High-speed and broadband electro-optic silicon switch with submilliwatt switching power

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Abstract: We present a 2x2 silicon electro-optic switch with a submilliwatt switching power (0.6 mW), a broad bandwidth (60 nm), and ultrafast speed (6 ns). Free-carrier injection Mach-Zehnder interferometers are employed.

1. Introduction

Silicon-photonics-based optical interconnects are expected to provide high bandwidth and low power consumption for chip-level communication [1-5]. On-Chip optical network architects have been proposed by several groups [5-8]. A key optical component to realize reconfigurable communication is a silicon optical switch, with a broad bandwidth to facilitate wavelength division multiplexing (WDM) optical links, a low switching power and a sub-microsecond switching time. A comb switching technique using a large-radius silicon ring resonator to realize multi-wavelength operation was proposed in [9-11] wherein the free spectral range of the ring matches the wavelength spacing in a WDM optical link. However, it is known that such rings must be tuned to compensate fabrication errors and temperature variations. In order to provide 'true' broadband operation free from these effects, Mach-Zehnder interferometers (MZI) can be employed to achieve either thermo-optic [12-13] or free-carrier-injection electro-optic switches [14-15]. The switching time of thermo-optic silicon switches is usually longer than a few microseconds. Free-carrier driven MZI based switches have been demonstrated to realize a large bandwidth and a fast switching time simultaneously. The switching power for such switches was reported to be as low as 3.1 mW [14]. With this amount of power, self-heating effects, which act in the opposite direction of free carrier induced index change, would still degrade the optical performance [14].

In this paper, we report carrier-injection MZI switches with a 0.6 mW of π-phase switching power at a drive voltage 0.83 V. The arm length of MZIs needs to be about 4 mm to achieve this low power. The 10%-90% switching time is demonstrated to be 6 ns. Optical crosstalk levels lower than -17 dB are obtained for an optical bandwidth of 60 nm.

2. Design and fabrication

We design a symmetric MZI with two 2x2 3 dB couplers at input and output ends to function as a 2x2 switch. The switching is realized if the phase of either of the two arms can be tuned (Fig. 1(a)). The 2x2 3 dB couplers are realized by multimode interference couplers (MMIs) which are expected to have higher fabrication tolerance than directional couplers. The silicon waveguide in MZIs has a cross section of 0.50 μm x 0.25 μm with a 0.05 μm slab. The buried oxide thickness is 3 μm and the top cladding oxide thickness is 1.2 μm. In order to achieve phase modulation, a p-i-n junction is created across the silicon waveguides in the two arms of the MZIs (Fig. 1(b)). Both p and n have a doping level of 10^{20} cm^{-3} to minimize the series resistance of the junction, which is critical to minimize unwanted thermal effects due to the current flow through the device. The device fabrication is similar to our silicon modulators presented in Ref. [16]. We have fabricated MZIs with a range of arm lengths, from a few hundred microns to 6 mm. Fig. 1(a) shows an example with an arm length of 0.25 mm.

3. Measurement results

Low switching power is experimentally demonstrated in a MZI switch with an arm length of 4 mm. We test this device using an optical detector and a tunable laser source together with a voltage-current source-meter. In this measurement, the input wavelength is fixed at 1520 nm and the applied voltage is scanned from 0.6 V to 1 V (the p-i-n junction will turn on at about 0.7 V). The electrical current is measured at the same time and the electrical power is calculated from the product of the measured current and the applied voltage. Fig. 2 shows the experimental results of the normalized optical power at two outputs as a function of electrical power, respectively. With a power of 0.6 mW at a voltage of 0.83 V, the optical power is observed to switch from output 2 to output 1, namely, a π-phase shift has been realized. With a power of 1.8 mW at the voltage of 0.88 V, a 2π-phase shift can be achieved. In the case that fabrication errors cause random phase variations between the two arms of MZIs, a 2π-phase shift can compensate any initial phase difference. The sub-1 V drive voltage is useful in the design of electrical drivers to minimize power and retain compatibility with CMOS voltage scaling. The total optical power drops as the injected electrical power rises due to free-carrier absorption. The extinction ratios also decrease due to increased power imbalance between the two MZI arms since only one active arm experiences free carrier absorption loss.

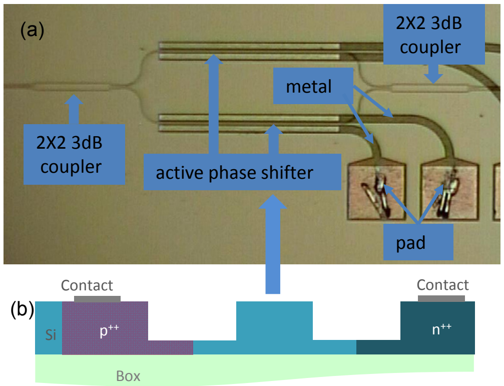

Fig. 1. A typical 2x2 switch based on symmetric MZIs.

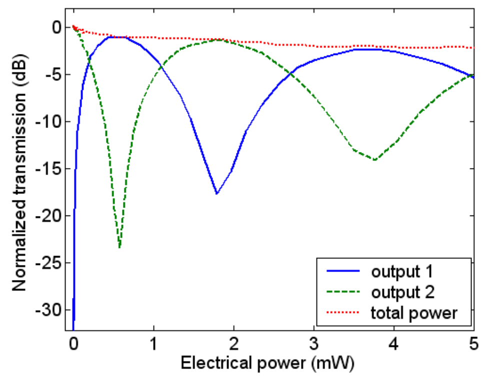

Fig. 2. (a) Transmission power as a function of the applied power.

We define the switch 'off' and 'on' states corresponding to applied voltage of 0 V and 0.83 V, respectively. The steady-state transmission spectra T_{ij} (i, j =1, 2) for both states were collected, and are shown in Fig. 3 for the wavelength range from 1480 nm to 1540 nm. The central wavelength of the MMIs is 1510 nm, off the nominal design target of 1550 nm as a result of fabrication errors and non-idealities. Nevertheless even with these variations, the power splitting ratio of MMIs is close to 1 at a wavelength of 1540 nm, which is relevant to achieving low crosstalk. The output power is normalized to the total power at the 'off' state at a wavelength of 1510 nm. The optical crosstalk between the two outputs is found to be below -17 dB for both 'off' and 'on' states in the wavelength range from 1480 nm to 1540 nm. This optical bandwidth is mainly limited by the MMI bandwidths.

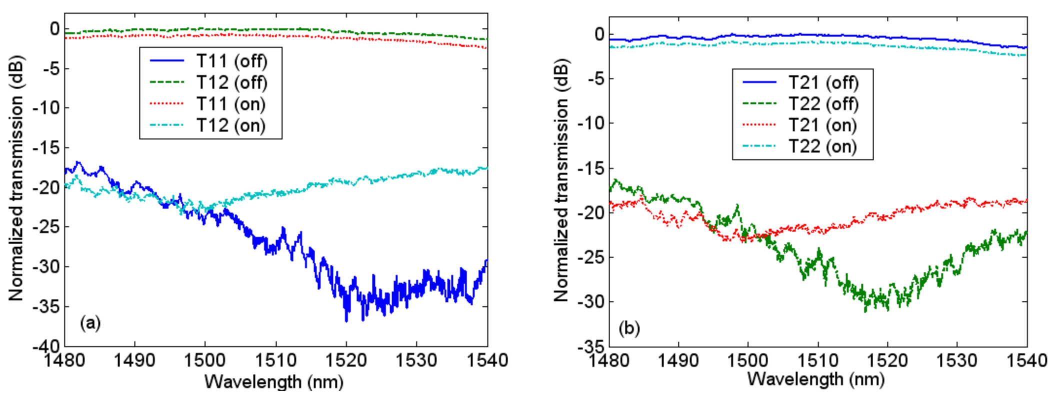

Fig. 3. Steady-state transmission spectra of the 2x2 switch.

We measured the switching time for the device by driving the device with a 20 MHz square-wave voltage signal, with a peak-to-peak voltage 0.83 V and a d.c. bias of 0.42 V, shown in Fig. 4(a). The rise and fall times of the electrical signal is about 25 ps. The optical transmission was measured by a high speed detector, capable of detecting 40 Gbps optical signal. The optical waveforms, presented in Fig. 4(b), demonstrate a 10%-90% switching time of 6 ns and 0.4 ns, corresponding to the free carrier injection process (from 0 V to 0.83 V) and extraction process (from 0.83 V to 0 V), respectively. The free carrier extraction time is much faster than the injection time due, in part, to the built-in potential of the p-i-n junction. Similar switching behaviors have been observed in previously reported free-carrier-injected switches [14].

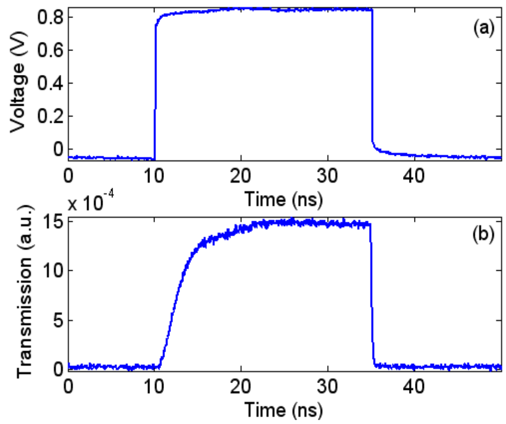

Fig. 4. Electrical drive signal (a) and optical switching response (b).

4. Conclusion

In this paper, we present 2x2 silicon electro-optic switches with a submiliwatt switching power (0.6 mW), a broad bandwidth (60 nm), and ultrafast speed (6 ns). Such low-power and ultrafast silicon switches are particularly useful to realize reconfigurable communication in on-chip optical networks.

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