High-Efficiency Silicon Mach-Zehnder Modulator with U-Shaped PN Junctions

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Abstract: We demonstrate a silicon Mach-Zehnder modulator with U-shaped PN junctions to achieve a high modulation efficiency of 0.34 V·cm at 0 V bias. On-off key modulation is obtained at 32 Gb/s data rate.

OCIS codes: (130.3120) Integrated optics devices, (130.4110) Modulators.

1. Introduction

Recently, intense research has been done on silicon modulators to achieve high modulation efficiency and high speed [1]. On-off keying (OOK) modulation is achieved with modulation speed up to 110 Gb/s in Mach-Zehnder modulators (MZMs) [2]. To drive the silicon modulators with CMOS microelectronic circuits, the modulation efficiency should be improved to allow a low drive voltage of less than 2 V. The modulation efficiency ($V_\pi \cdot L_\pi$) of silicon micro-ring modulators based on interleaved PN junctions is 1.24 V·cm when the reverse bias is 2 V, and OOK modulation at 25 Gb/s is realized using a peak-to-peak voltage (V_{pp}) of 2 V [3]. However, this kind of junction requires a very small window size for ion implantation. On the other hand, by optimizing the PN junction profile in the waveguide cross-section, the modulation efficiency can also be improved. The micro-ring modulator with an L-shape PN junction has a $V_\pi \cdot L_\pi$ of 0.52 V·cm at a reverse bias voltage of 2 V and 0.4 V·cm at the 0 V bias, allowing for 64 Gbit/s OOK modulation and 128 Gb/s PAM4 modulation [4]. U-shaped PN junction modulators have also been put forward as one of the candidates for high modulation efficiency [5, 6]. In [6], the U-shaped PN junction in the MZM has a $V_\pi \cdot L_\pi$ of 0.46 V·cm at -0.5 V and 0.94 V·cm at -2 V, achieving 24 Gb/s OOK modulation in the O-band. Michelson interferometer (MI) modulators could also have an improved $V_\pi \cdot L_\pi$ as light passes through the modulation arm twice [7, 8], but the modulation bandwidth is sacrificed.

In this work, we present a silicon Mach-Zehnder modulator with an optimized U-shaped PN junction to achieve both high modulation efficiency and high modulation speed in the C-band. The extracted $V_\pi \cdot L_\pi$ is 0.34-0.55 V·cm at the bias of 0 V to -2 V. OOK modulation with a data rate of 32 Gb/s is successfully demonstrated.

2. Device structure

Figure 1(a) shows the schematic of the single-drive push-pull Mach-Zehnder modulator, which consists of two 3-dB multimode interferometers (MMIs) as the input splitter and the output combiner. The length of the active arm integrated with a U-shaped PN junction is 3 mm and the arm length difference is 90 μm. Figure 1(b) shows the cross-sectional structure of the single-drive push-pull modulation arms. The waveguide width is 500 nm and the height is 220 nm with a 90-nm-thick slab. The n-type and p-type doping concentrations of the PN junctions are $\sim 1.5\times10^{18}$ cm^{-3} and $\sim 8\times10^{17}$ cm^{-3}, respectively. The heavily n^{++} and p^{++} doping concentrations are $\sim 1\times10^{20}$ cm^{-3} for good ohmic contact. The p^{++} doping regions are connected to the ground (G) and signal (S) lines of the traveling-wave electrode (TWE). A DC bias line is connected to the n^{++} doping region in the middle of the two arms. Figure 1(c) shows the microscope image of the fabricated device.

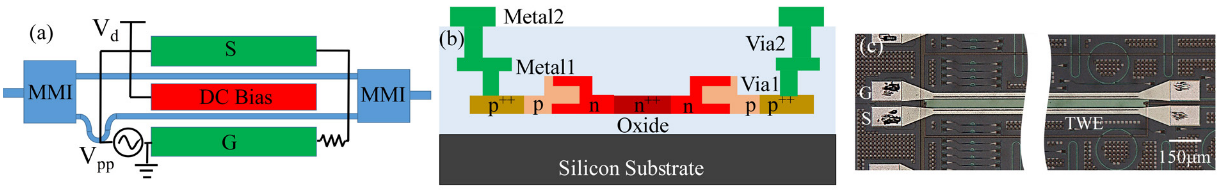

Fig. 1 (a) Schematic structure of the MZM. (b) Cross section of the modulation arms. (c) Microscope image of the fabricated device.

3. Experimental results

Figure 2(a) shows the transmission spectrum of the MZM under several reverse bias voltages on one arm. The on-chip insertion loss of the modulator is about 9.1 dB at zero bias. The insertion loss of each MMI is around 0.1 dB. The PN junction doping induced extra loss in the modulation arm is approximately 7.5 dB. The static extinction ratio is about 25 dB at zero bias, indicating relatively balanced interference between the two arms.

The extracted phase change as a function of the reverse bias voltage is shown in Fig. 2(b). The π phase shift is achieved at a reverse bias voltage of 1.7 V, corresponding to a DC modulation efficiency of $V_\pi \cdot L_\pi$ = 0.51 V·cm. From the phase shift curve, we could extract the small-signal $V_\pi \cdot L_\pi$ at different reverse biases. The $V_\pi \cdot L_\pi$ is 0.34 V·cm at 0 V bias, and it increases to 0.55 V·cm at -2V bias. Figure 2(c) shows the EE-S_{21} response of the modulator measured by a 67G vector network analyzer (VNA). The EE-S_{21} was normalized to the reference frequency of 10 MHz. The 6.4 dB bandwidth is about 18.6 GHz at -2V bias and it increases to 27.7 GHz at -4V bias.

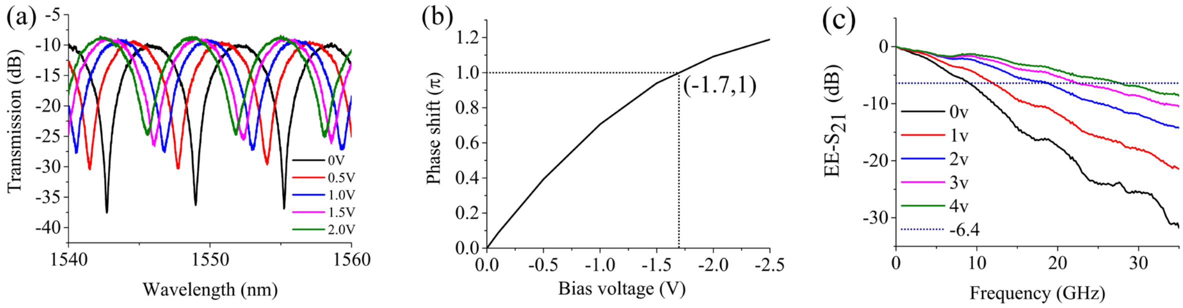

Fig. 2 (a) Measured transmission spectra of the MZM under different reverse bias voltages. (b) Extracted phase shift versus bias voltage. (c) EE-S_{21} responses of the modulator under different reverse bias voltages.

We next measured the high-speed OOK modulation using the MZM. The voltage of the pseudo-random binary sequence (PRBS) signal, generated from a pulse pattern generator (PPG), was set to V_{pp} = 2 V. The PRBS signal was applied to the modulator through a 40 GHz GS probes. The other end of the MZM was terminated with an external 50 Ω resistor. The DC bias voltage is 1.5 V. The modulated optical signal was amplified by an erbium-doped optical amplifier (EDFA) and filtered before entering a 50 GHz photodiode (PD). Figure 3 shows the modulation results. The OOK eye diagram at 32 Gb/s exhibits a modulation extinction ratio (ER) of 3.6 dB and signal-to-noise ratio (SNR) of 2.7dB.

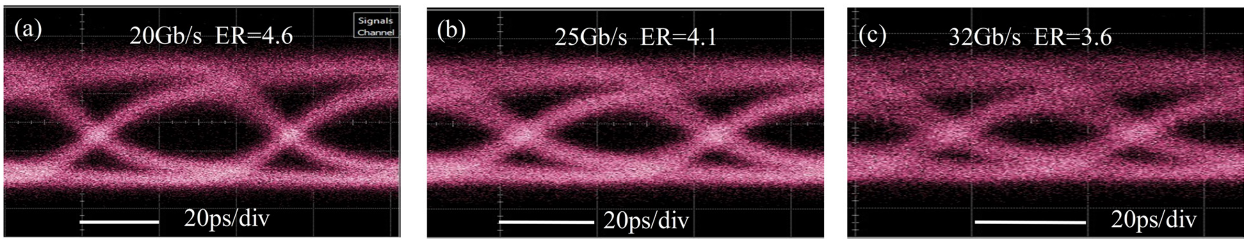

Fig. 3 OOK eye diagrams at data rates of (a) 20 Gb/s, (b) 25 Gb/s, and (c) 32 Gb/s.

4. References

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