Microring Modulators in a New Silicon Photonics-Optimized 45 nm Monolithic Electronics-Photonics SOI CMOS Platform

Kenaish Al Qubaisi[1,*], **Anatol Khilo**[1,2], **Hayk Gevorgyan**[1], **and Miloš A. Popović**[1,†]
[1] *Department of Electrical and Computer Engineering, Boston University, Boston, MA 02215, USA*
[2] *Ayar Labs, Emeryville, CA 94608, USA*
[*] *kalqubai@bu.edu,* [†] *mpopovic@bu.edu*

Abstract: We report on microring modulators in the new 45CLO photonics-optimized 45 nm electronic-photonic CMOS platform. Interdigitated disk and vertical-junction rib microring designs are demonstrated, with 20 GHz bandwidth at 25 Gbps data rate.

Microring modulators (and photodiodes) are key enablers of emerging dense photonic I/O based on wavelength parallelism and monolithic electronics-photonics (E-P) integration [1–3]. Some of the most complex such E-P systems-on-chip were realized in "zero-change" 45 nm SOI CMOS, an unmodified [1,2] or mildly customized [3] advanced CMOS electronics platform. But, integration in an advanced CMOS process comes with limitations: a thin silicon device layer; no partial etch step; no shallow doping implant (to implement vertical pn junctions [6]); but most importantly a thin buried oxide, no epitaxial Germanium for photodiodes, and challenging edge coupling and packaging. While SiGe broadband [7] and ring detectors [8] at shorter wavelengths as well as wideband silicon-defect detectors [9] have been developed in zero-change CMOS, they currently do not match Ge. Development of a "spoked-ring" active optical resonator [4] enabled efficient modulators and photodiodes [1–5], but a process optimized for photonics can provide major benefits. GlobalFoundries' 90WG (was IBM 9WG) [10] process was developed as a photonics-optimized custom CMOS electronic-photonic platform, supporting state-of-the-art edge coupling/packaging [11] and Ge detectors. However, its 90 nm-node CMOS circuits are insufficient to support emerging state-of-the-art dense photonic I/O.

A new 45 nm-node photonics-tailored electronics-photonics platform, 45CLO [12], under development by GlobalFoundries, combines the benefits of fast 45 nm-node transistors that were previously demonstrated in "zero-change" electronic-photonic integration (IBM 12SOI/GF 45RFSOI [1, 2]) and the silicon-photonics-optimized 90WG custom photonics developed by IBM [10]. 45CLO supports efficient edge coupling and packaging for both polarizations (0.7-1.4 dB) [12], developed first for 90WG [11]. The device portfolio demonstrated to date in 45CLO has focused on broadband passive and active devices. To realize the full potential of this powerful and promising platform, microring active modulators and photodiodes are needed. 45CLO's features allow a wider variety of microring modulator designs, due to a partial etch step, multiple doping implant layers, and high resolution lithography [13]. This shows potential for modulator geometries with horizontal, interdigitated [4], vertical [6], or hybrid p-n junctions [14].

In this paper, we report on the first designs of microring modulators in the 45CLO platform. Two different, novel microring depletion modulator types are demonstrated: an interdigitated lateral junction "spoked-ring"/disk modulator [Fig. 1(a-b)], and a rib-waveguide ring vertical pn junction device [Fig. 1(c-d)]. The spoked ring has an outer radius of 4.36 μm and inner radius of 3.05 μm. To avoid exciting higher-order resonant modes, a mode-selective coupler which wraps around a portion of the resonator is used [4]. Modulation is achieved using T-shaped interdigitated p-n junctions [5] within the device ring, connected to spoked contacts as shown in Fig. 1(a-b). A second device, a more conventional single-mode rib-waveguide based microring modulator, is implemented, but using a vertical pn junction for high efficiency [Fig. 1(c-d)]. This resonator has a radius of 8 μm and a ring width of 410 nm. A nominal n-doping implant is counter-doped with a shallow p-doping implant to realize the vertical p-n junction within the ring.

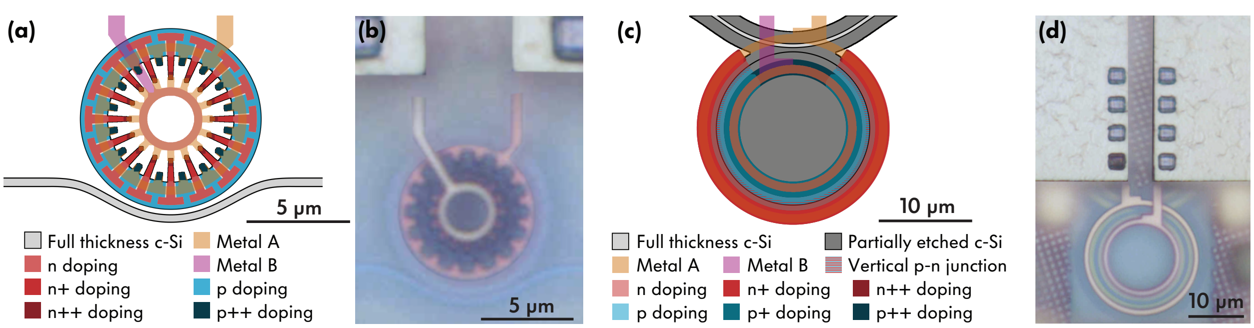

Fig. 1: (a) Geometry of spoked ring modulator as laid out on the design mask. (b) Optical micrograph of spoked ring modulator. (c) Geometry of rib waveguide ring modulator as laid out on the design mask. (d) Optical micrograph of rib waveguide ring modulator.

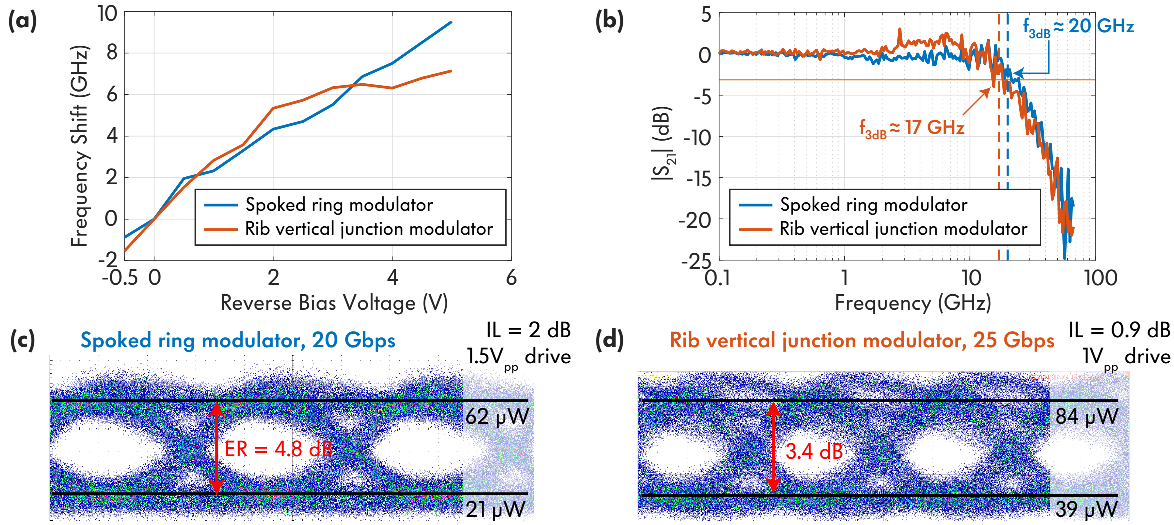

Fig. 2: (a) Resonance frequency shift as a function of applied voltage. (b) Electro-optic response frequency response of the modulators with 0 V applied at the terminals. (c) 20 Gbps optical eye diagram with 4.8 dB modulation depth and insertion loss of 2.05 dB in response to voltage swing from -1.75 V to -0.25 V applied at the terminals. (d) 25 Gbps optical eye diagram with 3.4 dB modulation depth and insertion loss of 0.9 dB in response to voltage swing from -1 V to 0 V applied at the terminals.

The modulators were designed to operate in the O-band near 1300 nm. The loaded quality factors of the devices were measured to be 4,210 (spoked) and 5,000 (rib). The free-spectral ranges (FSRs) were 18 nm i.e. 3.2 THz (spoked) and 8.6 nm i.e. 1.5 THz (rib). DC characterization data is shown in Fig. 2(a) (resonance frequency shift vs. applied voltage). The shift efficiencies are 2.8 GHz/V (spoked) and 3.1 GHz/V (rib). The limited shift is attributed to weak dopings designed for (long) Mach-Zehnder devices, an issue that is easily addressed by adjusting (up) the dopings.

The electro-optical bandwidth of the devices is shown in Fig. 2(b), showing 17 and 20 GHz 3 dB bandwidth at zero bias. A measurement of the same spoked ring modulator more strongly coupled to the bus waveguide resulted in a bandwidth exceeding 30 GHz, indicating that the bandwidth of the current device is limited by its optical line-width (easily increased in design), as expected from the high Q factor, suggesting a higher RC bandwidth. Measured optical eyes from the devices fed by a non-return-to-zero (NRZ) PRBS31 signal, indicating insertion loss and extinction ratio, are shown in Fig. 2(c) (20 Gbps, spoked ring) and Fig. 2(d) (25 Gbps, rib ring). Waveform voltages of $1.5V_{pp}$ and $1V_{pp}$ drive the devices, not including the up to 2× reflection-induced voltage bump due to the capacitive device impedance.

This first demonstration of high-speed microring modulators in the new GlobalFoundries 45CLO 45 nm CMOS monolithic electronics-photonics platform focused on two of several possible geometries, and showed 25 Gbps operation with a clear path to higher speeds and shift efficiencies. We have identified several simple optimization paths (tailored doping, optical linewidth) to improve the shift efficiency, and take bandwidth above 30 GHz.

Acknowledgments: We thank the GlobalFoundries 45CLO process team and Ayar Labs, Inc. for extensive support and interaction. Fabricated on the Haystack test vehicle. Funding: National Science Foundation Award #2023751 (ASCENT), ODNI/IARPA via U.S. ARO grant W911NF-19-2-0114 (SuperCables), and a fellowship from the Abu Dhabi National Oil Company.

References

1. C. Sun, M. T. Wade, *et al.*, “Single-chip microprocessor that communicates directly using light.” *Nature* **528**, 534–538 (2015).
2. V. Stojanović, R. J. Ram, M. Popović, S. Lin, S. Moazeni, M. Wade, C. Sun, et al., Opt. Express. **26**, 13106–13121 (2018).
3. M. Wade *et al.*, “TeraPHY: A Chiplet Technology for Low-Power, High-BW In-Package Optical I/O,” IEEE Micro, 40:2, 63-71, Mar 2020.
4. J.M. Shainline, *et al.*, “Depletion-mode carrier-plasma optical modulator in zero-change...” *Opt. Lett.* **38.15**, (2013): 2657-2659.
5. L. Alloatti, *et al.*, “High-speed modulator with interleaved junctions in zero-change CMOS photonics.” *APL* **108**:13, 131101 (2016).
6. E. Timurdogan, *et al.*, “An ultralow power athermal silicon modulator” *Nature Communications* **5.1**, (2014): 1-11.
7. L. Alloatti, S.A. Srinivasan, ... and R.J. Ram, “Waveguide-coupled detector in zero-change CMOS,” Appl. Phys. Lett. 107:4, 041104 (2015).
8. L. Alloatti and R.J. Ram, “Resonance-enhanced waveguide-coupled silicon-germanium detector,” Appl. Phys. Lett. 108:7, 071105 (2016).
9. A.H. Atabaki, *et al.*, “High-speed polysilicon CMOS photodetector for telecom and datacom” Appl. Phys. Lett. 109:11, 111106 (2016).
10. K. Giewont, *et al.*, “300-mm Monolithic Silicon Photonics Foundry Technology,” IEEE JSTQE, vol. 25, no. 5, pp. 1-11, Sept. 2019.
11. T. Barwicz, *et al.*, “A Novel Approach to...” IEEE J. of Sel. Topics in Quantum Electron., 22 (6), 8200712, Nov (2016).
12. M. Rakowski, *et al.*, “45nm CMOS - Silicon Photonics Monolithic Technology (45CLO) ...” OFC, OSA, paper T3H.3 (2020).
13. K. Al Qubaisi, *et al.*, “Reflectionless dual standing-wave microcavity resonator units...” *Opt. Express* **28.24**, (2020): 35986-35996.
14. E. Timurdogan, *et al.*, “An interior-ridge silicon microring modulator.” *IEEE/OSA J. Lightwave Technol.* **31.24**, (2013): 3907-3914.