Vertical Junction Silicon Microdisk Modulator with Integrated Thermal Tuner

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Abstract: We demonstrate an approach to integrate the most efficient thermal tuner (4.9-µW/GHz) into a microdisk modulator without sacrificing junction area for the first time. The 6-um diameter modulator achieves low-power (11-fJ/bit) and high-speed (13-Gb/s) operation.

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

1. Introduction

Low power and high speed vertical cavity surface emitting lasers (VCSELs) and CMOS electronics are currently used to enable high performance computing (HPC) and communication applications. HPC machines, in the exascale range, will require a significant number of fibers, reduction in power and increase in data rates per cable/fiber. Silicon photonics, because it enables wavelength division multiplexed (WDM) systems, will help to minimize the number of fibers required in HPC systems. It also promises to do so with low power and high speed resonant devices. Resonant electro-optic modulators will likely be used to transmit data in the WDM links, and 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, distort the alignment between the modulators and the desired WDM channels. Electro-optic tuning can be used for temperature variations of ~$\pm 2.5^0$C. However, processor core activity on chip yields temperature fluctuations on the order of $\pm 10^0$C. Therefore, thermo-optic control of the resonators is necessary [3]. The integration of heaters within microring filters and modulators achieves the best optimization of thermal tuning power (4.4 µW/GHz) and speed (1 µs) [4]. Unfortunately, heaters are usually integrated within resonant modulators at the expense of area and/or performance. A large ridge microring modulator (400μm^2) with ~42µW/GHz tuning efficiency and ~67% junction area coverage around the periphery [5] and a compact microdisk modulator (50μm^2) with 7µW/GHz tuning efficiency and 50% junction area coverage around the periphery[6] have been demonstrated in the literature. Junction area coverage limits the modulation efficiency and leads to an insertion loss of >5dB [5] and >3db [6]. For a normal distribution of $\pm 10^0$C temperature fluctuations and a ~100GHz resonance frequency offset due to fabrication/wafer variations, the total modulation and heater energy was >322fJ/bit [5] and >200fJ/bit [6].

Here, we propose a ~6-µm diameter (footprint ~ 28 μm^2) microdisk modulator with a CMOS compatible integrated heater in the center that allows for high performance modulation and minimum thermal capacitance. The hard outer walls of the microdisk modulator enable minimum bend radii and high-Q operation[1,2,6]. High-speed modulation is enabled by a vertical *p-n* junction near to the edge of the microdisk modulator and low resistance interior contacts. The proposed microdisk modulator is measured to have a 4.9µW/GHz thermal tuning efficiency and ~11fJ/bit performance at a data rate of 13 Gb/s, a 5.8dB extinction ratio and a 1.22dB insertion loss. This is the most efficient heater integration yet with total modulation and heater energy predicted to be less than <50fJ/bit.

2. Device Characterization and Experimental Results

The microdisk modulator, coupled to a bus waveguide, has an integrated vertical *p-n* junction around the edge of the microdisk with *p* and *n* type doping concentrations of 1×10^{18} cm^{-3} and interior *p*+ and *n*+ contacts with doping concentrations at a level of 1×10^{20} cm^{-3} (Fig. 1, left). The integrated heater is formed in the center of the microdisk

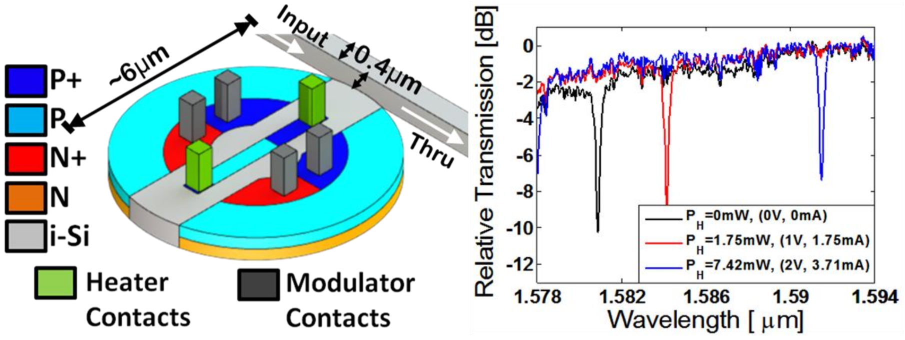

Figure 1 – 3D sketch of the microdisk modulator showing size, doping and contacts (left), and measured DC spectral response of the integrated heater inside the microdisk modulator with an applied bias voltage to heater pins (right).

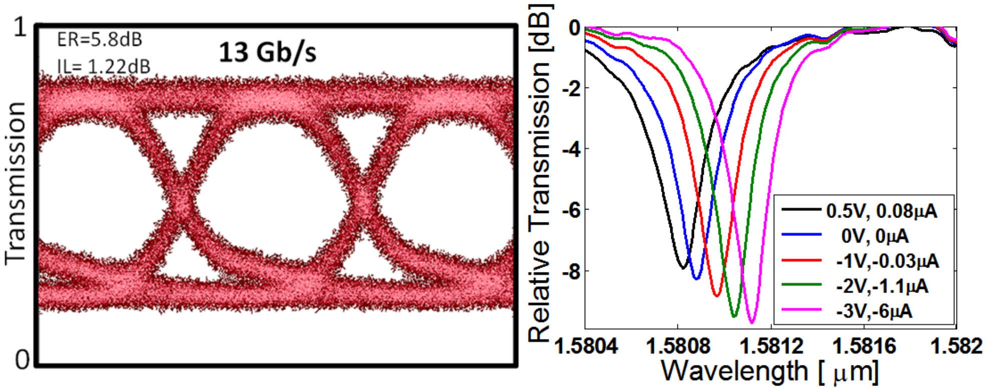

Figure 2 – High-Speed Optical Eye Diagrams at a data rate of 13-Gb/s with an ac-coupled 1.5Vpp drive and 2V applied across heater contacts. The extinction ratio is 5.8dB and insertion loss is 1.22dB (left). Measured spectral response of the microdisk modulator with applied DC bias voltage to modulator pins from -3V to 0.5V (right).

using the same p and $p+$ type doping levels to minimize the number of necessary mask layers and fabrication cost (Fig. 1, left). This design allows, for the first time, almost full peripheral junction area coverage (~90%) of the vertical junction around the edge of the microdisk without compromising high speed operation. The polarity of the heater bias is chosen to minimize electrical crosstalk with the diode. The silicon waveguide thickness is 220nm and the bus waveguide width is 400nm.

Thermal tuning of the microdisk 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 DC voltage for 0V, 1V and 2V, as shown in Fig. 1, right. Wavelength shifts of 3 nm (~360 GHz) and 10 nm (~1.2 THz) are observed at heater power consumptions of 1.75 mW (1V) and 7.42 mW (2V). These values correspond to a heater efficiency of 4.9 μW/GHz and 6.2 μW/GHz, respectively.

The microdisk modulator is characterized with a DC bias voltage applied across modulator pins from -3V to 0.5V as shown in Fig. 2, right. For a probe wavelength ~1581nm, a DC extinction ratio of 6dB is measured between -1V and 0.5V bias. The DC insertion loss is 1.2dB. In order to demonstrate high speed performance, the microdisk modulator is initially tuned to a frequency offset of 1.2 THz by applying 2V to the heater. The modulator contacts are driven electrically with a terminated probe and an AC coupled 1.5 V_{pp} 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 diagram is obtained by a digital sampling oscilloscope at a data rate of 13-Gb/s, as illustrated in Fig. 2, left. The dynamic extinction ratio is 5.8dB and insertion loss of 1.22dB, in good agreement with the DC characterization (Fig. 2, right). Modulator capacitance is calculated to be 20fF based on Sentaurus simulations and the energy of the modulator is estimated to be ~11fJ/bit for a voltage swing of 1.5Vpp similar to [2]. The modulator is PRBS source limited to 13Gb/s and experiments to achieve higher data rate operation are ongoing.

If the proposed microdisk modulator has a frequency offset of ~100GHz due to fabrication variation and is on a processor chip with $\pm 10^{0}$C temperature variation, the required heater power for compensation is ~1.5mW. Combined with an electro-optic modulation power of 0.22mW at a data rate of 20Gb/s, the microdisk modulator will have a realistic energy performance of 85 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 48fJ/bits at a data rate of 20Gb/s.

3. Conclusions

A silicon heater is integrated into a vertical junction silicon microdisk modulator without affecting modulator performance or size. Low-power modulation (11fJ/bit) at a data rate of 13-Gb/s, a 5.8-dB extinction ratio, a 1.22-dB insertion loss, a record-low thermal tuning (4.9-μW/GHz) of a high-speed modulator is achieved. A record low total energy of 48fJ/bit is predicted at a data rate of 20Gb/s for a frequency offset of ~100GHz and $\pm 10^{0}$C temperature variation.

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4. References

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