Adiabatic Resonant Microring (ARM) Modulator

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Abstract: A high-speed adiabatic resonant microring silicon modulator, which simultaneously enables interior electrical contacts, 4-µm diameter, and 6.9-THz free spectral range, is demonstrated with open eye diagrams up to 12Gb/s, and extinction ratios up to 7.3dB.

1. Introduction

High-performance devices and systems based on CMOS-compatible silicon photonics are increasingly gaining momentum in the optical interconnects community as essential building blocks for high-speed, energy-efficient communication systems. In silicon photonic interconnects, a critical role is played by the integrated modulator, which represents one of the major components still being refined. Silicon modulators operate by free-carrier injection [1], by modulating the width of the depletion region [2–5], or based on charging metal-oxide-semiconductor (MOS) capacitors [6]. Already, compact 3.5-µm microdisk modulators have been demonstrated with a power consumption of only 3 fJ/bit and 1-V operation [3,5]. Microdisks were chosen for the ease of implementing interior contacts, and a hard outer waveguide wall to enable minimal bend radii. However, microdisks support higher-order modes that corrupt the otherwise extensive free spectral range (FSR) by introducing unwanted resonances. Maintaining a large, uncorrupted FSR is important for wavelength-division multiplexing (WDM) multiple resonant modulators on a single communication line. Microrings eliminate the undesired modes, but directly contacting a microring leads to scattering and loss. And, the use of external ridge waveguides to enable electrical contact increases the diameter to 10 µm, thereby increasing the area by nearly an order of magnitude [1,4].

In this paper, we demonstrate a new class of modulators, adiabatic resonant microring (ARM) [4,5] modulators, which enable the integration of vertical *p-n* junctions and interior contacts while maintaining a high quality factor and compact size, while preserving single radial mode propagation and thereby achieving an uncorrupted FSR [1]. Adiabatic resonant microrings (ARMs) have been shown both numerically [7] and experimentally [8] to enable interior contacts and a compact size while maintaining high quality factors. ARMs operate on the principle of mode-evolution. In the coupling region the ring waveguide is made narrow to ensure single-mode operation and the waveguide is then slowly widened to enable contact to the microring where there is no optical field. Here, we demonstrate a vertical *p-n* junction based on the ARM modulator operating in depletion mode, with data rates up to 12 Gb/s, while occupying less than a 12.5 µm^2 of chip area and maintaining an uncorrupted 6.9 THz FSR.

2. Experiments and results

The demonstrated device is an ARM modulator coupled to a bus waveguide, which has an integrated vertical *p-n* junction formed by counter-doping the silicon waveguide. Doping concentrations inside the ring are optimized at a level of 1×10^{18} cm^{-3} for both *p* and *n* doping concentrations, with contacts at a level of 1×10^{20} cm^{-3} for both *p+* and *n+* regions in order to minimize resistance. (Fig. 1, left). The bus width, coupling gap, and ring width in the coupling region is 320, 360, and 400 nm, respectively (Fig. 1, left). The height of the silicon waveguide is 240 nm. In order to determine DC characteristics of the ARM modulator, we apply a DC bias from –6 to 1 V, and observe current passing through the modulator, (Fig. 2, left). Frequency shifts of -26GHz and 90GHz are achieved for –6 and 1 V, respectively. With a diameter of only 4µm, it has a FSR of 6.9THz (Fig. 1, middle).

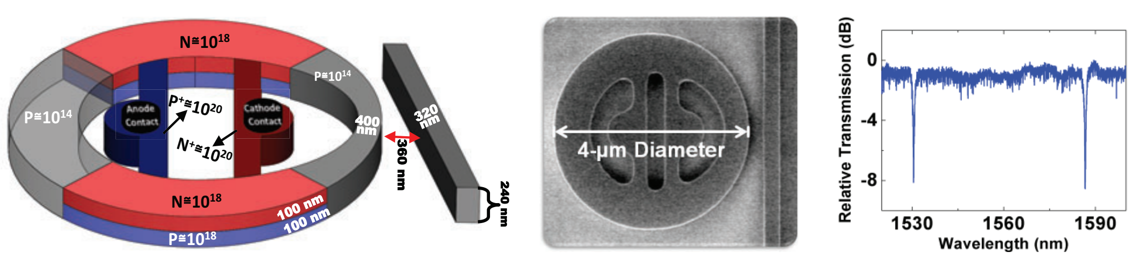

Figure 1 – 3D diagram of the ARM modulator that we used in these experiments (left), scanning electron micrograph (SEM) of the silicon layer of the ARM modulator (middle), and measured spectral response showing the FSR (6.9 THz) of the resonator (right).

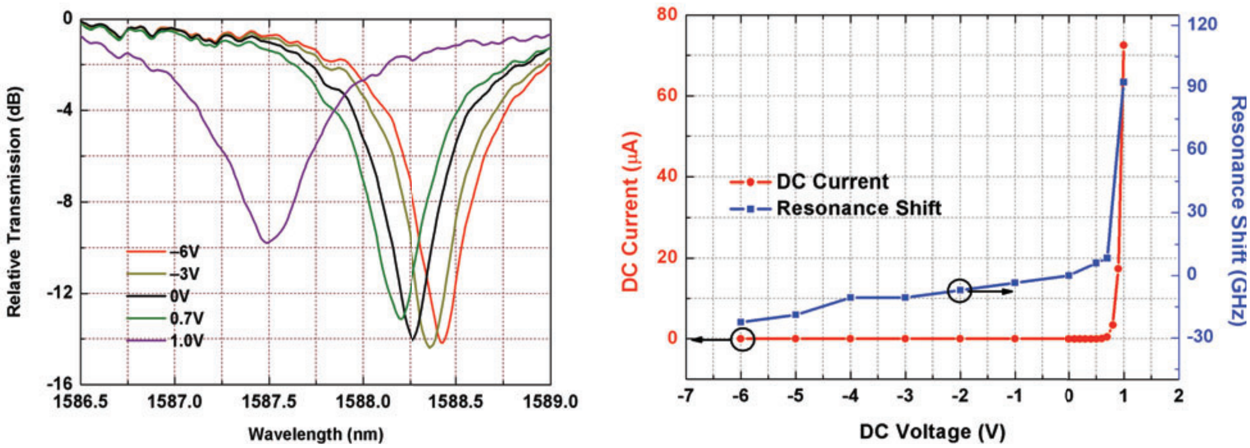

Figure 2 – Spectral response as a function of DC modulator bias (left), and *I-V* relationship and resonance shift with respect to voltage (right).

The modulator was driven electrically 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, a drive voltage V_{PP} of 2.4 V, and a DC bias of –2.2 V. Due to the high impedance of the modulator and the resulting RF reflections, a maximum V_{PP} of 4.8 V is effectively applied across modulator terminals. Output optical eye diagrams at 5-, 12-, and 15-Gb/s data rates are subsequently obtained using a digital sampling oscilloscope. We observe open eye diagram for 5 Gb/s, achieving a 6.7-dB extinction ratio, defined as the ratio in dB between the logical 1 and the logical 0 of the optical signal, referenced to the recorded true 0 (shown in Fig. 3). The eye diagram degrades for a 12-Gb/s signal, while producing a 7.3-dB extinction ratio. Finally, we drive the modulator at 15 Gb/s, observing further significant degradation and a 5.1-dB extinction ratio.

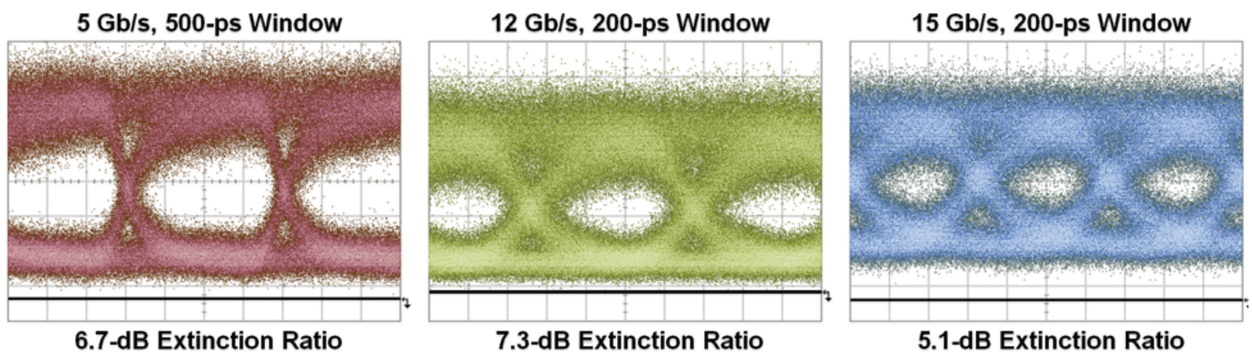

Figure 3 – High-speed output optical eye diagrams for data rates; **5Gb/s** (left), **12Gb/s** (middle), **15Gb/s** (right).

3. Conclusions

We demonstrate an integrated ARM modulator, achieving high-speed (up to 12 Gb/s with open output optical eye diagrams) operation in a compact (4-µm) structure while maintaining single-mode operation, enabling direct WDM across an uncorrupted 6.9-THz FSR. At a 70-GHz channel spacing, the 6.9-THz FSR would enable well over 100 WDM channels along a single microphotonic communication line. To our knowledge, 6.9 THz is the widest demonstrated FSR of any microring modulator.

4. References

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