Sub-nanosecond optical switch based on silicon racetrack resonator*

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We experimentally demonstrate a small-size and high-speed silicon optical switch based on the free carrier plasma dispersion in silicon. Using an embedded racetrack resonator with a quality factor of 7400, the optical switch shows an extinction ratio exceeding 13 dB with a footprint of only 2.2×10^{-3} mm^2. Moreover, a novel pre-emphasis technique is introduced to improve the optical response performance and the rise and the fall times are reduced down to 0.24 ns and 0.42 ns respectively, which are 25% and 44% lower than those without the pre-emphasis.

Keywords: resonator, silicon-on-insulator, optical switch, pre-emphasis technique

PACC: 4282, 4280S, 4280L

1. Introduction

Silicon optical modulators/switches are critical components in the integrated optoelectronics and optical interconnection systems for their compactness and compatibility with CMOS processes. In the past few years, several high-speed silicon optical modulators/switches based on the free carrier plasma dispersion effect[1] in silicon have been demonstrated experimentally.[2−10]

The operation speed of the silicon optical modulator/switchis essentially determined by how fast electrons and holes can be injected into or removed from the optical transmission region. Three different electrical configurations have been proposed to achieve carrier density modulation in silicon: MOS capacitance,[2] p-i-n diode through carrier injection,[3−7] and pn junction through carrier depletion.[8−10] The p-i-n diode modulators/switches have been proved to provide the largest modulation efficiency and the most compact size. However, it is forward-biased, and the operation speed is limited by the carrier injection time. Previously, we reported a forward biased Mach–Zehnder interferometer (MZI) silicon optical switch at nanosecond levels. The rise and the fall times of the optical switch were 6.8 ns and 2.7 ns, respectively.[11]

Microring/racetrack modulators/switches based on the p-i-n diode can break the speed limitation because of their nonlinear transfer characteristics.[12] In the past few years, some groups have realized modulators/switches of this kind with switch on-off times under nanosecond levels.[3−6] Luo *et al.*[6] recently reported a silicon microring optical switch based on the forward bias p-i-n diode with rise and fall times of ~ 0.7 ns and ~ 0.85 ns respectively.

In this paper, we present a silicon racetrack optical switch based on the forward bias p-i-n diode. Racetrack resonators are employed here for the large coupling efficiency between the resonator and the straight waveguide.[13] Meanwhile, we demonstrate a new method to generate pre-emphasis driving signals, with the aim of improving the operation speed of the optical switch. Finally, the rise and the fall times are reduced down to 0.24 ns and 0.42 ns respectively, which are 25% and 44% lower than those without the pre-emphasis. To our best knowledge, it is the fastest silicon optical switch ever reported in mainland China.

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2. Device design and fabrication

The ultra-compact racetrack resonator optical switch was designed by using submicron rib waveguides with embedded p-i-n diodes. The rib waveguide was 420-nm wide and 260-nm high, with an 80-nm thick slab layer. The racetrack resonator has been realized with a track length (L_t) of 3 μm, bending radius (R) of 6 μm and spacing gap of 260 nm. Figure 1(a) shows the top-view and cross-section diagram of the device.

The device was fabricated on a silicon-on-insulator (SOI) wafer with a 340-nm thick top silicon layer and a 2-μm thick buried oxide layer. Electron beam lithographic (EBL) technology was used to determine the submicron rib waveguides and the racetrack resonator. Then, aligned photolithography technology was applied to perform anode (boron, $p^+ \sim 1 \times 10^{20}$ cm^{-3}) and cathode (phosphorus, $n^+ \sim 1 \times 10^{20}$ cm^{-3}) implants. The doped regions are 1 μm away from the edge of the rib waveguide. A 15-nm thick nickel was evaporated onto the heavy-doped regions and annealed to ensure good ohmic contact. A 1-μm thick aluminum was then evaporated to form contact pads. The microscope image of the fabricated device is shown in Fig. 1(b).

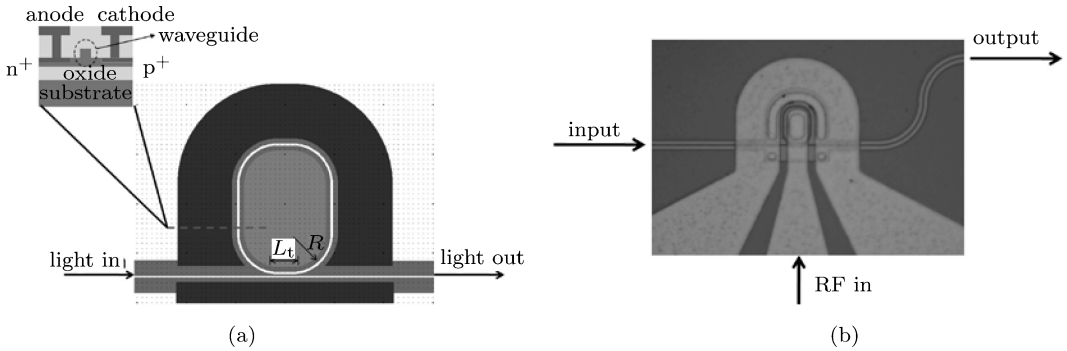


Fig. 1. (a) Schematic of the racetrack optical switch with the inset for cross-section view of the device, and (b) microscope image of the fabricated racetrack optical switch.

3. DC and static characteristics

An electrical I–V characteristic curve of the device is shown in Fig. 2(a). A small forward differential resistance of 26 Ω is obtained to minimize the RC limitation of the frequency response of the optical switch and ensure low power consumption.

In order to measure the transmission spectrum of the device, continuous-wave light from a tunable laser with a resolution of 1 pm was first polarized into TE-mode, and then coupled to the straight waveguide with a polarization-maintained lensed fibre. The normalized transmission spectra under different forward biases are shown in Fig. 2(b). A few slight ripples (nearly 1 dB) on the spectra are produced by the reflections between both ends of the straight waveguide, which can be suppressed by introducing an antireflection coating.[14,15]

The resonant wavelength λ_0 under the forward bias 0 V is 1560.67 nm where optical power has a distinctive drop since most light is coupled to the racetrack and lost for the side-wall roughness of the racetrack. The optical switch is then in the OFF state. The extinction ratio of the resonant wavelength exceeds 13 dB, and the quality factor (Q) of the racetrack is 7400.

When the forward bias is increased to 0.9 V, the injection current increases greatly since much more free carriers are accumulated in the racetrack. The effective index of the junction then decreases according to the relationship between the changes in carrier and refractive index, i.e.[1]

$$\Delta n = -8.8 \times 10^{-22} \Delta N_e - 8.5 \times 10^{-18} (\Delta N_h)^{0.8}, \quad (1)$$

where Δn is the refractive index change, ΔN_e (cm^{-3}) and ΔN_h (cm^{-3}) are the concentration changes of electrons and holes, respectively. Thus, the resonant wavelength will be blue shifted as described by the

following expression:[16]

$$\Delta\lambda = \frac{\Delta n_{\rm eff} \times \lambda_0}{n_{\rm g} - n_{\rm eff}}, \tag{2}$$

where $\Delta\lambda$ is the wavelength shift, $\Delta n_{\rm eff}$ is the change in effective index, λ_0 is 1550 nm, $n_{\rm g}$ is the group index, and $n_{\rm eff}$ is the effective index at λ_0. The transmission spectrum under the bias 0.9 V is illustrated by the gray dash line in Fig. 2(b). The optical switch is then changed to the ON state. The reduction in extinction ratio under the bias 0.9 V is due to the increased optical absorption in the resonator induced by the injected electrons and holes.[12]

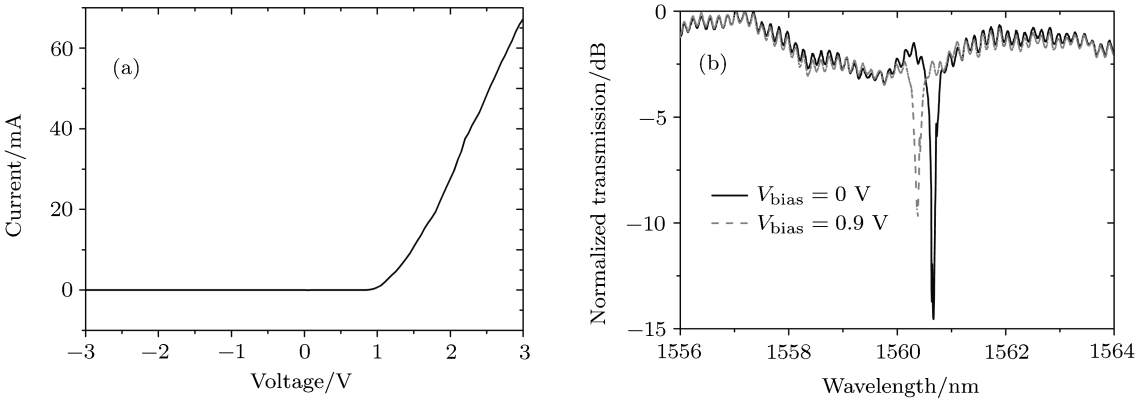


Fig. 2. (a) I–V characteristic curve of the racetrack optical switch, and (b) normalized transmission spectra of the racetrack optical switch under the forward biases of 0 and 0.9 V.

4. Fast optical response realization

For a microring/racetrack resonator optical switch, the optical transmission coefficient T is nonlinearly related to total charge $Q_{\rm c}$ injected into the p-i-n diode by[5]

$$T = 1 - \frac{1}{1 + (Q_{\rm c}/Q_{\rm c0})^2} \tag{3}$$

with

$$Q_{\rm c0} = \frac{q \cdot n_{\rm g} \cdot V_{\rm c}}{2 \cdot \Gamma \cdot |n_{\rm f}| \cdot Q}, \tag{4}$$

where q is the electron charge, $n_{\rm g}$ is the group index, $V_{\rm c}$ is the volume of the p-i-n diode, Γ is the mode confinement factor, $n_{\rm f}$ is the ratio between the change in the refractive index of silicon and that in the carrier density of the p-i-n diode, and Q is the quality factor of the racetrack.

The microring/resonator optical switch can break the limitation of the slow charge injection since the optical rise time can be much shorter than the electrical rise time as long as the charge $3Q_{\rm c0}$ is much smaller than the steady-state charge $Q_{\rm s}$ of the p-i-n diode.[5] Increasing the voltage can reduce the optical rise time, however, it results in longer time to extract more steady-state charge, and the optical fall time will become longer.

The pre-emphasis technique is an appropriate method to shorten the optical rise and fall times.[5,7] Figure 4 shows the waveform of pre-emphasis driving signals achieved with our method which will be discussed in detail later. An overshoot signal is artificially added to the rising edge of a square-wave signal which could reduce the optical rise time. In order to shorten the optical fall time, an undershoot signal is added to the falling edge to advance the reverse extracted voltage, and the high levels at the remained periodic time are reduced to a lower level to reduce the stead-state charge.

5. Pre-emphasis driving signal generation method

The pre-emphasis driving signals can be generated in virtue of the following setup (shown in Fig. 3). Two synchronous square-wave signals (CH1 and CH2) with transition times lower than 90 ps are first generated from a pattern generator. The CH1 signal is am-

plified by a broadband amplifier while the CH2 signal is inverted and delayed by an inverter and a delay controller respectively. Then, the two channel signals are combined by a power combiner. The original square-wave signal and pre-emphasis driving signal are shown in Fig. 4. Compared with the method given by Xu *et al.*,[5] the setup here is simple since there is no need to employ an impulse generator network (IGN) to generate impulse signals, and the waveform quality of the pre-emphasis driving signals here is much better, ensuring a high-quality modulated optical output.

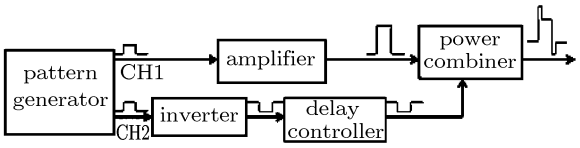


Fig. 3. Experimental setup of the pre-emphasis driving signal generation method.

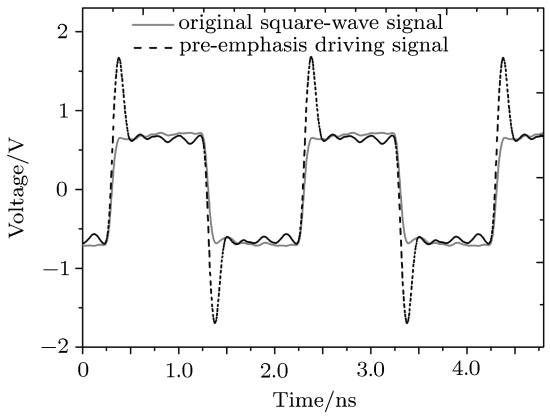


Fig. 4. Square-wave signals without (gray solid line) and with (black dashed line) pre-emphasis.

The optical switch on-off time is measured without and with the pre-emphasis, respectively. The output optical response (as shown in Fig. 5) is reversed to the input square-wave signal since the output optical signals are converted into the electronic signals by a high-speed photodetector with a negative transimpedance amplifier. Without the pre-emphasis, a 500-MHz square-wave signal with $V_{\rm pp} \sim 2$ V and offset ~ -0.1 V is applied to the device directly and the waveform of the output optical response is illustrated by the black solid line. The rise and the fall times are ~ 0.32 ns and ~ 0.75 ns, respectively.

With the pre-emphasis, a 500-MHz square-wave signal (CH1) with $V_{\rm pp} \sim 0.9$ V and offset ~ -0.1 V is first amplified to $V_{\rm pp} \sim 7.2$ V and offset ~ -0.8 V. Meanwhile, a synchronous 500-MHz square-wave signal (CH2) with $V_{\rm pp} \sim 0.9$ V is inverted and delayed -3.39 ns with respect to the CH1 signal. The waveform of output optical response is illustrated by the black dash line. The rise and the fall times are reduced to ~ 0.24 ns and ~ 0.42 ns, respectively.

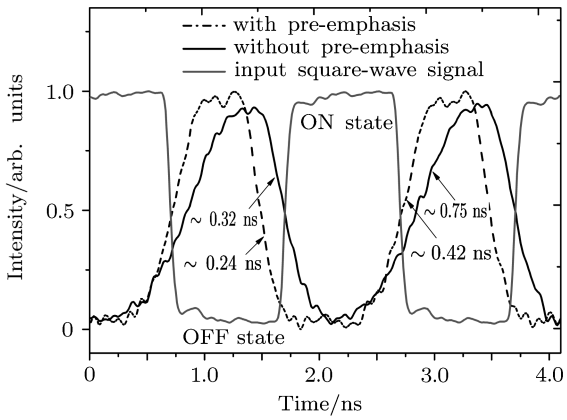


Fig. 5. Normalized output optical intensity by the square-wave signal with (black dash line) and without (black solid line) pre-emphasis.

6. Conclusion

We present a high-speed silicon racetrack optical switch with an ultra-compact footprint of only 2.2×10^{-3} mm^2. The racetrack resonator is employed for its high coupling efficiency between the resonator and the straight waveguide. A novel pre-emphasis method is proposed to reduce the rise and the fall times. In experiment, 25% and 44% reductions in rise and fall times are obtained, compared with those without the pre-emphasis. The optical switch on-off time of 0.24/0.42 ns is achieved, which is the fastest silicon optical switch on-off time ever reported in mainland China to our best knowledge. The switch on-off time can be further reduced by improving the amplitudes of overshoot and downshoot signals.

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