

First Demonstration of Error-Free Operation of a Full Silicon On-Chip Photonic Link

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Abstract: We report first 3-Gb/s data measurements for a photonic link including a microring modulator connected optically by a waveguide to a Germanium detector. Error-free operation is achieved with a 2-dB electrical power penalty.

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1. Introduction

The continuous trend toward increased computing parallelism is presenting ever increasing bandwidth demands from the on-chip and off-chip interconnection networks for chip multiprocessor (CMP) systems. As the number of computing cores continues to scale, electronic networks-on-chip (NoC) architectures are expected to hit a performance wall due to bandwidth and power density limitations. Optical networks present a viable alternative to the classic electronic NoCs as they offer improved scalability prospects as well as immense bandwidth capacity per link utilizing wavelength division multiplexing (WDM) schemes. The penetration of optical communications into the CMP systems is enabled by the emergence of the silicon photonic platform, providing a new technological alternative for realizing massive communication networks on the chip scale level.

Recent silicon photonic advancements have introduced a slew of miniaturized photonic devices including modulators [1], waveguides [2], switches [3], and receivers [4]. An important step toward realization of complete photonic networks is the joint fabrication of several of these devices into a sub-system of a network, demonstrating the ability of these devices to work as a cohesive system. Recent proof-of-concept demonstrations of photonic links [5-6], including modulators, waveguides, and photodetectors, have taken a step toward enabling full photonic NoCs by implementing a point-to-point photonic channel connecting two electronic entities on a chip-scale system. Both reported systems have been characterized in terms of their physical properties and manner of operation. In this work we perform the first ever data measurements on a silicon photonic link, measuring performance in terms of bit-error-rate curves, and showing error-free (defined as having BERs less than 10^{-12}) operation of the sub-system, thus validating its functionality. As well, we characterize data integrity in terms of electronic power penalty, showing minimal data-integrity degradation through the link.

2. Photonic Link

The photonic link reported in this paper was fabricated at the Cornell Nanofabrication Facility [6]. It includes includes a silicon microring electro-optic modulator of 12- μm diameter and a waveguide-integrated Germanium metal-semiconductor-metal (MSM) photodetector, both connected serially to a silicon bus waveguide (Fig. 1.A). The total optical propagation loss in the link up to the photodetector was estimated to be 8 dB. The photodetector is limited to 5-GHz bandwidth and has an estimated net responsivity of 0.8-0.9 A/W. The optical transmission spectrum of the microring modulator (Fig. 1.B) shows slightly undercoupled resonances with extinction ratios of 7-9 dB and quality factors of 5000-6500. Modulation is achieved by carrier injection through a P-I-N junction formed around the microring, thus shifting the microring resonances through the plasma-dispersion effect, and imprinting amplitude modulation on optical continuous wave (CW) light in the vicinity of the resonance [1].

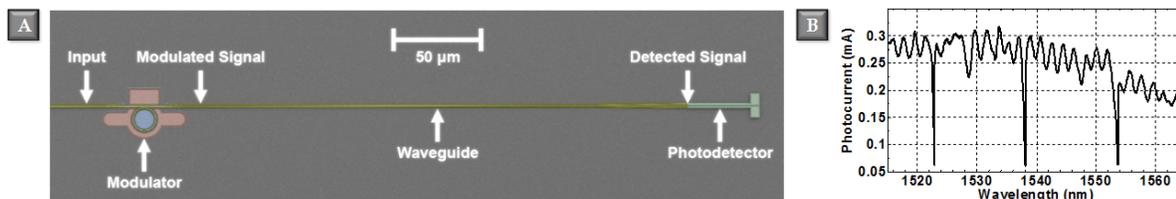


Fig. 1: A. Scanning-electron microscope (SEM) image of the bus waveguide with microring modulator and Germanium photodetector. B. Spectral scan of the device response with 7 dBm launched onto the chip and 1-V photodetector bias depicting the microring resonances as well as the Ge spectral response profile.

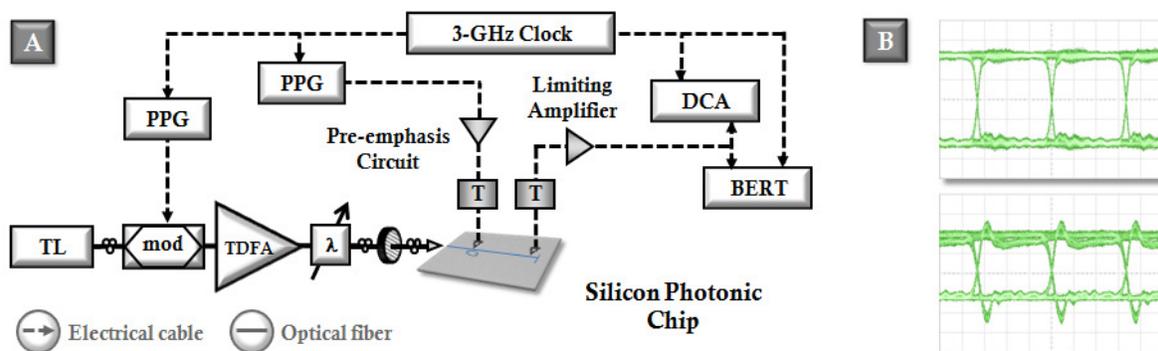


Fig. 2: A. Experimental setup capable of off-chip or on-chip modulation and on-chip photodetection. B. Eye diagrams of the RF signal produced by the PPG (top) and the pre-emphasized signal driving the microring modulator on-chip (bottom). The driving signal has a magnitude of 0.55 Vpp without the pre-emphasis pulsing and 0.87 Vpp including the pre-emphasis.

3. Experimental Setup

For data transmission characterization we implement an experimental setup in which light can be either modulated off-chip by a commercial LiNbO₃ Mach-Zehnder modulator (MZM) when it is supplied with a driving RF signal, or on-chip by the microring modulator driven by separate circuitry.

The optical setup includes a tunable laser (TL) which produces CW light. The CW light passes through a MZM (mod) before being amplified by a thulium-doped fiber amplifier (TDFA), filtered by a 1.5-nm wide band-pass filter (λ), and passed through a polarizer and polarization controllers to set it to transverse-electric polarization. The light is then coupled into the waveguide using a tapered fiber. The optical average power entering the TDFA as well as the TDFA amplification is kept constant throughout the different experiments in order to keep the optical signal to noise ratio (OSNR) constant. A 2⁷-1 pseudo-random bit sequence (PRBS) is generated at pulsed pattern generators (PPG) in order to drive the modulators. The microring drive signal goes from the PPG through a pre-emphasis circuit to provide pulse-shaping (Fig. 2.B) for improved modulator response. A bias T (T) is used to add a 0.57-V DC bias to the modulating signal. The photodetector is provided with a 1-V DC bias for photocurrent generation by a bias T which also functions as a DC block. When modulated light enters the photodetector, an AC signal enters a Gigoptix IT3011E high-sensitivity limiting amplifier (LA) before being received by a digital communications analyzer (DCA) and a bit-error-rate tester (BERT). The on-chip photonic devices are electronically interfaced by high-speed RF probes. A central RF 3-GHz clock source is distributed to the relevant electronic devices.

4. Data Transmission Experiments

In order to characterize device performance with regard to data transmission, we conduct several experiments gradually scaling to full link operation. As the device has internal electronic crosstalk on the order of a few mV at the photodetector output, we inspect its effect on signal transmission as well. As the data input and output of the device under test are electronic, we measure BER curves by varying the electronic power incident on the BERT by varying the LA gain. Due to the presence of electrical crosstalk and the microring-modulator behavioral dependence on incident optical power (power dissipation in the ring leading to thermal shift), variation of the incident optical power cannot provide consistent characterization of device performance. The back-to-back test case is defined as the RF output of the PPG directly measured on the BERT for which power is varied by means of the PPG controls.

In the first experiment detector performance is characterized using externally modulated light without driving the microring modulator. For this experiment, CW light is generated off-resonance (at 1526 nm) and encoded with PRBS data using the external modulator. We launch 7 dBm of modulated light into the waveguide and extract 390 μ A of average DC current from the photodetector. The electric signal directly from the photodetector is AC-coupled through the bias T and inspected on the DCA (Fig. 3.A) showing an AC voltage swing of approximately 24.5 mVpp. The transition time constant shows the bandwidth limitation introduced by the photodetector. The RF data signal is then amplified by a LA. The output of the LA is inspected on a DCA (Fig. 3.B) and analyzed on a BERT to provide a BER curve measurement (Fig. 3.G) showing a power penalty of 1 dB electrical compared to the back-to-back at a BER of 10⁻⁹. At high BER values (10⁻⁶ to 10⁻⁷) the transmitted signal exhibits negative penalty which is attributed to rail-clamping by the LA which is not included in the back-to-back.

In a second experiment the externally modulated signal is injected into the chip while concurrently driving the microring modulator with a separate pre-emphasized PRBS pattern in order to examine potential signal degradation as a result of the electrical crosstalk. Since the signal wavelength is detuned from the microring resonance by a few

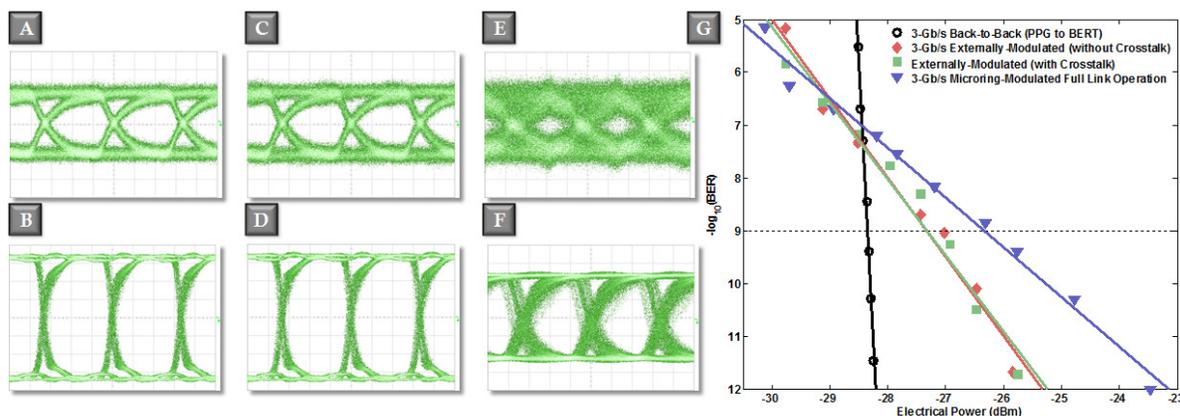


Fig. 3: A-F: Eye diagrams of electrical output of photodetector for experiments one through three (A, C, and E respectively) and eye diagrams of LA electrical output for experiments one through three (B, D, and F respectively). G. BER curves measured for the back-to-back and experiments one through three.

nanometers, the optical modulation crosstalk on this signal is negligible. The signal output from the photodetector is recorded before and after the LA (Fig. 3.C-D). BER characterization shows no measurable signal degradation as a result of the presence of the microring driving-signal (Fig. 3.G) at the given optical input power and modulation extinction ratio.

In a third experiment we turn off the external modulator and change the CW wavelength to 1523 nm in order to modulate it by the microring modulator and demonstrate full operation of the photonic link. The CW light incident on the waveguide is set to 10 dBm so as to have similar optical power incident on the photodetector as in the first two experiments. As the microring modulation extinction ratio is significantly lower than that of the external modulator, the AC voltage swing produced at the output of the photodetector is also proportionally lower at approximately 10 mVpp, approaching the limit of the DCA measurement sensitivity (Fig. 3.E). The LA output signal (Fig. 3.F) in this case shows some noise degradation which is attributed to reduced modulation quality as well as more pronounced crosstalk due to the lower AC voltage swing produced by the optically modulated light at the photodetector. Never-the-less, error-free operation is observed with full link operation and a power penalty of 1 dB electrical relative to the external modulation is measured, in agreement with previously extracted power penalty measurements for microring modulators [1]. We measure an overall link 2-dB electrical power penalty relative to the back-to-back, showing minimal data integrity degradation.

5. Conclusions

We have demonstrated for the first time, to the best of our knowledge, error-free operation of a silicon-photonic link showing reasonable signal degradation – totaling a 2-dB electrical power penalty compared to the back-to-back, while using only CMOS-compatible AC voltage levels (less than 1 Vpp). This initial demonstration provides an additional stepping stone toward integration of multiple silicon photonic devices into a single NoC, envisioned as an enabling platform for scaling toward highly parallelized CMP systems.

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