Low-Voltage 60Gb/s NRZ and 100Gb/s PAM4 O-band Silicon Ring Modulator

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***Abstract*— We demonstrate 60Gb/s NRZ and 100Gb/s PAM4 data modulation with an O-band silicon ring modulator with only 1.6V$_{pp}$ and 2.5V$_{pp}$ drive swing respectively, leveraging the large modulation efficiency (55pm/V) and electro-optical bandwidth (35GHz) realized by an optimized vertical PN diode phase shifter design.**

Keywords—optical interconnect, silicon photonics, ring modulator, PAM4, NRZ

I. Introduction

Exponentially growing demand for I/O bandwidth in datacenter switches and high-performance computing nodes drives the need for Tb/s-scale inter-rack and intra-rack interconnects and silicon photonics based optical interconnects are one of the most promising candidates to meet such demands [1]. 100Gb/s four-level pulse amplitude modulation (PAM4) is a preferred modulation format for inter-rack optical links [2], while 50Gb/s NRZ may be preferred for future very-short-reach chip-to-chip optical links. Among the different types of modulators such as Mach-Zehnder modulators, electro-absorption modulators and ring modulators (RM), the RM is of special interest as it can provide very large electro-optical bandwidth with small size and low dynamic power consumption, low driver complexity, and potential for dense wavelength-division multiplexing (WDM) transmitter functionality owing to its inherent wavelength selectivity [4]. In this paper, we report a demonstration of a 60Gb/s NRZ and 100Gb/s PAM4 Si RM with optimized vertical PN phase shifter design.

II. Device Design

Figure 1(a) shows a top-view schematic of the depletion type Si RM used for our demonstration, which is manufactured on 300mm SOI wafers in an R&D CMOS fab [4]. It has 5µm radius and a vertical PN (VPN) diode embedded in 330-nm×220-nm Si rib waveguide on a 2µm thick buried oxide (BOX) layer, as depicted in Fig. 1(b). The overlap between the optical mode and the depletion region is designed to maximize with VPN junction structure to increase the modulation efficiency. The electrically isolated top N-doped region helps to reduce the loss of the waveguide which enables a resonator quality factor Q ~5000 despite the high doping

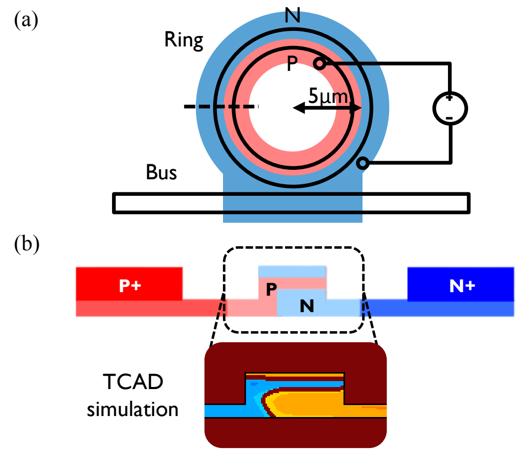

Fig. 1. (a) Top-view schematic of the Si RM (b) cross-section view for phase shifter

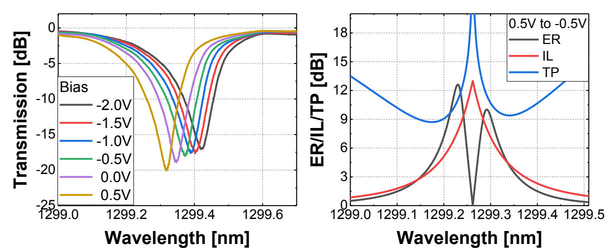

Fig. 2. (a) Measured transmission spectra at different bias voltage (b) Transmission penalty, extinction ratio and insertion loss

level. To realize this complex junction design, we optimized implant process conditions with Synopsys TCAD and Lumerical MODE Solutions simulations. By implementing the RM thermo-optic control with an integrated tungsten heater on top of the waveguide, the PN phase shifter can occupy 100% of the ring circumference, thus maximizing modulation efficiency. To lower the series resistance from the 60nm thick slab region of the rib waveguide for high-speed operation, the slab region is doped with a 5 times higher concentration than in the center of the rib waveguide.

III. Measurement Result

A. DC characteristics

Figure 2(a) shows the transmission spectra of the fabricated Si RM with different bias voltages. The

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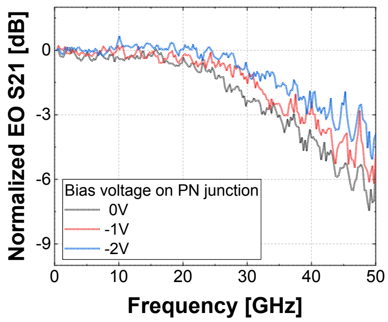

Fig. 3. Electro-optical S_{21} response of Si RM

measured quality factor Q is ~4800 and the free-spectral range is 12.8nm, which enables future implementation of an 8 channel WDM transmitter. The modulation efficiency is 55pm/V between -0.5V to 0.5V applied drive voltage, which is equivalent with a $V_{\pi}L$ value of the phase shifter of 0.37V·cm. A comparison of the extinction ratio (ER) and insertion loss (IL) versus wavelength offset with voltage swing from 0.5V to -0.5V is shown in Fig 2(b). We used transmission penalty $TP(dB) = 10\log(2P_{IN}/(P_1 - P_0))$ as a figure of merit , where P_1 and P_0 are the power transmitted during a 1-bit, and during a 0-bit, respectively, and P_{IN} is the input optical power. The minimum TP from -0.5V to 0.5V is 8.7dB and ER and IL at minimum TP wavelength location are 4.4dB and 3.8 dB, respectively. This low-drive voltage requirement enables the use of low-power drivers directly implemented in advanced CMOS host-ICs [5].

B. *S-parameter measurement*

Figure 3 shows the electro-optical S_{21} frequency response of the Si RM which is characterized using a light component analyzer (LCA) at 3 different bias voltages. The responses of the cables and probe are de-embedded through calibration. Reported responses are measured at the detuning point which gives maximum electro-optical responses and corresponds to the minimum TP or maximum OMA operating point. The 3dB bandwidth of the electro-optical responses are 35GHz, 40GHz, and 42GHz at 0V, -1V, and -2V, respectively.

C. *Large-signal measurement*

Figure 4 illustrates NRZ and PAM4 data transmission. The eye diagrams in green color are the input electrical signals generated with a 65GSa/s arbitary waveform generator (AWG) and a 67GHz amplifier and blue are the output optical signals measured with a 40GHz optical reciever after SOA and band-pass filter. At 60Gb/s NRZ data rate, 1.6V_{pp} voltage swing, and optimized operating point to minimize TP or maximize OMA, Si RM shows 2.59dB extinction ratio (ER), 4.05 SNR, and 1.36ps RMS jitter. At 100Gb/s PAM4 data rate, 2.5V_{pp} voltage swing, and an optimized operating wavelength, the ER between the outer PAM-4 levels is 4.5dB.

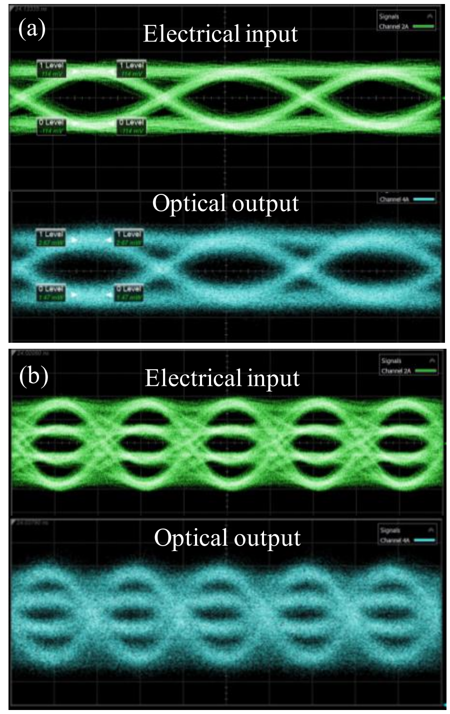

Fig. 4. (a) 60Gbps NRZ (b) 100Gbps PAM4 electrical (green) and optical (blue) eyes

IV. Conclusion

We demonstrate 60Gb/s NRZ data modulation with 1.6V_{pp} voltage swing and 100 Gb/s PAM4 data transmission 2.5V_{pp} with an O-band silicon depletion type ring modulator with an optimized design of the vertical PN phase shifter. With 12.8nm free-spectral range, these results show the possibility for future 8×100Gb/s WDM demonstrations.

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