High-Speed-Operation of Compact All-Silicon Segmented Mach-Zehnder Modulator Integrated with Passive RC Equalizer for Optical DAC Transmitter

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Abstract: We experimentally demonstrated 70Gbaud PAM4 and 90Gbaud NRZ operations of all-silicon segmented modulator for optical DAC transmitter. Monolithic integration of MIM capacitor enabled broad EO bandwidth of 43.9GHz and small footprint of 300×600μm^2.
OCIS Codes: (250.4110) Modulators, (250.5300) Photonic integrated circuits, (230.3120) Integrated optics devices

1. Introduction

The exponential growth of the data traffic in optical network demands advanced optical modules with large capacity of 400 Gbps and beyond. For both IM-DD and coherent transmissions, the large transmission capacity and a low power consumption should be necessary in compact transceivers such as QSFP-DD or OSFP pluggable modules. Silicon (Si) photonics is one of the promising platform for these applications, because it can realize a highly dense photonic integrated circuit having a good temperature immunity due to high index contrast in Si/SiO$_2$ waveguide. However, its main challenge remains in higher baud rate operation of an optical modulator. Among Si photonics modulators, high speed modulations of 100 Gbaud or beyond have been demonstrated in organic hybrid modulators, plasmonic modulators, and all-Si traveling wave (TW) modulators [1-3]. These modulators were mostly driven with an electrical analog-to-digital converter (DAC) and a large-swing linear driver. However, as the symbol rate of the system increases, limited analog bandwidth of DAC and a large power consumption of these electronics become critical.

Optical domain DAC (oDAC) technique is one of the promising solutions to generate multi-level optical signals without a high-speed electrical DAC. The oDAC transmitter synthesizes an analog signal in an optical domain by using a combination of a segmented electrode modulator and a binary driven driver array. This architecture has demonstrated its very low power consumption in multi-level operations [4-6], especially with efficient lumped-electrode optical phase shifters (PSs). At present, although high-speed oDAC operation is limited to PAM4 or 16QAM modulation format, oDAC operations in higher-order modulations can be realized by increasing the number of segments. In that case, precise designs (size and layout) of the segments become important in order to maintain both a compact footprint and a dense connection to the driving electronics. From this viewpoint, all-Si PS is suitable for realizing the oDAC transmitter due to its high flexibility in a waveguide layout and a compatibility with dense packaging technology based on a flipchip bonding.

We have so far developed all-Si segmented Mach-Zehnder Modulators (MZM) for multi-level operation. We investigated a performance optimization technique of all-Si forward-biased PIN-PS by introducing a passive RC equalizer [7]. Then, we demonstrated a very-low-power operation (1.59 mW/Gbps) of a 56-Gbps PAM4 oDAC transmitter by combining a CMOS inverter driver and a segmented MZM [6]. We also reported a higher-speed 70 Gbaud-NRZ operation [8]. In this paper, we experimentally investigated the feasibility of higher-speed operation of an all-Si segmented MZM aiming at an oDAC transmitter. We achieved a wider 3dB bandwidth of 43.9 GHz by integrating an extremely compact RC equalizer composed of metal-insulator-metal (MIM) capacitor and a Si register. Then we demonstrated a 90-Gbaud NRZ operation and a 70-Gbaud PAM4 oDAC operation by multi-segments configuration. The segmented MZM was as small as the size of 300×600 μm^2.

2. Device structure and experimental setup

In general, operation bandwidth of a lumped Si PS is limited by a capacitance and a series resistance of the Si PS. On the other hand, a Si PS with a large capacitance is advantageous for achieving higher modulation efficiency. Therefore, there is a trade-off between operation bandwidth and modulation efficiency. By using a Si forward-biased PIN-PS integrated with a passive RC equalizer (PIN-RC), an optimization of the PS performance considering the above trade-off can be easily done [7]. Figure 1 (a) and (b) show a cross sectional view and an equivalent circuit of a PIN-RC modulator. The passive RC equalizer is composed of a MIM capacitor and an n-doped Si resister. We adopted a longer PIN-PS length of 500 μm compared to our previous report [8] to reduce the series resistance, but it imposed a large capacitance of 26.5 pF. To achieve the 3dB bandwidth exceeding 40 GHz, we set capacitance C_E and resistance R_E of the RC equalizer to 71.1 fF and 23.9 kΩ for demonstration in a typical 50Ω system (R_{drv}= 50 Ω). In case a low-impedance CMOS inverter driver is integrated with the segmented MZM [6], the C_E (modulation efficiency) can be enhanced while maintaining the same bandwidth.

We fabricated the PIN-RC modulators by using a standard Si photonics process at a commercial CMOS foundry. Top view of the modulators was shown in Fig. 2 (a). The device consisted of four PIN-PSs (LSB1, LSB2, MSB1, and MSB2) for differential driving and multiplexing NRZ signals into a PAM4 signal in optical domain. The passive RC equalizer had a very compact footprint of 100×30 μm^2 and can be placed near PIN-PSs easily. Thus, we could realize dense segmented MZM layout employing U-shaped-PSs and eight 150-μm-pitch pads applicable also for flipchip bonding. Total footprint of the modulator was only 300×600 μm^2. Figure 2 (b) shows the measurement setup of DC characteristics, electro-optic (EO) response, and large signal operation. In the large signal measurement, we used an arbitrary waveform generator (AWG M8196A), RF phase shifters, four pairs of RF phase matching cables, RF amplifiers (SHF L810A for MSB segments, and SHF 807A for LSB segments), bias-tees, and RF probes in a push-pull manner. The total frequency response of these RF components except for RF probes was compensated by the AWG. The modulator was driven with a pseudorandom binary sequence NRZ signal of 2^{11}-1 generated from the AWG with a raised cosine filter of α = 0.1~0.5. The skew of the RF path between MSB and LSB was adjusted manually by the RF phase shifter. The phase bias of the segment MZM was set to the quadrature point. In experiment, we fixed the bias voltage at 6 V.

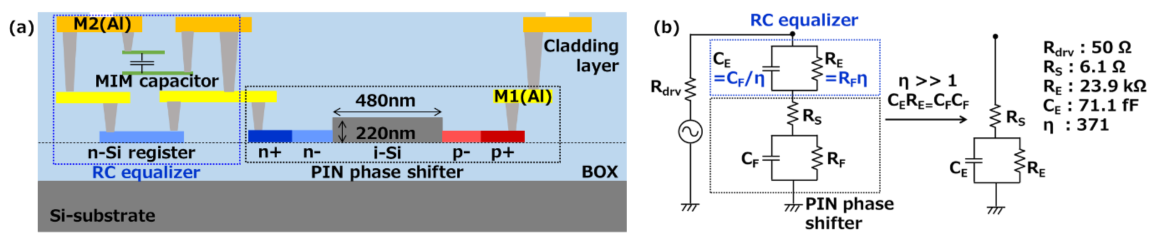

Fig. 1. (a)Cross-sectional view of PIN phase shifter integrated with passive RC equalizer (PIN-RC), (b) equivalent circuit model of PIN-RC.

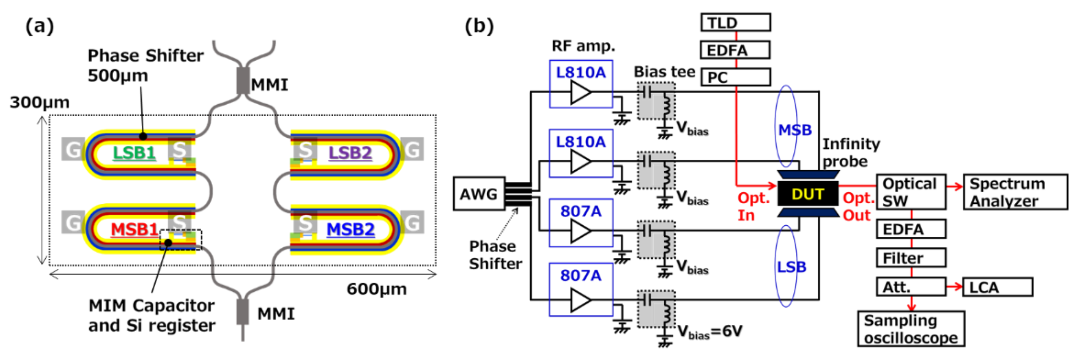

Fig. 2. (a) Top view of segmented MZM and (b) block diagram of experimental setup.

3. Experiment results of silicon modulator

At first, we confirmed DC characteristics of the PIN-PSs in C-band at room temperature. The I–V characteristics exhibited a forward-biased diode response with a resistance R_E of ~22 kΩ on each segment. A DC modulation efficiency $V\pi L$ was derived to be 2 Vcm from the measured optical phase shift at a forward bias voltage of 6 V (Fig. 3(a)). Figure 3(b) shows the measured small-signal EO responses of the fabricated modulator with each segment at a forward bias of 6 V. The EO responses were normalized in the low frequency range. For all segments, broad 3 dB EO bandwidths of 42.6~43.9 GHz were obtained because of the optimized RC equalizer setting. As can be seen in Fig. 3 (a) and (b), all segments exhibited almost the same DC and RF characteristics. It proves that the fabricated RC equalizer has a good process uniformity enough for the desirable operation of the oDAC transmitter.

In the high speed large signal measurement, the modulated signal light was amplified by an EDFA and recorded by a sampling oscilloscope without any receiver equalization. At first, we measured high speed operation with NRZ signal by driving only MSB segments. The input electrical and output optical waveforms for 70~90 Gbaud NRZ signals are shown in Fig. 3 (c). The clear optical eye opening of each data rate is confirmed with the extinction ratio (ER) of >1.0 dB at 70 ~ 90 Gbaud. For each modulation speed, we observed that the optical waveforms were similar to the input electrical waveforms of the drive signals. It indicates that the EO bandwidth of the modulator was large enough for these modulation signals. Figure 3 (d) shows the output optical waveform for 60 and 70 Gbaud PAM4 operations by multiplexing two uncorrelated electrical NRZ signals by oDAC operation of the segmented MZM. In the case of PAM4 measurement, the amplitude of input electrical signals into LSB segments was adjusted to the half of that of MSB segments to achieve the equally spaced four modulation levels. Thanks to the broadband and uniform characteristics of each segment, the segmented MZM exhibited a good oDAC waveforms with clear four-level separations. The outer ER of PAM4 optical signals were measured to be 3.7 dB at 60 Gbaud and 2.5 dB at 70 Gbaud. As for our PIN-RC device, these ER were mainly determined by output impedance of the driver (50Ω). In case of combining a low-impedance CMOS driver, we estimate that VπL can be significantly improved to 0.4 Vcm, leading to a larger ER operation even with a lower drive voltage swing. In such case, the phase swing between MSB and LSB can be weighted by the number of segments without adjusting the amplitude of electrical signal.

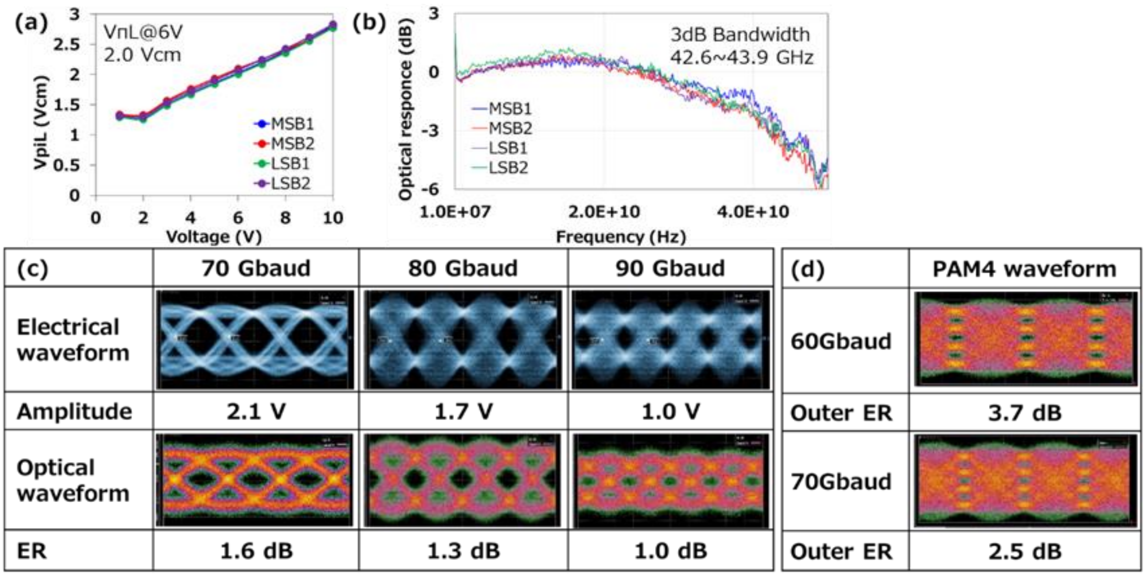

Fig. 3. (a,b) Modulation efficiency (VπL) dependence on bias voltage (a) and measured EO responses (b) of each segment. (c) Electrical and optical waveform with 70~90 Gbaud NRZ signals by using MSB segments. (d) Optical waveform with 60~70 Gbaud PAM4 oDAC operation.

4. Summary

We demonstrated broadband operations of the all-Si segmented MZM equipped with PIN-RC PSs. The equalizer consisted of a MIM capacitor and a simple n-doped Si register that were easily fabricated by the standard foundry process. The EO bandwidth were measured to be ~43.9 GHz in the 50 Ω system. With this wide and uniform bandwidth characteristics, we successfully demonstrated the 90-Gbaud NRZ operation. We also achieved the 70-Gbaud PAM4 oDAC operation by using the segmented MZM with a compact footprint of 300×600 μm^2. The fabricated PIN-RC modulator shows significantly suitable performance to function as a high-speed oDAC transmitter its due to the broad EO bandwidth, compactness, and the uniform characteristics.

References

[1] H. Zwickel, et al., “Silicon –organic hybrid (SOH) modulators for intensity-modulation / direct-detection links with line rates of up to 120Gbit/s,” Opt. Express, vol. 25, no. 20, pp. 23784-23800, Oct. 2017
[2] U. Koch, et al., “Monolithic high-speed transmitter enabled by BiCMOS-plasmonic platform,” Proc. ECOC2019, paper PD.1.4
[3] M. Jacques, et al., "200Gbit/s Net Rate Transmission over 2 km with a Silicon Photonic Segmented MZM," Proc. ECOC2019, paper PD.1.6
[4] M. Webster, et al., "Low-Power MOS-Capacitor Based Silicon Photonic Modulators and CMOS Drivers," Proc. OFC2015, paper W4H.3
[5] J. Lambrecht, et al., "Low-Power (1.5 pJ/b) Silicon Integrated 106 Gb/s PAM-4 Optical Transmitter" J. Light Wave Technol., in press.
[6] S. Tanaka, et al., "Ultralow-Power (1.59 mW/Gbps), 56-Gbps PAM4 Operation of Si Photonic Transmitter Integrating Segmented PIN Mach-Zehnder Modulator and 28-nm CMOS Driver," J. Light wave Technol., Vol. 36, No. 5, pp. 1275-1280 Mar. 2018
[7] T. Baba, et al., “25-Gb/s broadband silicon modulator with 0.31 Vcm VπL based on forward-biased PIN diodes embedded with passive equalizer,” Opt. Express, vol. 23, no. 26, pp. 32950-32960, Dec. 2015
[8] Y. Sobu, et al., "70 Gbaud Operation of All-Silicon Mach-Zehnder Modulator based on Forward-Biased PIN Diodes and Passive Equalizer," Proc. OECCPSC2019, paper MD2-2