12.5 Gb/s carrier-injection silicon Mach–Zehnder optical modulator*

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Abstract: We demonstrate a 12.5 Gb/s carrier-injection silicon Mach–Zehnder optical modulator. Under a non-return-zero (NRZ) pre-emphasized electrical drive signal with voltage swing of 6.3 V and forward bias of 0.7 V, the eye is clearly opened with an extinction ratio of 8.4 dB. The device exhibits high modulation efficiency, with a figure of merit $V_\pi L$ of 0.036 V·mm.

Key words: optical modulator; Mach–Zehnder interferometer; PIN diode; silicon-on-insulator

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1. Introduction

With chip multiprocessors (CMPs) continuously demanding more communication bandwidth, metallic-based interconnects gradually become the bottleneck for improving the performance of CMPs due to their higher power consumption, limited bandwidth, and longer latency. Optical interconnects based on silicon photonics are considered as a potential solution to overcoming the limitations of their electrical counterparts[1]. As a device transforming data from the electronic domain to the optical domain, the silicon optical modulator has attracted much attention. Compared with the microring optical modulator[2−4], the carrier-injection Mach–Zehnder optical modulator[5−7] is stable against process and temperature variations. Compared with the carrier-depletion Mach–Zehnder optical modulator[8−13], the carrier-injection Mach–Zehnder optical modulator has high modulation efficiency and a small footprint. In this paper, a high-speed carrier-injection silicon Mach–Zehnder optical modulator operating at 12.5 Gb/s is demonstrated. With doping on both arms to balance the losses of the two arms, a high static extinction ratio of 20 dB is obtained when the operating wavelength is located on the wave trough of the spectrum without a voltage applied to the device. The high static extinction ratio indicates that the potentially dynamic extinction ratio is high.

2. Device design and fabrication

The device presented here is based on an asymmetric Mach–Zehnder interferometer structure with a built-in arm length difference of 60 μm. Two multimode interference (MMI) couplers are adopted as an optical 1 × 2 splitter and a 2 × 1 combiner. The silicon ridge waveguide is 400 nm in width, 220 nm in height, and 70 nm in slab thickness, as shown in Fig. 1(a), which only supports the quasi-TE fundamental mode. A PIN diode is formed around the ridge waveguide to electrically control the injection of electrons and holes into the intrinsic region. The width of the intrinsic region is 1 μm. The device is doped on both arms to balance losses of the two arms to obtain a high static extinction ratio. The length of the phase shifter is 200 μm.

A top-view micrograph of the device is shown in Fig. 1(b). It is fabricated on silicon-on-insulator substrate with a 2 μm thick buried oxide layer. 248 nm deep ultraviolet lithography and inductively coupled plasma etching are used to define the ridge waveguides. The anode (boron, $p^+ \approx 5.5 \times 10^{20}$ cm^{-3}) and cathode (phosphorus, $n^+ \approx 5.5 \times 10^{20}$ cm^{-3}) implants are formed using an ion implantation process. 1.8 μm thick SiO_2 is deposited as a separate layer by plasma enhanced chemical vapor deposition. Spot size converters are formed on the input and output terminals of the waveguides to enhance the coupling efficiency between the waveguides and lensed fibers. Finally, aluminum wires and pads are formed, through which a high-frequency digital signal is applied to the optical modulator.

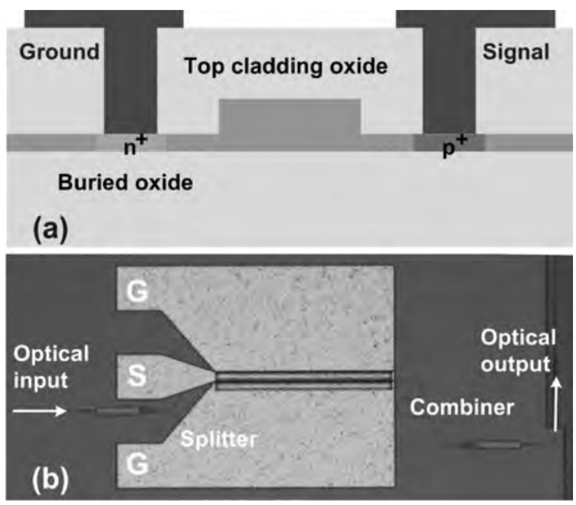

Fig. 1. (a) Cross-sectional view of a PIN junction waveguide phase shifter of the carrier-injection silicon Mach–Zehnder optical modulator. (b) Microscope image of the demonstrated silicon optical modulator.

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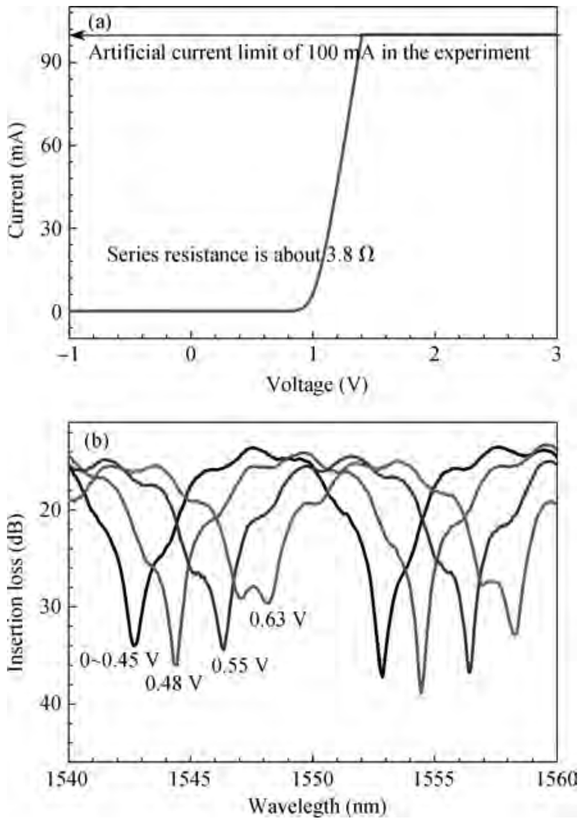

Fig. 2. (a) Current–voltage curve of the device. (b) Transmission spectra of the device with various voltages applied to the phase shifter.

3. Experimental results and discussion

The current–voltage curve of the device is shown in Fig. 2(a). It can be deduced from the curve that the series resistance of the device is about 3.8 Ω. It indicates that a good ohm contact is formed between the aluminum electrodes and heavily doped regions.

The static transmission spectrum of the device is characterized using an amplified spontaneous emission (ASE) source and an optical spectrum analyzer. It can be seen from Fig. 2(b) that the insertion loss is about 14 dB, which includes ∼6.5 dB coupling loss between the waveguides and the lensed fibers, ∼7 dB propagation losses of the MMI splitter and combiner, and ∼0.5 dB transmission loss of the phase shifter. The relatively large losses of the MMI splitter and combiner are due to non-optimal parameters chosen in fabrication. It can be seen that the static extinction ratio is about 20 dB at the wavelength of 1552.8 nm, which is on the wave trough of the spectrum when no voltage is applied to the device. When the applied forward voltage is smaller than 0.45 V, the PIN junction is not yet opened and no carriers are injected into the intrinsic waveguide, thus the transmission spectrum is unchanged in the process. As the forward voltage increases to 0.45 V, carriers begin to be injected into the intrinsic region of the waveguide and the transmission spectrum starts to shift. As the forward voltage increases to 0.63 V, π phase shift has been achieved for the device. Thus, V_π is 0.63–0.45 V, and its value is 0.18 V. The figure of merit $V_\pi L$ is 0.036 V·mm.

A pre-emphasized pseudorandom binary sequence (PRBS) (2^7–1) electrical signal is adopted to drive the modulator to enhance the frequency-response characteristics of the device[3]. The experimental setup for high-speed modulation measurement is shown in Fig. 3. Two non-return-to-zero (NRZ) signals from the DATA and the XDATA of a pulse pattern generator (PPG) propagating along two coaxial cables with 40 ps delay are combined together to create a pre-emphasized NRZ signal. The pre-emphasized signal is amplified by a commercial radio-frequency (RF) amplifier, and direct-current (DC) bias is added into the signal by a bias tee. Two erbium doped fiber amplifiers (EDFA) are adopted in the experimental setup to minimize their deteriorations of the dynamic extinction ratio due to the nonlinear amplification effect of the EDFA[13].

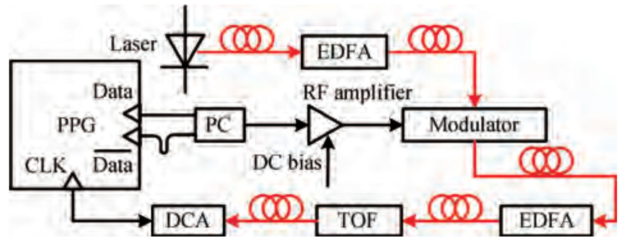

Fig. 3. Schematic of the experimental setup for the high-speed modulation experiment. PPG: pattern pulse generator; PC: power combiner; RF: radio-frequency; DCA: digital communication analyzer; EDFA: erbium-doped fiber amplifier; TOF: tunable optical filter; DC: direct-current.

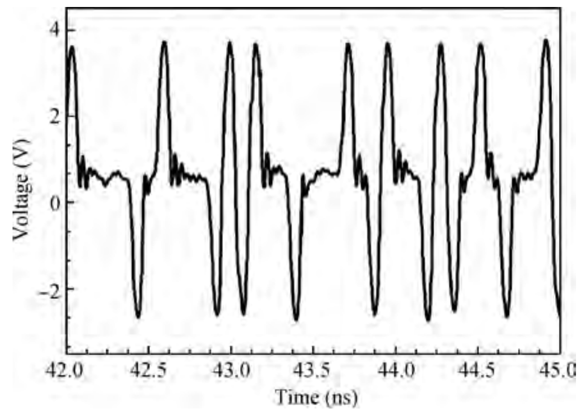

Fig. 4. Pre-emphasized electrical driving waveform of the device at 12.5 Gb/s.

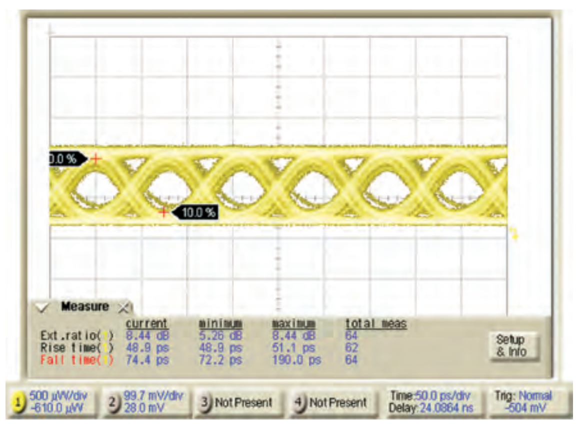

Fig. 5. Eye diagram of the optical modulator at the speed of 12.5 Gb/s.

A high-speed modulation experiment of 12.5 Gb/s is performed. The operating wavelength is located at 1552.8 nm. The pre-emphasized electrical driving signal is shown in Fig. 4. It has a voltage swing of 6.3 V and forward bias of 0.7 V. The eye diagram is shown in Fig. 5. It can be seen that the eye is clearly opened with an extinction ratio of 8.4 dB.

4. Conclusion

A high-speed carrier-injection silicon Mach–Zehnder optical modulator operating at 12.5 Gb/s is demonstrated adopting an NRZ pre-emphasized electrical drive signal with a voltage swing of 6.3 V and a forward bias of 0.7 V. The eye is clearly opened with an extinction ratio of 8.4 dB.

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