

Adiabatic Resonant Microring (ARM) Modulators with Integrated Thermal Tuner

Erman Timurdogan¹, Cheryl M. Sorace-Agaskar¹, Gerald Leake², Douglas D. Coolbaugh² and Michael R. Watts¹

¹Research Laboratory of Electronics, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, Massachusetts 02139, USA

²College of Nanoscale Science & Engineering, University at Albany, 1400 Washington Avenue, Albany, New York 12222, USA
 ermant@mit.edu

Abstract: We integrate an efficient thermal tuner (6.2- $\mu\text{W}/\text{GHz}$) within ARM modulators for the first time, yielding 5-THz uncorrupted FSR. The 5.4- μm diameter modulator achieves low-power (9-fJ/bit) and high-speed (13-Gb/s) operation with 5.9dB extinction ratio.

OCIS codes: (130.3120) Integrated optics devices; (230.5750) Resonators; (230.7370) Waveguides

1. Introduction

Although the compute bandwidth and power is scaling according to Moore's law, a similar scaling for communications does not exist. High bandwidth communications still tend to require high power. Wavelength division multiplexed systems can achieve high bandwidth by utilizing many channels on a single fiber as opposed to current single channel per cable or fiber interconnects. Silicon photonics can readily enable wavelength division multiplexed (WDM) systems through the use of compact, inherently wavelength selective micro-ring/-disk resonators. Such devices have been demonstrated to have energies as low as 3fJ/bit at a data rate of 12.5Gb/s [1] and 13fJ/bit at a data rate of 25Gb/s [2]. However, resonance drifts, induced by process/wafer variations and dynamic temperature fluctuations of the processor chip, integrated in close proximity of the photonic chip, detune the alignment between the modulators and the WDM lasers. These effects need to be compensated. However, electro-optic tuning can compensate only for temperature variations of $\sim \pm 2.5^\circ\text{C}$, while processor core activity on chip yields temperature fluctuations on the order of $\pm 10^\circ\text{C}$. Therefore, thermo-optic tuning and control of resonators is required [3]. A silicon heater can be directly integrated within microring filters and modulators. Integrated silicon heaters simultaneously optimize thermal tuning efficiency (4.4 $\mu\text{W}/\text{GHz}$) and tuning speed (1 μs) [4]. Unfortunately, heaters are usually integrated within resonant modulators at the expense of area and/or performance. A single-mode large ridge microring modulator ($400\mu\text{m}^2$) with $\sim 42\mu\text{W}/\text{GHz}$ tuning efficiency [5] and compact multi-mode microdisk modulators ($50\mu\text{m}^2$ and $28\mu\text{m}^2$) with $7\mu\text{W}/\text{GHz}$ and $4.9\mu\text{W}/\text{GHz}$ tuning efficiency [6,7] have been demonstrated in the literature. Ridge based modulators support single mode operation but do not provide as low-power modulation and/or tuning as microdisk based modulators. Adiabatic resonant microrings (ARM), which support single mode operation and can be formed as small as $4\mu\text{m}$ in diameter with a hard outer wall, have been demonstrated with up to 12.5Gb/s modulation prior to this work [8].

Here, we demonstrate a 5.4- μm diameter ARM modulator with a CMOS compatible integrated heater allowing for single mode operation, high performance modulation and minimum thermal capacitance. The hard outer walls of the ARM modulator enable a tight bend radius and high-Q operation [4,8]. High-speed modulation is created through a vertical p - n junction around the edge of the ARM modulator and low resistance interior contacts. The proposed ARM modulator is measured to have a 6.2 $\mu\text{W}/\text{GHz}$ thermal tuning efficiency, $\sim 9\text{fJ}/\text{bit}$ performance at a data rate of 13 Gb/s, and a 5.9dB extinction ratio. This is the first demonstration of an integrated heater and modulator within an ARM resonator and the most compact microring modulator with a directly integrated heater.

2. Device Characterization and Experimental Results

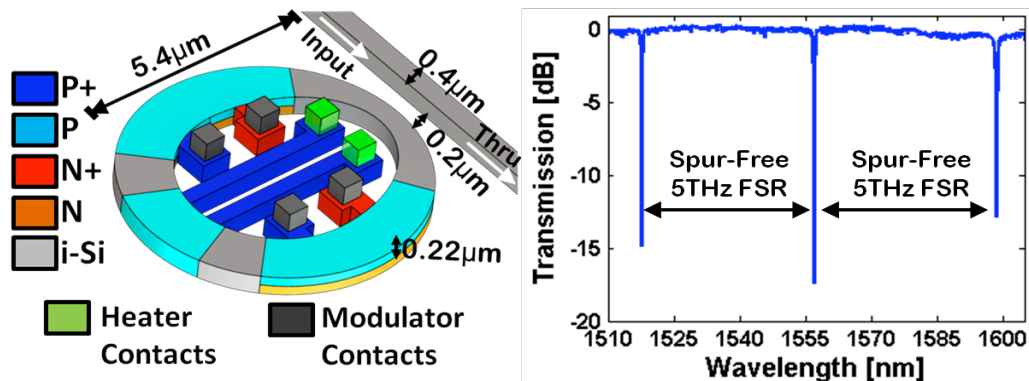


Figure 1 – 3D sketch of the ARM modulator showing size, doping and contacts (left), and measured spectral response of the ARM resonator with uncorrupted (spur-free) 5THz ($\sim 40\text{nm}$) free spectral range (right). Single mode operation extends over 80nm range.

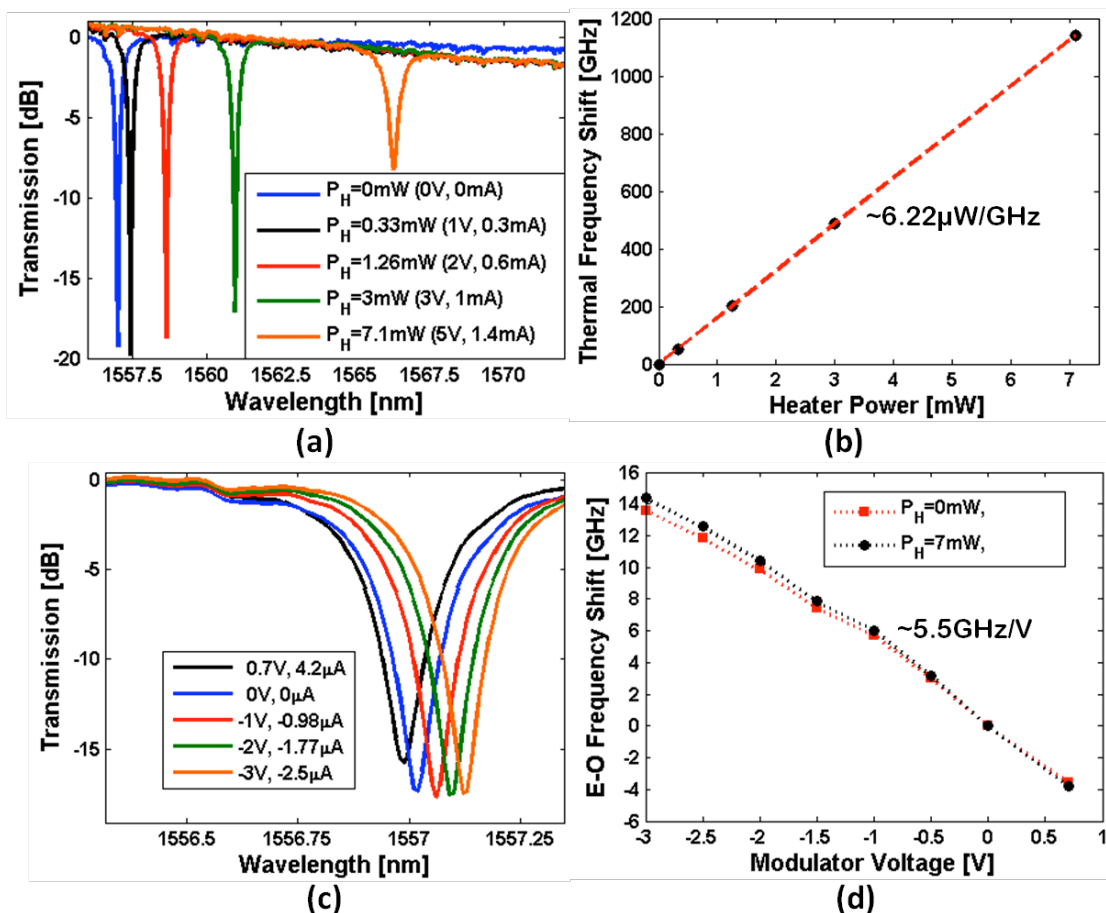


Figure 2 – DC characterization of the ARM modulator with integrated heater: (a) measured spectral response of the integrated heater within the ARM modulator with an applied bias voltage to heater pins, (b) thermo-optic frequency shift as a function of heater power. The heater resistance is determined to be $\sim 3\text{k}\Omega$ and the tuning efficiency, defined as the slope of the linear fit (red dashed line), is $6.2\mu\text{W}/\text{GHz}$. (c) Measured spectral response of the microdisk modulator with applied DC bias voltage to modulator pins from -3V to 0.7V , (d) electro-optic frequency shift as a function of modulator voltage. The modulator electro-optic shift is compared when the heater is not active and is dissipating 7mW which shifts the ARM modulator by $\sim 1.15\text{THz}$. There was no significant crosstalk between electrical connections.

The ARM modulator, coupled to a $400\text{nm} \times 220\text{nm}$ bus waveguide, has an integrated vertical p - n junction around its edge with p and n type doping concentrations of $\sim 2 \times 10^{18}\text{ cm}^{-3}$ and interior p^+ and n^+ contacts with doping concentrations at a level of $1 \times 10^{20}\text{ cm}^{-3}$ (Fig. 1, left). The coupling region, single mode (400nm wide), is tapered up to a wide multi-mode waveguide ($1\mu\text{m}$) to allow low loss direct contacts. Since the taper is designed to be adiabatic, the radial fundamental TE mode does not couple to higher order modes. This preserved the single-mode operation throughout the ARM modulator. An uncorrupted free spectral range (FSR) of 5THz ($\sim 40\text{nm}$) is measured over an 80nm range (Fig. 1, right). In a WDM system with 50GHz channel spacing, the large 5THz FSR can support 100 channels on a single bus waveguide or a single mode fiber. In order to enable integration of a heater and minimize the resistance of the modulator, half of the ARM modulator is used for modulation. The integrated heater is formed by p type doping in the wide waveguide and contacted by p^+ type doped insulating silicon straight tethers (Fig. 1, left). The tethers are elongated to achieve thermal isolation. The p and p^+ type doping levels are the same as the modulator doping levels in order to minimize the number of necessary mask layers and, thus, fabrication cost. This design allows, for the first time, the integration of a heater and modulator within an ARM resonator successfully. The polarity of the heater bias is chosen to minimize electrical crosstalk with the modulator diode.

Thermal tuning of the ARM modulator is achieved by applying a DC bias voltage across the heater contacts. Spectral response is measured with a CW tunable laser for an applied heater voltage of 0V , 1V , 2V , 3V and 5V as shown in Fig. 2 (a). Thermo-optic frequency shifts up to $\sim 1.15\text{THz}$ are observed at heater power consumptions of 7mW (5V). This corresponds to a heater efficiency of $6.2\mu\text{W}/\text{GHz}$ (Fig. 2 (b)). Extinction ratio is degraded down to $\sim 6\text{dB}$ due to variable coupling into the modulator when the ARM is tuned by 1.15THz . However, in a WDM system, the required frequency shifts will be on the order of $\pm 100\text{GHz}$ and the extinction ratio is preserved for such a shift.

The ARM modulator is characterized with a DC bias voltage applied across modulator pins from -3V to 0.7V. The spectrum for each bias point is shown in Fig. 2 (c). For a probe wavelength of $\lambda \sim 1556.9\text{nm}$, a DC extinction ratio and insertion loss of 7.5dB and 4.1dB is measured between -2V and 0V bias. Since half the ARM is used for the modulator, electro-optic frequency shifts were expected to be half of a fully doped microdisk modulator ($\sim 11\text{GHz/V}$) [2]. Indeed, the ARM modulator electro-optic frequency shift is determined to be $\sim 5.5\text{GHz/V}$ (Fig. 2 (d)). The electro-optic frequency shifts remained similar even after the ARM is tuned by $\sim 1.15\text{THz}$.

High-speed performance of the ARM modulator is characterized. The modulator contacts are driven electrically with a terminated probe and a 1.8V_{pp} (0 to -1.8V) non-return-to-zero-on-off-keying (NRZ-OOK) signal encoded with a pseudo-random-bit-sequence (PRBS) at a pattern length of $2^{31}-1$. The optical eye diagrams are obtained by a digital sampling oscilloscope at a data rate of 5-, 10-, and 13-Gb/s, as illustrated in Fig. 3. The dynamic extinction ratio is 6dB and insertion loss of 4.3dB, in good agreement with the DC characterization (Fig. 2 (c)). The insertion loss can be further minimized with higher drive voltages or at the expense of extinction ratio. When the modulators integrate with CMOS circuits, unterminated drive can be used to further minimize drive voltages. Modulator capacitance is calculated to be $\sim 11\text{fF}$ based on Sentaurus simulations and the energy of the modulator is estimated to be $\sim 9\text{fJ/bit}$ for a voltage swing of 1.8V_{pp} similar to [2,7]. The modulator is PRBS source limited to 13Gb/s and experiments to achieve higher data rate operation are ongoing.

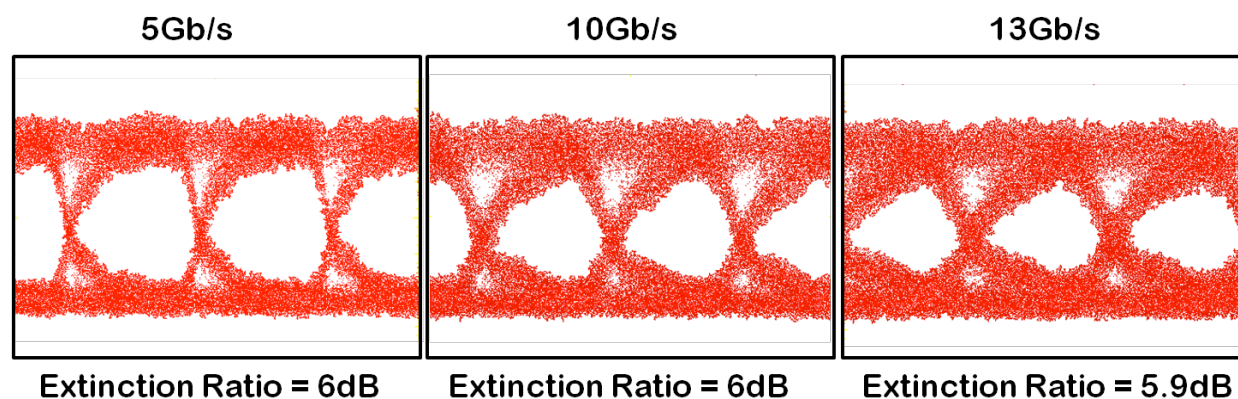


Figure 3 – High-Speed Optical Eye Diagrams at data rates of 5-, 10-, 13-Gb/s. Extinction ratio is denoted below the eye diagrams. Open eye diagrams with $\sim 6\text{dB}$ extinction ratio and up to 13Gb/s data rate is observed.

If the proposed microdisk modulator has a frequency offset of $\sim 100\text{GHz}$ due to fabrication variation and is on a processor chip with $\pm 10^\circ\text{C}$ temperature variation, the required heater power for compensation is $\sim 1.8\text{mW}$. Combined with an electro-optic modulation power of 0.12mW at a data rate of 13Gb/s, the microdisk modulator will have a realistic energy performance of $\sim 147\text{fJ/bit}$ when one includes both heater and modulator energy. If the necessary tuning variations of the multiple microdisks in a WDM link obey a Gaussian distribution, then the required thermal compensation can be halved, and a more realistic performance estimate would be $\sim 78\text{fJ/bit}$ at a data rate of 13Gb/s.

3. Conclusions

A silicon heater is successfully integrated within an ARM resonant modulator for the first time. The $2.7\mu\text{m}$ radius modulator is also the most compact tunable microring modulator to date. Low-power modulation (9fJ/bit) at a data rate of 13-Gb/s, a 5.9-dB extinction ratio, and an efficient thermal tuning of $6.2\text{-}\mu\text{W/GHz}$ is achieved. The demonstrated 5THz spur-free FSR can support above 100 channels (1.3Tb/s per fiber at a data rate of 13Gb/s/channel) with 50GHz channel spacing. An ultra-low total energy of 78fJ/bit is predicted at a data rate of 13Gb/s for a frequency offset of $\sim 100\text{GHz}$ to the laser line and $\pm 10^\circ\text{C}$ temperature variation.

This work was supported in part by the Defense Advanced Research Projects Agency (DARPA) Microsystems Technology Office's (MTO) POEM and EPHI program, grant no. HR0011-12-2-0007 and C. M. Sorace-Agaskar acknowledges support from NSFGRP, No. 0645960.

4. References

- [1] M. R. Watts *et al.*, "Vertical junction silicon microdisk modulators and switches," *Opt. Express* 19, 21989–22003 (2011).
- [2] E. Timurdogan *et al.*, "Vertical Junction Silicon Microdisk Modulators at 25Gb/s," *OFC*, 2013.
- [3] E. Timurdogan, *et al.*, "Automated Wavelength Recovery for Microring Resonators," *CLEO*, 2012.
- [4] M. R. Watts *et al.*, "Adiabatic Resonant Microrings (ARMs) with directly integrated Thermal Microphotonics," *CLEO*, 2012.
- [5] G. Li *et al.*, "25Gb/s 1V-driving CMOS ring modulator with integrated thermal tuning," *Opt. Express* 19, 20435-20443 (2011).
- [6] W. Zortman *et al.*, "Integrated CMOS Compatible Low Power 10Gbps Silicon Photonic Heater Modulator," *OFC*, 2012.
- [7] E. Timurdogan, *et al.*, "Vertical Junction Silicon Microdisk Modulator with Integrated Thermal Tuner," *CLEO*, 2013.
- [8] A. Biberman, *et al.*, "Adiabatic Microring Modulators," *OFC*, 2013.