Mach-Zehnder electro-optic modulator based on silicon nanophotonic waveguide

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Abstract: An electro-optic modulator based on Mach-Zehnder interferometer and embedded PIN diode is demonstrated using silicon nanophotonic waveguide. Measurement results show that the device has high modulation efficiency with a $V_{\pi}L$ figure of merit of 1.14 V·mm, high modulation depth of 96.27%, and large optical bandwidth from 1500 to 1600 nm. Transmission data rate up to 0.2 Gbps is demonstrated and the rise and fall time are 3.74 ns and 640 ps, respectively.

Keywords: electro-optic modulator, Mach-Zehnder interferometer, plasma dispersion effect

I. Introduction

High speed and miniaturized silicon electro-optic modulator is an essential component in opto-electronics integration circuits (OEIC) and on-chip optical interconnection systems. This device is often based on free carrier plasma dispersion effect [1], in which the refractive index of silicon is varied with the carrier concentration. The carriers can be injected, depleted or accumulated in silicon waveguide through different electrical structures, such as PIN diode, PN junction and MOS capacitor. Among these structures, forward-biased PIN diode has the largest modulation efficiency and is easy to fabricate. However, because carrier diffusion is dominant in PIN diode, the modulation speed is not so high, typically ~20MHz based on rib waveguides with large cross-sections [2]. Fortunately, using nanophotonic waveguides with submicron cross-section, the transport distance can be shortened significantly in forward-biased PIN diode, thus modulation speed higher than 1GHz could be also achieved [3].

We present a high-speed PIN injected Mach-Zehnder electro-optic modulator here in this paper. The device has high modulation efficiency with a $V_{\pi}L$ figure of merit of 1.14 V·mm and transmission data rate up to 0.2 Gbps. Further simulation results show that the data rate can achieve 1 Gbps by shortening the distance between heavily doped regions or reducing the carrier lifetime in intrinsic region.

II. Device Structure

The electro-optic modulator presented here has an optical structure of 1×1 Mach-Zehnder interferometer and electrical structure of PIN diode. The MZI consists of two identical 1×2

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multimode interference (MMI) couplers and two long arms with submicron rib waveguide with the same length. Using this symmetric MZI, the modulator can be operated in a large optical bandwidth and insensitive to variation of environment temperature. The rib waveguide on each arm is 340 nm in height, 400 nm in width and with a thin 100 nm slab. These parameters are chosen to ensure that the waveguide satisfies the single-mode condition [4]. And the length of the modulation area is 1mm. The embedded PIN diode is formed across the waveguide, with heavily doped regions on its slab and intrinsic area in the waveguide core. The device is fabricated using CMOS-compatible processes. The microscope image of a fabricated modulator is shown in figure 1, together with the schematic of the cross-section of the modulation area. The heavily doped regions are 1.0μm away from the edge of waveguide core in order to reduce the absorption loss due to the overlap of the optical mode and the optically absorbing heavily doped regions. However, it will take longer time for carriers transporting cross the waveguide due to this long distance.

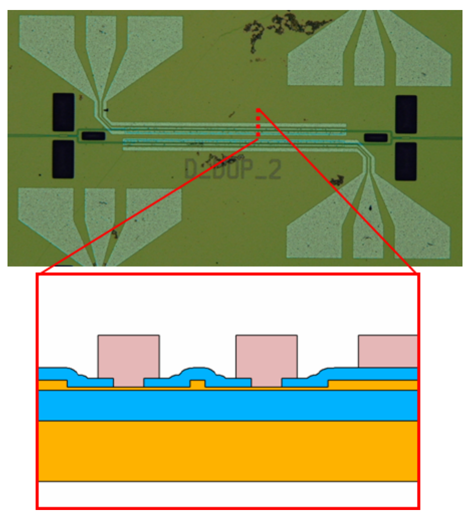
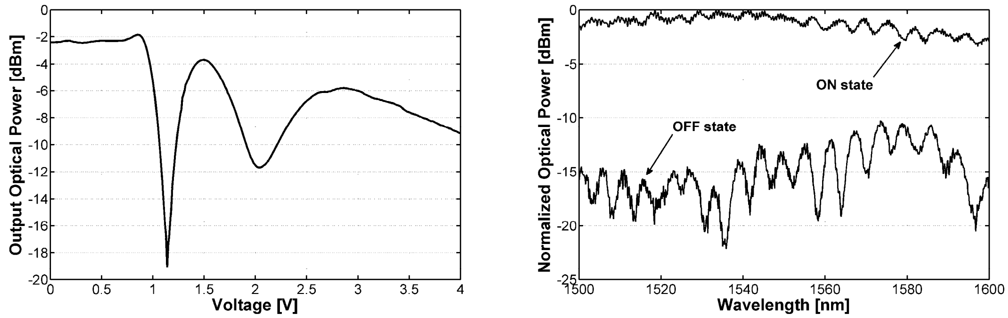


Fig. 1 The microscope image of the fabricated modulator and the schematic of the cross-section of the modulation area

III. Device Performances

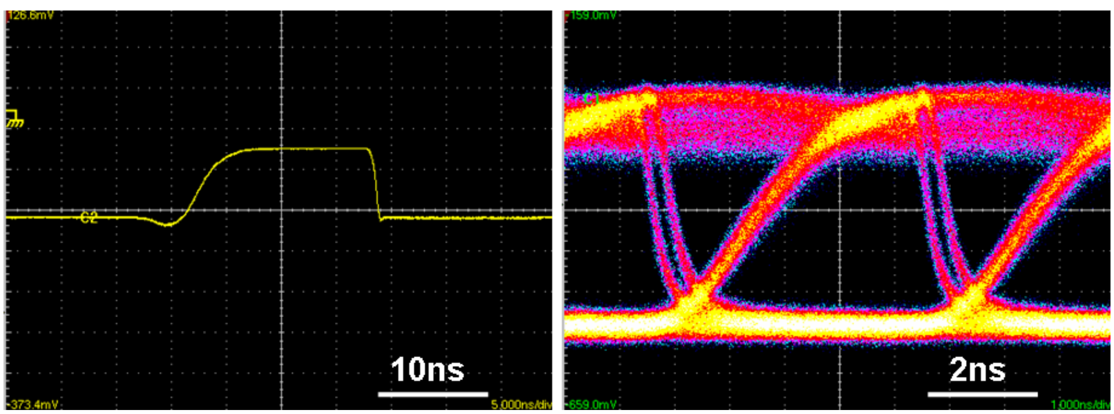
The static and dynamic performances of the modulator are measured. The TE-polarized light with a power of 19.6dBm is launched into the input port of the device through a tapered-lensed fiber. The output light is also coupled through a similar fiber into an optical powermeter. The operation optical wavelength is 1.55μm. Figure 2(a) shows the output optical power with different bias voltages. The output power decreases to the minimum while the voltage increases to 1.14 V, which corresponds to the π phase shift voltage. Thus the $V_\pi L$ is 1.14 V·mm for the modulator. The device has a large extinction ratio of 17.21dB, corresponding to a modulation depth of 96.27%. We also measure the output optical spectrum of the device in ON state (V=0) and OFF state ($V=V_\pi$), as shown in figure 2(b). The result shows that the modulator can be operated in a large bandwidth from 1500 nm to 1600 nm, with the largest extinction ratio of 21.55dB and smallest extinction ratio of 7.84dB.



(a) (b)

Fig. 2 (a) The output optical power of the modulator with different bias voltages, (b) The optical spectrum of the modulator in ON and OFF state

The dynamic performance of the switch is characterized by the switch time and transmission data rate. The switch time is measured by applying a pulsed electrical signal on the device. The device output is firstly directed to a high-speed detector with a maximum conversion gain of -600V/W for OE conversion and then displayed on the oscilloscope, as shown in figure 3(a). The 10%-90% rise and fall time are 3.74ns and 640ps, respectively. We also measure the transmission data rate by applying a 2^{31}-1 PRBS NRZ signal on the device. Fig 3(b) shows the eye diagram under 200 Mbps data rate.

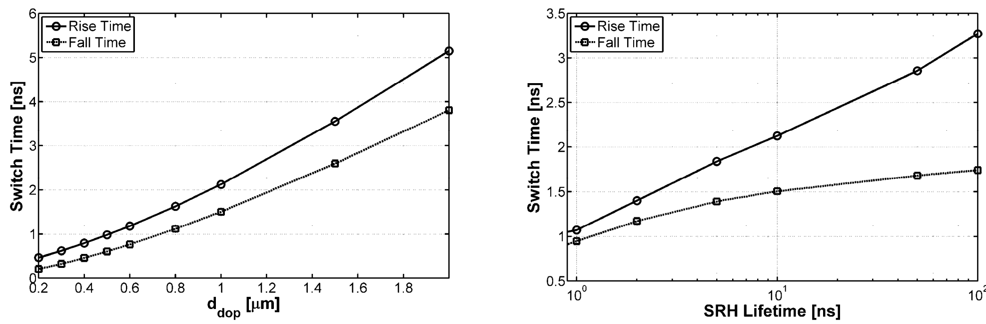


(a) (b)

Fig. 3 (a) The transmission eye diagram of 200 Mbps data, (b) The pulse response of the modulator

IV. Discussions

Our device has relatively high modulation efficiency - figure of merit $V_{\pi}L$ of 1.14 V·mm. By shortening the length of the modulation arms, the $V_{\pi}L$ can be decreased further. Due to our careful design for the optical structure, the modulator has large static extinction ratio. The switch time is significantly dependent on the carrier transport distance across the waveguide. The relationship of the switch time of the modulator and the distance between the edge of heavily doped region and waveguide ridge d_{dop} is shown in figure 4(a). It can be shown that by shortening the d_{dop} to 0.5μm, the switch time can be reduced to sub-nanosecond. In addition, carrier lifetime reduction is another efficient way to reduce the switch time [5]. The switch time of modulators with different SRH lifetime in the intrinsic region is shown in figure 4(b). As the lifetime is decreased to sub-nanosecond, the switch time can be also decreased to sub-nanosecond. The carrier lifetime in the intrinsic region of PIN diode can be reduced by helium [6], oxygen [7], silicon [8] or some other ion implantations. Taking these two improvements together, it is easy to realize a silicon-based electro-optic switch with sub-nanosecond switch time, thus up to 1 Gbps data rate.



(a) (b)

Fig. 4 The switch time of modulators with (a) different d_{dop}, (b) different SRH lifetime

V. Conclusions

We demonstrated a PIN injected Mach-Zehnder interferometer based electro-optic modulator with data rate up to 0.2 Gbps. The device is based on SOI submicron rib waveguides thus shows good static and dynamic performance. The measured modulation efficiency figure of merit $V_\pi L$ is 1.14 V·mm for 1000 μm long MZI arm and the extinction ratio is 17.21dB. The optical spectrum shows that the device can be operated in a large optical bandwidth. Transmission data rate up to 0.2 Gbps is also reallized and the rise and fall time are 3.74 ns and 640 ps, respectively. The switch time can be reduced further through shortening the distance between the edge of heavily doped region and waveguide ridge and the carrier lifetime.

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