Characterization of a 4 × 4 Gb/s Parallel Electronic Bus to WDM Optical Link Silicon Photonic Translator

Benjamin G. Lee, *Student Member, IEEE*, Benjamin A. Small, *Member, IEEE*, Qianfan Xu, *Student Member, IEEE*, Michal Lipson, *Member, IEEE*, and Keren Bergman, *Member, IEEE*

***Abstract*—A 4×4 Gb/s microring modulator cascade, which can directly convert data from a parallel electrical bus to a multiple-wavelength optical signal in a single silicon-on-insulator waveguide, is demonstrated and characterized. The integrity of the modulated optical signal is verified using Q-factor extrapolations. In addition, the frequency characteristics and crosstalk, in terms of total harmonic distortion, are quantified. A transparent translator from electronics to optics such as this is crucial for the development of large-scale high-bandwidth interconnects based on photonic integrated circuits.**

***Index Terms*—Microresonators, modulation, silicon-on-insulator (SOI) technology.**

I. Introduction

THE interconnect communications bottleneck is becoming an increasingly dominant impediment to the performance of high-end computing systems. Optical interconnects offer a possibly attractive solution for delivering ultrahigh bandwidths through wavelength-division multiplexing (WDM). The large package size and high cost of alignment associated with many bulk optical components can be greatly reduced when these components are integrated together on a common substrate, such as in photonic integrated circuits (PICs). Also, PICs have the ability to realize low power consumption and low latencies due to the micrometer-sized components. As a result, integrated optical networks are being envisioned for use as board-to-board, chip-to-chip, and intrachip interconnects [1], [2].

Silicon, III–V, and polymer material systems have all demonstrated integrated devices with planar processing abilities [3]–[10]. However, silicon-on-insulator (SOI) has established itself as a key platform for PIC technologies because of the spatial density afforded by the high index contrast, along with current silicon process compatibility and the potential juxtaposition with complimentary metal–oxide–semiconductor electronics [5], [6].

The conversion of data from the electrical domain into the optical domain is an essential part of any realistic PIC implementation. Electronics frequently scale data capacities with space-division multiplexing by adding wires in parallel to form a bus, while optical signal capacity is often scaled by WDM, adding parallel wavelengths to a single waveguide [2]. Therefore, the translator should convert directly from space-parallel electronics to wavelength-parallel photonics in a manner that conserves chip space as the translator scales in capacity. This can be implemented using microring resonator modulators. Here, we report four 4-Gb/s modulators simultaneously encoding four wavelengths in a single SOI waveguide, resulting in a transmission capacity of 16 Gb/s.

II. Electronic-to-Photonic Translator

Thermooptic-based silicon switches are limited to low-speed operation (∼MHz); however, fast electrooptic switching devices (∼GHz) have been developed using the free carrier plasma dispersion effect [11] to modulate the refractive index [5]–[10]. Since this effect is relatively weak in silicon, long propagation lengths are required in order to accumulate appreciable changes in phase. Resonator-based devices may be employed to enhance the effects of the index modulation, allowing small-area devices to achieve high-speed switching with low-power carrier-injecting electronics [7]–[10].

Microring resonator structures, consisting of a ring coupled to a straight waveguide, exhibit a useful spectral response. Wavelengths that resonate within the ring are coupled from the waveguide and lost in the ring due to sidewall scattering so that an ideally Lorentzian-like dip occurs in the transmission spectrum. Recently, single-wavelength gigahertz modulation has been demonstrated using an active microring resonator with an integrated p-i-n diode [7]. This device creates index modulation by injecting and extracting carriers through a p-n junction surrounding the waveguide, which then shifts the wavelength of the resonator mode. Functionally, the wavelength of a probe signal is aligned in the center of the mode's transmission dip in the absence of carriers (reverse bias). The injection of carriers (forward bias) shifts the mode to lower wavelengths, and the probe signal, with no change in wavelength, experiences increased transmission. Electrooptic modulation results as carriers are injected and extracted [7].

Manuscript received December 12, 2006; revised January 11, 2007. The work of B. G. Lee, B. A. Small, and K. Bergman was supported by the National Science Foundation (NSF) under Grant CCF-0523771 and by the U.S. Department of Defense under subcontract B-12-664. The work of Q. Xu and M. Lipson was carried out as part of the Interconnect Focus Center Research Program at Cornell University, supported in part by the Microelectronics Advanced Research Corporation (MARCO), and its participating companies.

B. G. Lee, B. A. Small, and K. Bergman are with the Department of Electrical Engineering, Columbia University, New York, NY 10027 USA (e-mail: benlee@ee.columbia.edu; bas@ee.columbia.edu; bergman@ee.columbia.edu).

Q. Xu and M. Lipson are with the School of Electrical and Computer Engineering, Cornell University, Ithaca, NY 14853 USA (e-mail: qx23@cornell.edu; lipson@ece.cornell.edu).

Digital Object Identifier 10.1109/LPT.2007.893032

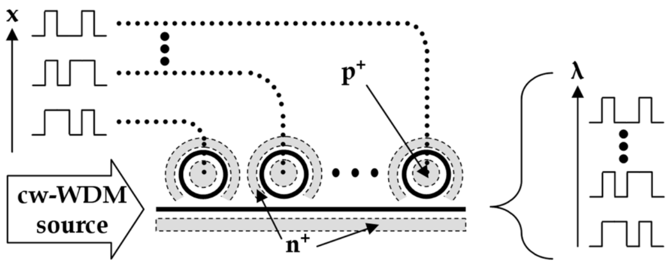

Fig. 1. Schematic of space-parallel electronic (dotted wires) to wavelength-parallel photonic (solid waveguides) translator.

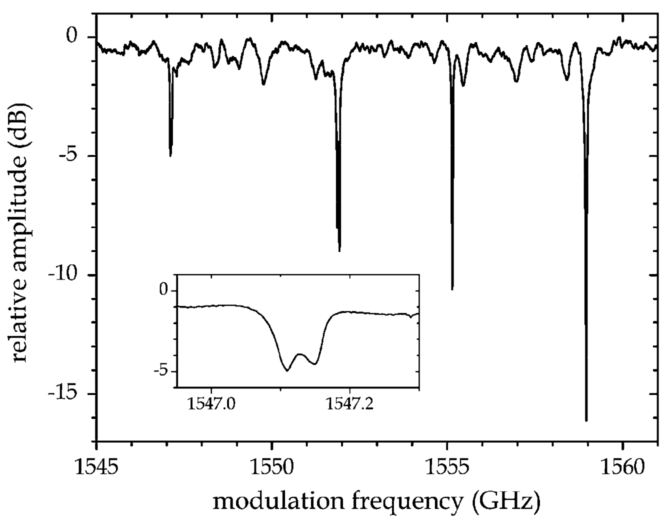

Fig. 2. Transmission spectrum of the waveguide coupled to four unbiased microrings with an inset of the lowest wavelength resonant mode.

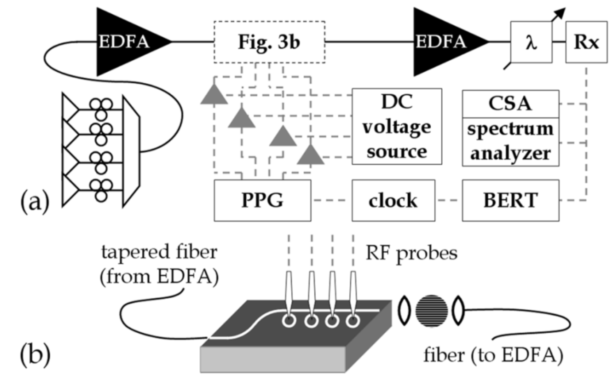

Fig. 3. (a) Experimental measurement and (b) chip-coupling setups. Lasers (open triangles), multiplexer (trapezoid), polarizer (circle), grating filter (λ), receiver (Rx), electrical amplifiers and bias tees (gray triangles), optical fiber (solid lines), and coaxial cable (dashed lines) are among the components.

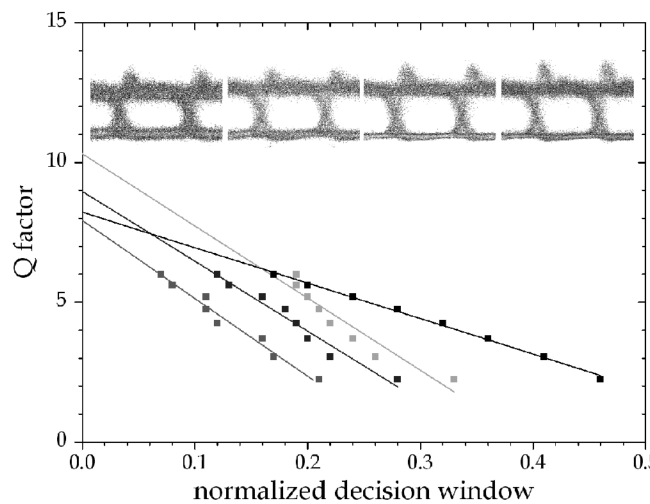

Fig. 4. Q-factor extrapolations from time-window measurements for the four modulated signals. The measured Q-factor (■) is plotted against the fraction of the eye sampling window with linear curve fits. The curves appear from lowest (darkest) to highest wavelength (lightest). Eye diagrams for the four optical signals are given from lowest (left) to highest (right) wavelength.

The translator, initially reported in [8] utilizing only one wavelength at a time, is characterized here with all four wavelengths in operation. The structure contains four microrings, each coupled to the same waveguide, with independent p-n junctions (Fig. 1). The rings were designed with radii of 4.98, 5.00, 5.02, and 5.04 μm. The full-widths at half-maximum of the rings' transmission spectra are all approximately 0.1 nm (Fig. 2). Because each modulator has such a narrow spectral bandwidth, the signals do not need to be demultiplexed and multiplexed before and after modulation. The wavelength-parallel signals share the same waveguide during modulation, and as a result, no couplers or gratings are required. Therefore, optical losses are reduced to the propagation losses in the waveguide. Further, space is conserved, by the small footprint of the microrings and by the omission of the unnecessary passive components. Finally, the electrical connections can be directed in parallel to several rings along a single waveguide (Fig. 1), rather than dividing an electrical bus across nonadjacent regions of the PIC, which could result in timing problems and electrical losses.

III. Experiments and Results

The experimental setup (Fig. 3) involves four lasers with independent polarization controllers, multiplexed and inserted into an erbium-doped fiber amplifier (EDFA). The continuous-wave light is coupled to an SOI waveguide where it encounters the microrings. As the modulated wavelength-parallel signal exits the chip, it passes through a polarizer and fiber collimator. At this point, the signal enters another EDFA; a tunable wavelength filter then selects one channel for analysis. A high-speed receiver sends the detected signal to a bit-error-rate (BER) tester and communications signal analyzer (CSA). To drive the ring modulators, a pulse pattern generator (PPG) supplies four electrically decorrelated 4-Gb/s nonreturn-to-zero ON–OFF-keying signals encoded with a 2^7-1 pseudorandom bit sequence. The parallel electronic signals receive amplification ($\sim$5 V_{pp}) and bias adjustments (~ -0.6 V_{DC}) before being injected into the contact pads through RF probes.

For each of the four modulated optical signals, error-free operation, i.e., BER $< 10^{-12}$, at 4 Gb/s was observed (eyes in Fig. 4 inset). In addition, Q-factor extrapolations were performed for each signal [12]. The Q-factor may be approximated through an extrapolation of data obtained

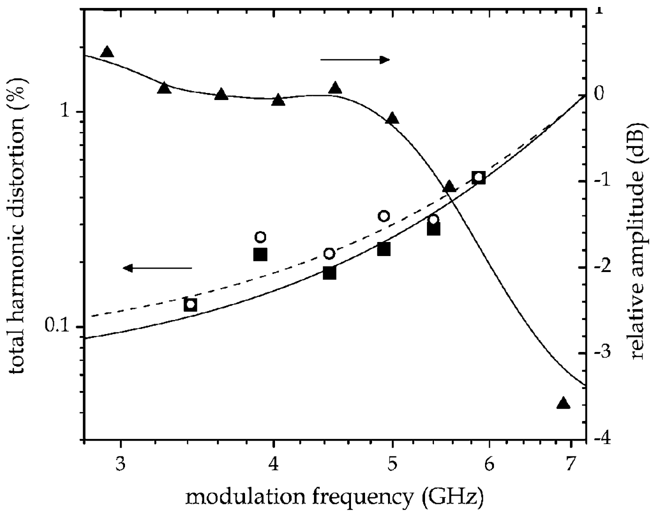

Fig. 5. Amplitude Bode plot and THD measurements plotted against the sinusoidal modulation frequency for the highest wavelength signal. The amplitude measurements (▲) were taken while modulating a single ring. The THD measurements, shown with exponential curve fits, were taken while modulating both a single ring (■) and four simultaneous rings (○).

from BER window measurements. The sampling window widths (time) and heights (amplitude) providing BERs of $10^{-2}, 10^{-3}, 10^{-4}, 10^{-5}, 10^{-6}, 10^{-7}, 10^{-8}$, and 10^{-9} were each recorded. Then, the Q-factors, obtained from the BERs using [13], were plotted against the widths (Fig. 4) and heights of the sampling window. An extrapolation of the Q-factor to the optimal decision threshold, where the window is equal to zero, is used to quantify the signal integrity.

The extrapolated Q-factors with confidence margins for the four optical signals from lowest to highest wavelength are: $8.2\pm 0.26, 9.0\pm0.95, 7.9\pm0.61$, and 10.3 ± 2.07. Since all four wavelengths are limited by the time extrapolation, rather than by the amplitude, which is attributed to the limiting amplifier following the receiver, only the time extrapolations are shown (Fig. 4). The variation between the extrapolated Q-factors is most likely due to small differences in the resonator lineshapes (Fig. 2). This is seen most drastically in the degraded slope of the lowest wavelength extrapolation; here, the transmission spectrum exhibits a slight double-dip (Fig. 2 inset), and has the lowest extinction ratio of the four signals. The double-dip is most likely a result of sidewall roughness in the ring waveguides, which causes reflections and coupling between counterpropagating modes [8]. The much larger Q-factor of the longest wavelength is due to a high extinction ratio.

In addition to signal quality, modulation speed is important to the scalability of photonic networks. The available bandwidth of a single microring modulator was characterized by taking an amplitude Bode plot of the highest wavelength ring (Fig. 5). This is obtained by measuring the amplitude of a sinusoid versus frequency. For this analysis, a high-speed p-i-n photodiode/transimpedance-amplifier (PIN/TIA) replaced the former receiver, which contained a limiting amplifier. The results show that the 3-dB frequency is greater than 6 GHz, indicating that even higher modulation speeds are obtainable with more complex electronics.

Finally, the total harmonic distortion (THD) of the modulator was measured (Fig. 5) for single-ring and four-ring configurations using the PIN/TIA detector and a spectrum analyzer. At the relevant frequencies, the THD in both cases is less than 1%. Furthermore, the crosstalk from the additional three data signals induces an average increase in the THD of only 0.036%, indicating the robustness of this technique for scaling to larger cascades of microrings.

IV. Conclusion

A compact, highly scalable translator between space-parallel electronics and wavelength-parallel optics has been demonstrated with error-free performance at 16 Gb/s. The signal quality has been quantified using Q-factor extrapolations, and the frequency characteristics have been analyzed with amplitude Bode plots and THD measurements. Also, the crosstalk between the four channels, evaluated with THD measurements, has been determined. The results indicate that the translator architecture may be a promising means of converting high-speed high-bandwidth data from electronics to photonics with high signal quality, low power consumption, low latency, and small device footprint.

Acknowledgment

The authors would like to thank A. Biberman, C. Lai, and J. Foster for their contributions.

References

[1] D. A. B. Miller, "Rationale and challenges for optical interconnects to electronic chips," in *Proc. IEEE*, Jun. 2000, vol. 88, no. 6, pp. 728–749.

[2] A. Shacham, K. Bergman, and L. P. Carloni, "Maximizing GFLOPS-per-Watt: High-bandwidth, low power photonic on-chip networks," in *Proc. P=ac2 Conf.*, IBM T. J. Watson Research Center, Yorktown Heights, NY, Oct. 2006, pp. 12–21.

[3] P. Rabiei, W. H. Steier, C. Zhang, and L. R. Dalton, "Polymer micro-ring filters and modulators," *J. Lightw. Technol.*, vol. 20, no. 11, pp. 1968–1975, Nov. 2002.

[4] M. H. Kwakernaak *et al.*, "Wavelength selective WDM modulator with high-Q ring resonators in deeply etched InP/InGaAsP waveguides," in *Proc. Conf. Lasers and Electro-Optics (CLEO)*, San Francisco, CA, May 2004, Paper CThH6.

[5] M. Lipson, "Guiding, modulating, and emitting light on silicon—Challenges and opportunities," *J. Lightw. Technol.*, vol. 23, no. 12, pp. 4222–4238, Dec. 2005.

[6] B. Jalali, M. Paniccia, and G. Reed, "Silicon photonics," *IEEE Microw. Mag.*, vol. 7, no. 3, pp. 58–68, Jun. 2006.

[7] Q. Xu, B. Schmidt, S. Pradhan, and M. Lipson, "Micrometre-scale silicon electro-optic modulator," *Nature*, vol. 435, pp. 325–327, May 2005.

[8] Q. Xu, B. Schmidt, J. Shakya, and M. Lipson, "Cascaded silicon micro-ring modulators for WDM optical interconnection," *Opt. Express*, vol. 14, no. 20, pp. 9430–9435, Oct. 2006.

[9] L. Zhou and A. W. Poon, "Silicon electro-optic modulators using p-i-n diodes embedded 10-micron-diameter microdisk resonators," *Opt. Express*, vol. 14, no. 15, pp. 6851–6857, Jul. 2006.

[10] B. G. Lee *et al.*, "Demonstrated 4 × 4 Gbps silicon photonic integrated parallel electronic to WDM interface," in *Optical Fiber Commun. Conf. (OFC)*, Mar. 2007, submitted for publication.

[11] R. A. Soref and B. A. Bennett, "Electrooptical effects in silicon," *IEEE J. Quantum Electron.*, vol. 23, no. 1, pp. 123–129, Jan. 1987.

[12] N. S. Bergano, K. W. Kerfoot, and C. R. Davidson, "Margin measurements in optical amplifier systems," *IEEE Photon. Technol. Lett.*, vol. 5, no. 3, pp. 304–306, Mar. 1993.

[13] B. A. Small, T. Kato, and K. Bergman, "Measurements of very low bit error rates for an optical packet switching node," *IEEE Photon. Technol. Lett.*, vol. 17, no. 11, pp. 2379–2381, Nov. 2005.