 3000 this absolute maximal power is measured to be ~ 7 dBm.

We acknowledge support from the NSF and Semiconductor Research Corporation under grant ECCS-0903406 SRC Task 2001.

References

[1] D. Miller, *IEEE JSTQE*, vol. 6, no. 6, pp. 1312–1317, Nov./Dec. 2000.
[2] Q. Xu *et al.*, *Nature* 435, 325-327, (2005).
[3] J. Chan *et al.*, *IEEE TCAD* **30** (10) 1507-1520 (Oct 2011).
[4] K. Preston *et al.*, *CLEO 2011*, paper CThP4.
[5] Q. Xu *et al.*, *Opt. Lett.* **31**, 341-343 (2006).
[6] S. Xiao *et al.*, *LEOS 2007,* pp.890-891, Oct. 2007