Segmented Silicon Photonic Modulator with a 67-GHz Bandwidth for High-Speed Signaling

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Abstract: We experimentally demonstrate an all-silicon segmented modulator with an electro-optic bandwidth beyond 67 GHz and a V_π of 5V. Transmission of 120-Gbaud 8-ASK (336.4 Gb/s net) is achieved.

1. Introduction

The ever-increasing demand for bandwidth has spurred the continuous evolution of high-speed optical transceivers. Silicon photonics technology will play an essential role in scaling the transmission capacity of next-generation fiber-optic systems thanks to its remarkable advantages such as low-cost mass production, reduction in footprint, CMOS compatibility, and low power consumption. [1, 2]. However, due to the relatively low efficiency and high loss of silicon phase shifters, the bandwidth of an integrated silicon photonic transceiver is usually limited by the modulators. Various modulator structures such as traveling-wave Mach-Zehnder modulators (TW-MZMs), micro-ring modulators (MRMs), and electro-absorption modulators (EAMs) have been investigated on the silicon-on-insulator (SOI) platform [3–5]. Silicon TW-MZMs with a 60-GHz bandwidth [3] and bit rates of up to 240 Gb/s [6] were reported for pulse amplitude modulation (PAM-4). For coherent transmission, we recently demonstrated 120-Gbaud quadrature amplitude modulation (QAM) for 600 Gb/s (480 Gb/s net) per polarization [7]. For MRMs, a bandwidth of 67-GHz with 200 Gb/s (187 Gb/s net) PAM-4 [4] was recently reported, which used optical peaking to achieve the high bandwidth. A similar bandwidth was reported in [5] for silicon-germanium (SiGe) electro-absorption modulators (EAM) with 200 Gb/s (169 Gb/s net) in amplitude shift keying (ASK). Nevertheless, MZMs are still the first option for broadband coherent transceivers. The bandwidth of silicon MZMs need to be further enhanced without increasing V_π to support higher-order modulation formats (e.g., 64-QAM) beyond 100 Gbaud.

Segmenting a TW-MZM can effectively improve its bandwidth while maintaining or reducing V_π. In our previous work, we achieved a segmented silicon MZM with a weighted binary coding configuration, however, its overall bandwidth is limited by the longest segment (43 GHz) [7]. In this work, we demonstrate an improved segmented TW-MZM design with three identical segments, showing a bandwidth greater than 67 GHz. Using this device, we achieved 120 GBaud 8-ASK for 360 Gb/s per polarization (336.4 Gb/s net). To the best of our knowledge, this is the highest bandwidth ever reported for a silicon MZM.

2. Device Design and Characterization

The schematic of our modulator is shown in Fig. 1. It consists of three segments with an identical length of 2 mm, two of which are located in a row and the last one is rotated by 90 degree to ease RF probing. Each segment is

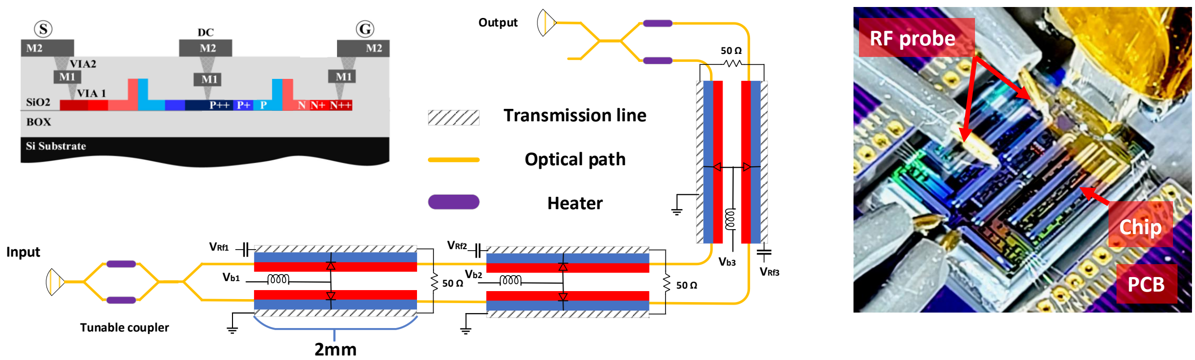

Fig. 1. Left: Schematic of the designed segmented silicon modulator (inset: cross-section of the phase shifter). Right: Photo of the chip under test.

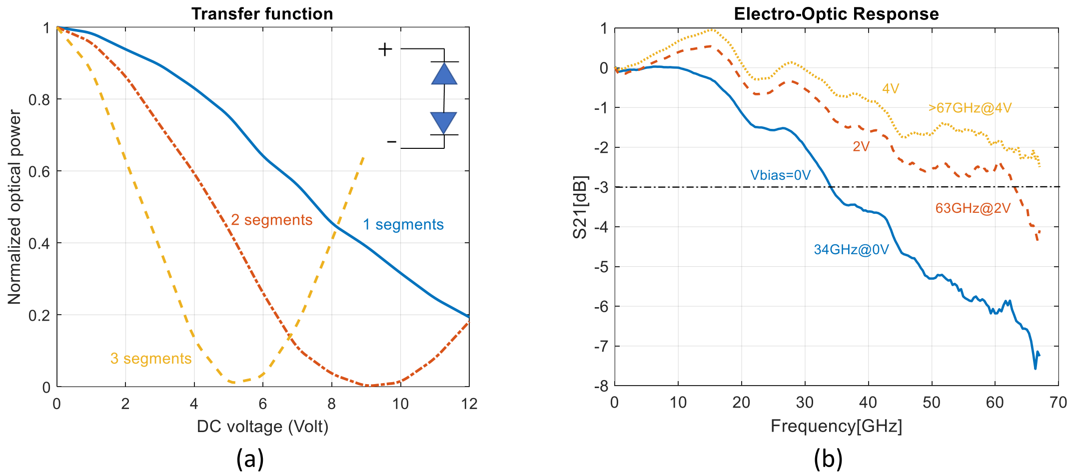

Fig. 2. a) Normalized optical power transmission when one, two, and three segments are driven; b) E-O frequency response of one of the segments at 0, 2 and 4V reverse bias.

driven by a TW electrode designed following the procedure given in [8]. The phase shifters use laterally doped PN-junctions with three levels of doping in a 220-nm-high silicon rib waveguide. The intermediate doping level helps to have a lower junction resistance resulting in a higher BW without a significant impact on the optical loss. A series push-pull driving configuration is used to reduce loaded capacitance leading to a higher BW. A coplanar strip with an integrated 50-ohm termination is used as the TW electrodes. To increase the extinction ratio, a thermally tunable coupler is implemented at the input of the MZM to balance the power in each arm. The device was fabricated using a 200-mm-wafer silicon photonics foundry process.

DC characterization of the phase shifters illustrates a $V_\pi L$ of about 3 V·cm, as shown in Fig. 2 a). The optical power transmission at the laser wavelength near 1548 nm as a function of the applied voltage was measured with one, two, and three segments, which shows clearly the reduction of V_π as the number of segments or the total phase shifter length increases, as expected. A V_π of 5V is measured when the 3 segments are driven simultaneously. The device has an optical loss of 23.5 dB including $\sim$ 15 dB fiber-to-chip coupling loss and $\sim$ 2.5 dB due to the long passive routing waveguide, which can be reduced through design optimization. Dividing the TW-MZM length into shorter segments improve BW while keeping the modulation efficiency and optical loss unchanged providing better BW/V_π performance. Figure 2 b) shows the frequency responses of one of the three segments at different bias voltages, which were measured using a vector network analyzer (VAN - Keysight N5227A) and 70-GHz photodetector. We can see that the 3-dB bandwidth is well beyond 67 GHz at the bias of 4 V (limited by the VNA). Other segments show similar performance. Control of the delay between different segments is critical for high-speed operation of a segmented modulator. We solve this issue with the digital delay in digital to analog (DAC) to compensate for the delay caused in the optical path.

3. Transmission Experiment and Results

We perform back-to-back transmission with our segmented modulator. Figure 3 shows the experimental setup. We transmit a 120-GBaud amplitude-shift keying (ASK) signal with coherent detection. Three digital to analog converters (DACs) are used each providing a signal to one of the three segments at 120 GSa/s. They produce identical signals but with time delays to assure synchronous driving at the modulator. We generate an order-19 pseudo-random binary sequence (PRBS) offline and map them to discrete levels $(\pm 1, \pm 3, \ldots)$. Pulses are shaped using a raised-cosine filter with a 0.01 roll-off factor. We use a digital finite impulse response filter to minimize mean square error (MMSE) for equalization of the DACs' response. Each DAC has a phase shifter for fine RF delay adjustment. The chip is tested using 67 GHz RF probes with 60-GHz amplifiers.

An external cavity laser (ECL) at 1548 nm with 100 kHz linewidth is boosted to 27 dBm by a high power erbium doped fiber amplifier (EDFA). We couple the light to the silicon chip via a fiber array. A two-stage EDFA at the chip output compensates for optical losses. An optical filter (Finisar Waveshaper) is placed between the two-stage EDFAs to suppress out-of-band amplified spontaneous emission noise; it also provides optical equalization for the modulator frequency response [9]. When applying a 6 dB depth pre-emphasis filter on the Waveshaper, we achieve a maximum optical signal-to-noise ratio (OSNR) of 36-39 dB for ASK modulation.

Our coherent receiver consists of an optical hybrid, a 15 dBm local oscillator (LO) and a 70 GHz balanced photodetector (BPD). We control received optical power with a variable optical attenuator (VOA). The electrical signal is captured by a 63 GHz real-time oscilloscope (RTO) at 160 GSa/s. Receiver DSP includes a 10$^{\text{th}}$ order, super Gaussian, low pass digital filter, followed by resampling and a T/2-spaced 2×2 multi-modulus algorithm

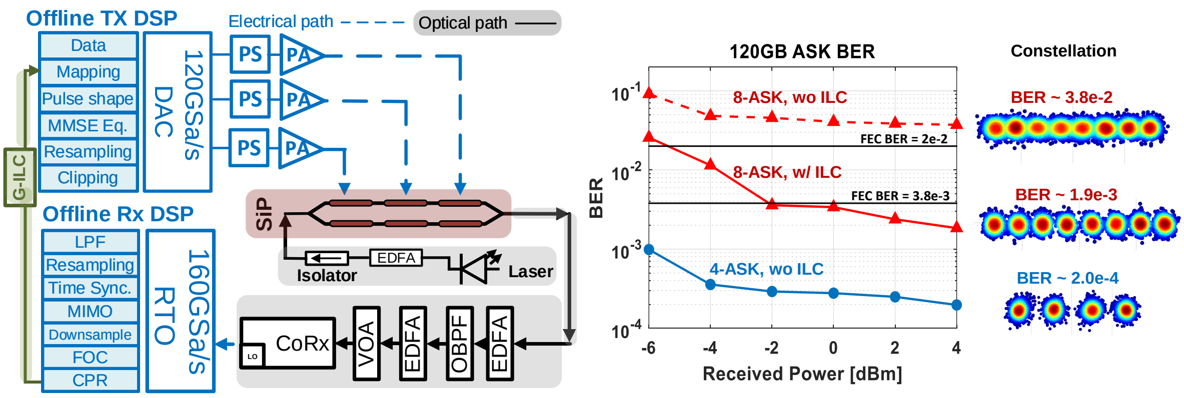

Fig. 3. Left: Experimental setup. Right: BER versus received optical power and recovered constellation of ASK.

(MIMO). We downsample the signal to one sample per symbol for frequency offset compensation (FOC) and a blind search carrier phase recovery (CPR). For 8-ASK, we utilize iterative learning control techniques to mitigate significant pattern-related distortion [10].

Bit-error-rate (BER) results and recovered constellations for ASK are shown in Fig. 3. We sweep received optical power and estimate BER from at minimum of 2e5 symbols. For 4-ASK, BER always stays below the 7% hard-decision forward error correction (FEC) of 3.8e-3, even for received power as low as -6 dBm. The best BER for 4-ASK is about 2e-4 at 4 dBm power. For 8-ASK, the BER remains above the 20% soft-decision FEC threshold (BER=2e-2) with conventional pre-compensation and decreases dramatically from 3.8e-2 to 1.9e-3 at 4 dBm received power, more than one order of magnitude and well below the 20% FEC threshold. This indicates sensitivity to nonlinear and pattern dependent distortion for 8-ASK transmission. This modulator, if used in an IQ configuration, should be capable of supporting 672.9 Gbps/pol net rate for 64-QAM coherent optical transmission.

4. Conclusion

We have demonstrated an all-silicon segmented modulator with a bandwidth greater than 67 GHz and successfully achieved 120-GBaud ASK-4 and ASK-8 for up to 360 Gb/s (336.4 Gbps net) on a single polarization. The transmission performance is limited by the bandwidth of the DAC and RTO.

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