L-Shaped Resonant Microring (LRM) Modulator

Erman Timurdogan[1], Cheryl M. Sorace-Agaskar[1], and Michael R. Watts[1]
[1]Research Laboratory of Electronics, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, Massachusetts 02139, USA
ermant@mit.edu

Abstract: A high-speed silicon L-shaped resonant microring modulator, enables directly integrated electrical contacts, 5-µm diameter, 5.3-THz free spectral range, is demonstrated error-free operation up to 30-Gb/s with 1.76-dB insertion loss and 2.8-dB power penalty.

1. Introduction

On- and off-chip bandwidth and energy scaling is pushing the limits of CMOS and VCSEL technology that allows only a single channel per fiber. Wavelength division multiplexed (WDM) systems based on silicon photonic interconnects can enable high-bandwidth, energy-efficient communications. Integrated resonant modulators play a major role in such links. Resonant silicon modulators utilize the plasma dispersion effect through free-carrier injection [1] or depletion [2–7] in a diode, or by charging a metal-oxide-semiconductor (MOS) capacitor [8]. Compact 3.5-µm microdisk modulators have been demonstrated with a power consumption of only 3 fJ/bit at 1-Vpp and 12.5 Gb/s operation [3,5]. Recently, 25Gb/s operation with 13fJ/bit at 1.2Vpp has been demonstrated with ~6-µm diameter microdisk modulator [7]. Microdisk modulators use a vertical *p-n* junction, have interior contacts, and a hard outer waveguide wall to enable compact devices. However, microdisks inherently support spurious modes that corrupt the free spectral range (FSR) by introducing unwanted resonance dips on the transmission. Therefore, only half of the FSR can be used for WDM channels in a silicon photonic link. Higher doping concentrations near the waveguide wall lower the quality factor (Q) of the fundamental mode and do not cut-off undesired higher-order modes. Microrings eliminate the undesired modes, but directly contacting the microring leads to scattering and loss. External ridge based waveguides to enable electrical contact increases the diameter to 10 µm due to low confinement, thereby increasing the area and power consumption by nearly an order of magnitude [1,4]. Recently, a 4-µm adiabatic resonant microring modulator, which enabled single-mode operation by adiabatic tapering of the single mode waveguide, was demonstrated but limited in data-rate to 12.5 Gb/s due to electrical resistance of the contacts [6].

In this paper, we introduce a new class of modulators, L-shaped resonant microrings (LRM), which allow for both hard outer walls and single mode propagation while maintaining low resistance electrical contacts. Thus, LRM modulators can have a compact size, high quality factor, and an uncorrupted FSR while maintaining high-speed operation. To allow for interior contacts, a hybrid junction consisting of a vertical and interdigitated *p-n* junction (see Fig. 1, left) is used. The L-shaped waveguide is formed by an internal ridge etch of a wide micro-ring/-disk, thus preserving the hard outer waveguide wall and enabling minimum bend radii and peripheral direct contact to full waveguide thickness. The thickness of the inner ridge is adjusted for single mode operation [9]. Since the L-shaped waveguide is inherently single mode, the coupling region does not require complicated waveguide geometry or phase matching. Here, we demonstrate a hybrid *p-n* junction based the LRM modulator operating in depletion mode, with data rates up to 30 Gb/s, and occupying chip area of < 20 µm^2 and maintaining an uncorrupted 5.3 THz FSR.

2. Device characterization and demonstrated results

The LRM modulator, coupled to a bus waveguide, has an integrated hybrid *p-n* junction formed by alternating doping of the ridge and full thickness silicon waveguide (Fig. 1, left). Doping concentrations around the edge of the microring are optimized at a level of 1×10^{18} cm^{-3} for both *p* and *n* doping concentrations, and inner contact areas are doped at a level of 1×10^{20} cm^{-3} for both *p*+ and *n*+ regions to minimize device resistance. The full and ridge silicon waveguide thicknesses are 220 and 110 nm, respectively. Spur-free FSR of 5.3 THz is demonstrated on a device

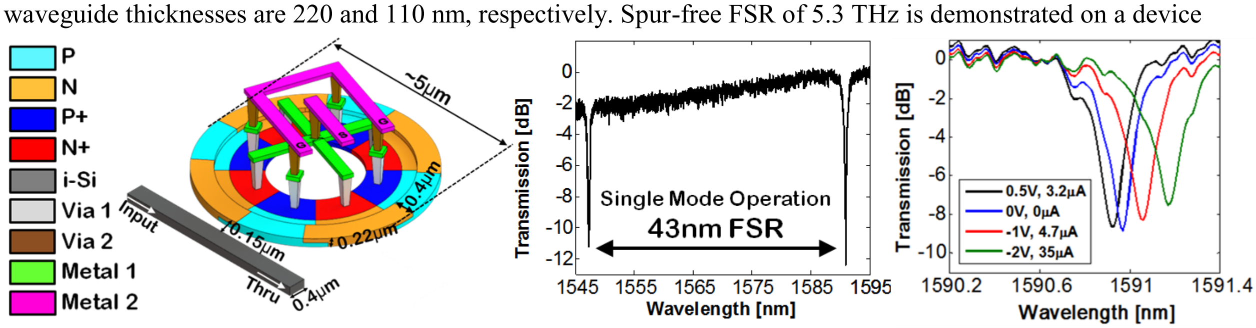

Figure 1 – 3D sketch of the LRM modulator showing size, doping and metal connections (left), Spur-free single mode operation of the LRM modulator with a FSR of 5.3 THz (middle), and measured spectral response at applied DC voltages (right).

with a diameter of only 5µm (Fig. 1, middle). Spectrum is measured at applied DC voltages from –2 to 0.5 V to characterize the modulator (Fig. 1, right).

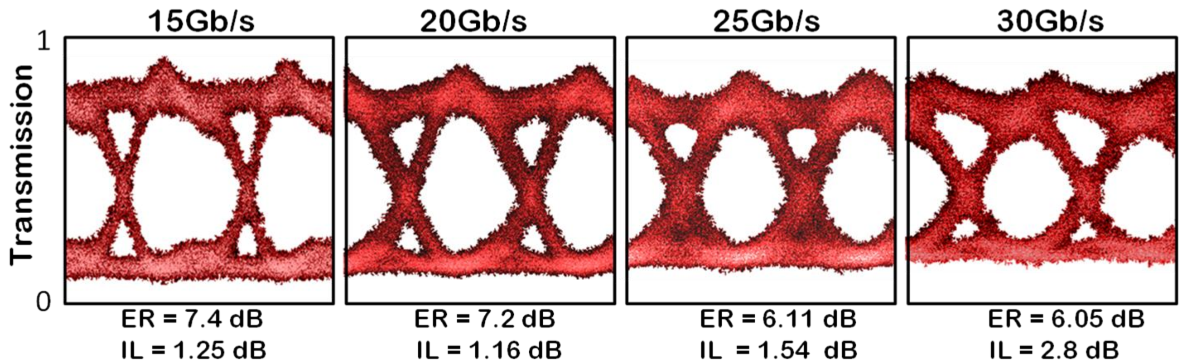

Figure 2 – High-Speed Optical Eye Diagrams at 15-, 20-, 25- and 30-Gb/s data rates. Extinction ratio (ER) and insertion loss (IL) is denoted below the eye diagrams.

The modulator was driven electrically with a terminated probe using a non-return-to-zero-on-off-keying (NRZ-OOK) signal encoded with pseudo-random-bit-sequence (PRBS) data with a pattern length of $2^{31}–1$, at 2.2 V_{pp} with a DC bias of –0.6 V. Optical eye diagrams at 15-, 20-, 25- and 30-Gb/s data rates are obtained using a digital sampling oscilloscope (Fig. 2). Extinction ratio and insertion loss is denoted below the eye diagrams. For further quantification of the modulator performance, BER measurements and power penalty analysis was performed from 15- to 30-Gb/s (Fig. 3). A commercial $LiNbO_3$ Mach-Zehnder modulator with 4dB insertion loss and 35GHz bandwidth is used for comparison. Error-free operation (BER $<10^{-12}$) up to 30Gb/s and < 2.8 dB power penalty at a BER of 10^{-9} were demonstrated.

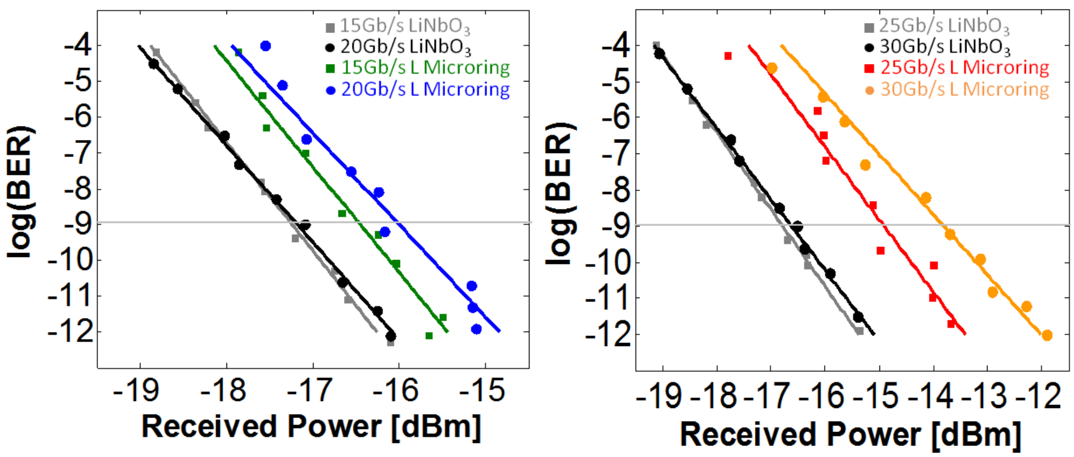

Figure 3 – Bit Error Rate (BER) curves measured for the L shaped and $LiBNO_3$ modulator at 15-, 20- (left), 25- and 30-Gb/s (right) data rates

3. Conclusions

We demonstrate an integrated LRM modulator that achieves 30 Gb/s error-free operation in a compact (< 20 μm^2) structure while maintaining single-mode operation, enabling direct WDM across an uncorrupted 5.3 THz FSR. At a 70-GHz channel spacing, the 5.3 THz FSR would allow 75 WDM channels along a single silicon photonic communication line.

This work was supported in part by the Defense Advanced Research Projects Agency (DARPA) Microsystems Technology Office's (MTO) POEM and EPHI program, and Cheryl Sorace-Agaskar acknowledges support from NSFGRP, No. 0645960.

4. References

[1] Q. Xu, B. Schmidth, S. Pradhan and M.Lipson, "Micrometre-scale silicon electro-optic modulator," *Nature* 435, 325-327 (2005).
[2] M. R. Watts *et al.*, "Ultralow power silicon microdisk modulators and switches," in *Proc. 5th IEEE Int'l Conf. Group IV Photonics*, Sorrento, Italy, Sept. 2008, pp. 4–6.
[3] M. R. Watts *et al.*, "Vertical junction silicon microdisk modulators and switches", *Opt. Exp.* 19, 21989–22003 (2011).
[4] P. Dong *et al.*, "Low V_{pp}, ultralow-energy, compact, high-speed silicon electro-optic modulator," *Opt. Exp.* 17, 22484–22490 (2009).
[5] W. A. Zortman, M. R. Watts, D. C. Trotter, R. W. Young and A. L. Lentine, "Low-Power High-Speed Silicon Microdisk Modulators," in Proc. CLEO/QELS, Technical Digest (CD) (Optical Society of America, 2010), paper CThJ4.
[6] A. Biberman *et al.*, "Adiabatic microring modulators," *Opt. Exp.* 20, 29223-29236 (2012).
[7] E. Timurdogan *et al.*, "Vertical Junction Silicon Microdisk Modulators at 25Gb/s," Proc. Optical Fiber Communication Conference (OFC) (2013).
[8] A. Liu *et al.*, "A high-speed silicon optical modulator based on a metal oxide semiconductor capacitor", *Nature* 427, 615–618 (2004).
[9] J. Song *et al.*, "Thermo-optical tunable planar ridge microdisk resonator in silicon-on-insulator," *Opt. Exp.* 19, 11220-11227 (2011).