Integrated CMOS Compatible Low Power 10Gbps Silicon Photonic Heater-Modulator

William A. Zortman[1,2], Anthony L. Lentine[1], Douglas C. Trotter[1] and Michael R. Watts[1,3]

Applied Photonic Microsystems, Sandia National Laboratories, Albuquerque, NM 87185, USA[1]
Center for High Technology Materials, University of New Mexico, Albuquerque, NM 87185, USA[2]
Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA[3]
wzortm@sandia.gov

Abstract: We quantify bit-error performance of a heater-modulator that uses CMOS compatible heater and modulator voltages, occupies 50μm^2, is compatible with differential signaling and shows consistent extinction ratio under tuning while consuming only 7μW /GHz.

OCIS codes: (130.3120) Integrated Optical Devices; (130.4110) Modulators; (230.7370) Resonators

1. Introduction

For exascale computing massive reduction in the energy used to transport data to and from memory and between processors along with a commensurate increase in the amount of data per fiber will enable machines that are manageable in power consumption and number of fiber interconnections. Solutions are being developed to accomplish this including low power vertical cavity surface emitting lasers (VCSELs), silicon-bonded edge emitting lasers and external modulation technology utilizing silicon photonics [1,2,3]. Silicon photonics offers wavelength division multiplexing (WDM) integrated into the chip stack, removes the laser heat source from the chip and is fully compatible with legacy silicon foundries. However, low power silicon photonics relies on resonators that are very sensitive to local temperature swings and heating must be included in the total external modulation energy. Intimately integrated heating elements provide the highest efficiency and fastest response time on the order of a microsecond [4,5]. Previous demonstrations on larger devices [6] show the great potential of heater-modulator integration but also exhibit a variation in extinction ratio with tuning and require up to 42μW/GHz. Additionally, we are not aware of bit error or power penalty quantification of any integrated heater-modulator in the literature.

Here we present a 2μm radius integrated heater-modulator that is uniquely compatible with CMOS potentials of less than 1V for both heating and modulation, has flat resonance depth across a wide tuning range, uses 7μW/GHz (1.14nm/mW), has an FSR that covers the entire C-Band and occupies only 50μm^2. This versatile device is compatible with differential signaling and we quantify the performance across a wide tuning range at 5Gbps and 10Gbps operation, favorably comparing the results to tuning using a thermo-electric cooler.

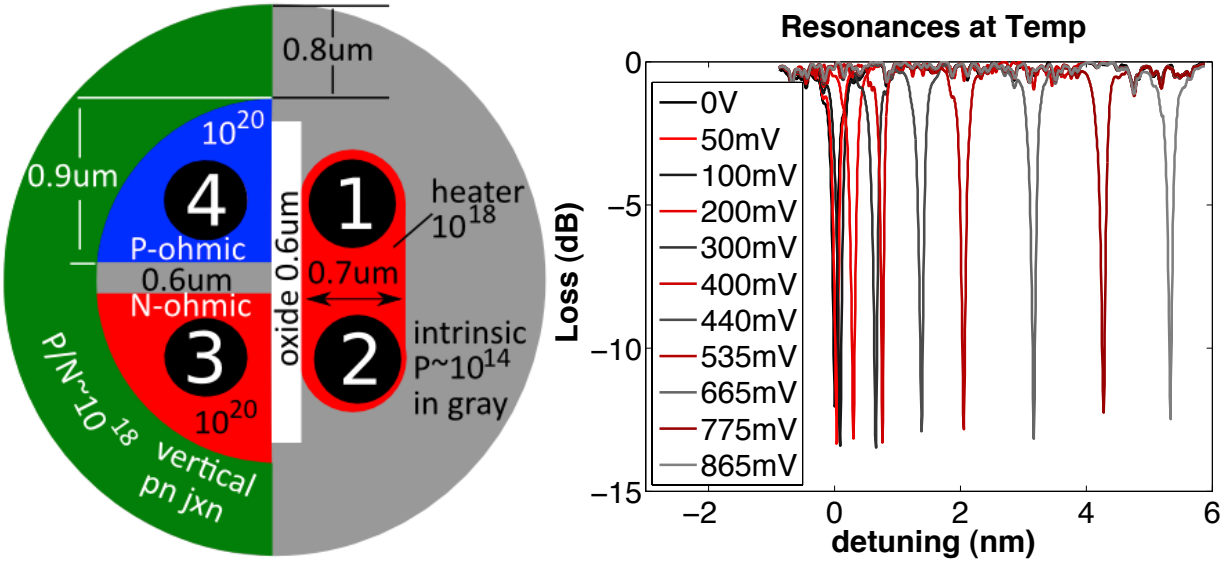

Figure 1(a) is a schematic of the 2μm integrated heater-modulator. The green vertical PN junction covers π radians of the device and is limited to one side of the device. An oxide electrical isolation strip separates the ohmic modulation contacts (#3 and #4) from the ohmic heater contacts (#1 and #2). The heater is a 10^{18} doped silicon strip between the contacts. (b) The resonances for 5nm of detuning are shown with consistent resonance depth, which varies by less than 1.5dB across the running range.

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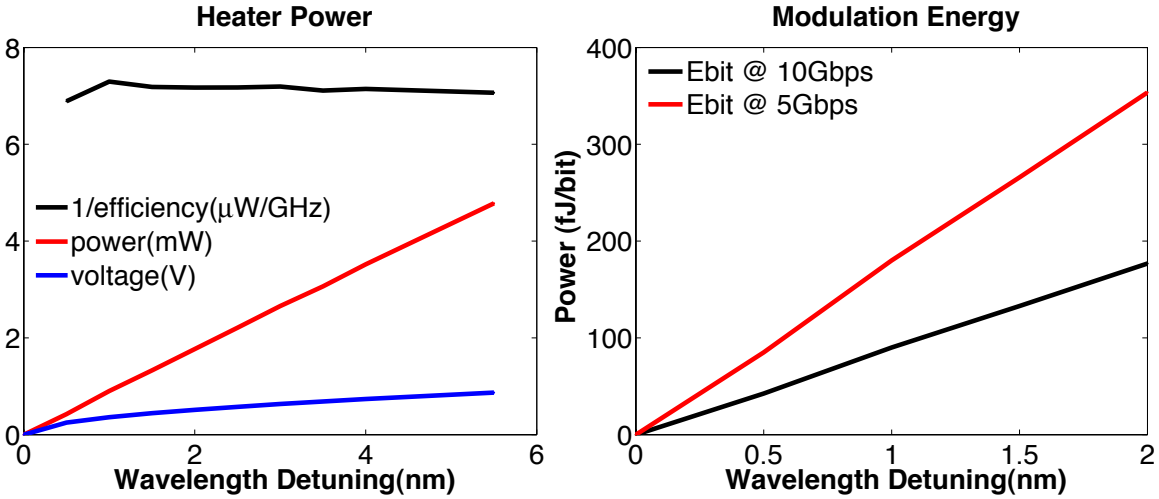

Figure 2(a) shows the power consumed by the heater-modulator and the voltages used to achieve the wavelength shift. The efficiency curve shows a stable 7 μW/GHz while the increase in power is seen to be linear across 5nm. The voltage used does not rise above 1V. Figure 2(b) shows the modulation energy per bit impact from the integrated heater.

2. Architecture

The device is based on the architecture and fab process shown in [7]. Fig. 1(a) shows a top down drawing of the device. This device is different because the π-radians of modulation electronics is moved to one side of the disk while the other half of the inner ohmic contact region is reserved for the heating element. The heater is a 200Ω resistor consisting of the ohmic contact regions joined together by a conductive stripe doped to $10^{18}/cm^3$ with phosphorus (n-type) implants. The drive signal line configuration and pad layout is designed to utilize differential signaling and therefore can operate with a CMOS V_{dd} well below 1V, consistent with future CMOS technology.

3. Characterization

The device heater is tested using single point DC probes. A DC voltage is applied and current measured using a Kiethley 5300 source-meter. The modulation performance is examined through the use of an Agilent 8164B tunable laser source (1550nm) and probing is done using GSGSG Cascade Microtech probes with 50Ω termination.

The resonances for 5nm of tuning are shown in Fig. 1(b). The resonance depths are all within 1.5dB of each other with a Q~10^4. This is an important outcome because while modulator temperature must remain constant, each modulator will be tuned to a channel against manufacturing and environmental variation. Variation in extinction ratio due to tuning would incur a built in variable power penalty and require another layer of compensation on the receive side to balance the system.

Fig. 2(a) demonstrates both the heater power (a) and the contribution of the heater operation to the modulation energy/bit (b). The black line in Fig. 1(a) shows that the heater consumes 7μW/GHz and that this is consistent across 6nm of tuning. The electrical potential across the heater, shown in blue, is less than 1V. Taking the power shown in red and dividing it by the bit rate yields the energy/bit; 5Gbps and 10Gbps operation are shown. Tuning over such a wide wavelength range is unlikely as has been analyzed in [8]. Using a conservative estimate for the required trimming for manufacturing tolerance and tuning for thermal variation, an estimate for realistic operation is calculated to be 180fJ/bit using 535mV which is compatible even with projected low power CMOS applications. This assumes 80GHz of manufacturing variation and a total environmental temperature swing of 40°C where ~10GHz/°C is used for the shift in the resonance for wavelengths around 1550nm in silicon. Note that if these variations are random within a bound and Gaussian, as is expected, then on average only half of either variation will be compensated for.

High speed testing was done by grounding the N-type modulator ohmic contact (#3 in Fig. 1(a)) and driving the P-type modulator contact (#4) into reverse bias with a pseudo-random bit sequence (PRBS) of 2^{31}-1. The heater contact closest to the modulator N-type (#2) is also grounded guaranteeing reverse bias from #4 to the rest of the device and no current between #2 and #3. The PRBS signal amplitude driven into contact #4 is 1V. The device can also be run differentially with consistent extinction, although this requires the total signal amplitude to increase progressively to 1.3V at 5nm (60μV/nm) of tuning to compensate for heater parasitics to the modulation contacts.

Modulation was done with the heater running at progressively higher power resulting in the tuning described in Fig. 1(b). The modulation results are shown for 10Gbps and 5Gbps operation using PRBS 2^{31}-1 in Fig. 3. The 10Gbps measured bit error rate was at 10^{-9} and $<10^{-12}$ for 2^{31}-1 and 2^{15}-1 PRBS patterns respectively. The modulator running at 5Gbps with PRBS 2^{31}-1 achieved a BER $<10^{-12}$. We believe that the reason for the higher BER

at 10Gbps results from a bandwidth limitation, which is clear from the peaked eye diagram. Resistance flowing from the modulation diode back to the ohmic contacts (#3 and #4) is high because of the long path along the upper and lower layers of the diode in this modified heater design. This slows carrier extraction and injection. This issue can be resolved with straightforward redesign such as radially connecting twice the number of contacts.

Finally, we confirmed the consistency of the device performance across temperatures by measuring the power penalties for both the device heated by the integrated heater and the device heated by a thermo-electric cooler (TEC). As is consistent with the eye diagrams and the repeatable resonance depth we measured 0-2dB power penalties referenced to the quiescent state for the tuning voltages in Fig. 1(b) using both TEC and integrated heater.

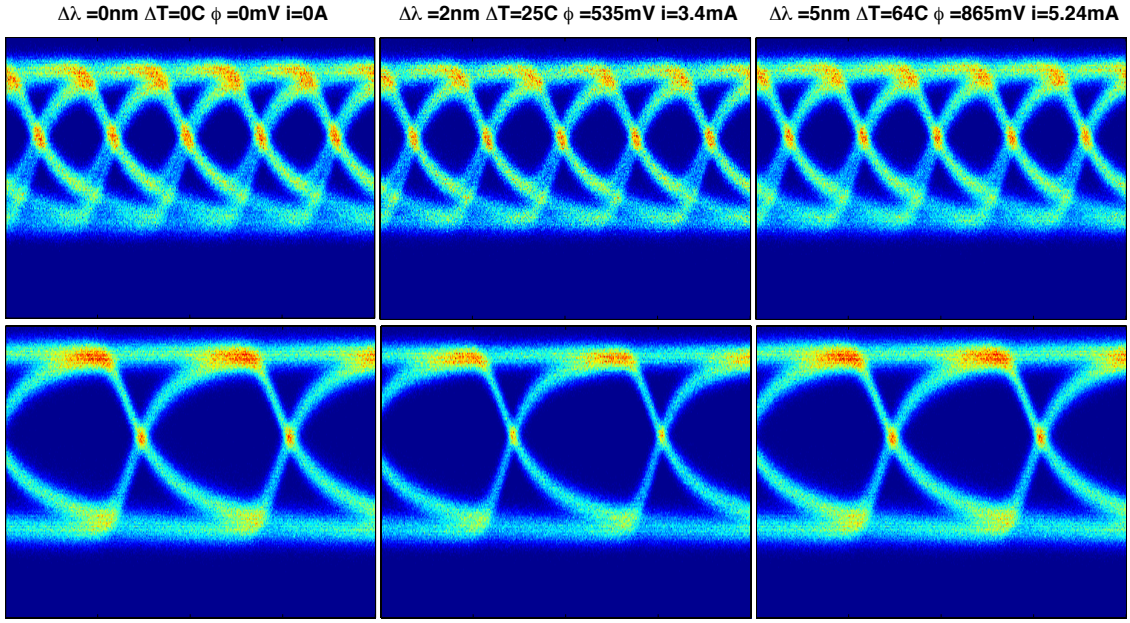

Figure 3 shows eye diagrams for 5Gbps and 10Gbps operation. The signal is a 2^{31}-1 PRBS. In the figure the detuning in nm, temperature change in ^{o}C, applied heater potential in Volts and current in mA is given at the top of each column. Applied modulation voltages for each of the above figures are 1V, 1.12V and 1.3V from left to right. Extinction ratios are 3dB for 10Gbps and 4dB for 5Gbps.

3. Conclusions

We demonstrated a 4μm silicon photonic vertical junction integrated heater modulator functioning at 10Gbps that includes quantification of heating on BER and the energy/bit. Among the unique characteristics of this technology are flat resonance depth, low tuning power penalty, smallest footprint (50μm^2) and heater voltages compatible with future CMOS technology. This results in record efficiency (7μW /GHz) in a heater for the purpose of wavelength recovery in a narrow band resonant 10Gbps modulator.

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