Ultra-High-Extinction-Ratio Electro-Optic Switch Element

(Student paper)

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We present a novel approach for designing 2×2 electro-optic switch elements with ultra-high extinction ratio that offsets the impact of modulating-indueced free-carrier absorption. A curved directional coupler with tunable coupling efficiency and a differential electro-optic phase shifter pair are employed to correct any loss and phase imbalance in a Mach-Zehnder interferometer structure. Simulations show that the proposed device can completely suppress the crosstalk at the designed wavelength of 1550 nm and maintain <-30 dB crosstalk over a bandwidth from 1530 nm to 1570 nm, ideally for constructing a large-scale electro-optic switch fabric.

Keywords: *Optical switches, photonic integrated circuits, high-extinction-ratio, electro-optic.*

Introduction

The exploding demands for cloud services have promoted the need for massive data traffic within data centres. To meet this rapid growth in data volume, switching technologies with high speed, large bandwidth, and low crosstalk are desired. Leveraging mature CMOS technologies, the silicon-on-insulator (SOI) platform features low cost, compact footprint, and low power consumption, and hence is regarded as a promising platform for developing high-performance optical switching technologies for data centre applications. Mach-Zehnder interferometers (MZIs) are widely used on the SOI platform for broadband optical switching, permiting nanosecond-scale switching speed by using electro-optic (E-O) phase shifters. However, current E-O switch elements usually have a limited extinction ratio, restricting them from being implemented for switches with large port counts. Due to the fabrication imperfections, the non-uniform power splitting ratio (i.e., deviating from the ideal 50:50) of the 3-dB couplers in the MZI increases the crosstalk. In addition, E-O phase shifters typically rely on p-i-n junctions that operate in carrier injection mode. The injected carriers not only modify the refractive index of the waveguide to realize the phase shift, but also induce undesired inherent insertion loss due to free-carrier absorption (FCA). This is problematic for an MZI-based switch operating in the bar state, where only one of the phase shifters is turned on. The FCA-induced loss causes a power imbalance inside the interferometer, leading to power leakage into the cross port (i.e., crosstalk). Efforts have been made to improve the crosstalk performance. For example, Ref[1] uses an additional MZI as a variable splitter to compensate for the splitting ratio mismatch between the front and rear splitters [1], whereas nested MZI phase shifters are applied to balance the loss in the two arms [2, 3]. However, these methods require extra active components, which increases the device footprint and complicates the control scheme.

In this paper, we propose a novel design approach of ultra-high-extinction-ratio E-O switch elements. Our design can, in theory, completely suppress the crosstalk and thus achieve an infinite extinction ratio at the designed wavelength by simultaneously balancing the losses in the two MZI arms using a differential E-O phase shifter pair and compensating the fabrication imperfection via a tunable curved directional coupler (DC). Further simulation results indicate a broad bandwidth of at least 40 nm with a crosstalk value below -30 dB.

Device schematic and principle

Figure 1(a) illustrates the schematic of the proposed 2×2 high-extinction-ratio E-O switch element, which consists of a curved tunable DC and a curved DC as the power-splitting elements and a pair of differential E-O phase shifters. As shown by Fig. 1(b), the two metal heaters are allocated asymmetrically on the tunable DC to vary the transverse temperature gradient between the two waveguide cores, such that its power splitting ratio can be tuned larger or smaller to compensate for the potential deviation in the splitting ratio of the other DC due to fabrication imperfections. A pair of differential E-O phase shifters are designed to operate simultaneously to keep the losses of the two MZI arms the same, as shown by Fig. 1(c). Specifically, the differential E-O phase shifter pair counts on the impact of Joule heating which opposes the index modification brought about by carrier injection. When the switch is set in the bar state (i.e., with a π phase difference), the two phase shifters are turned on at different voltage levels, so that one is minimally affected by the Joule heating whereas the other is severely affected that the change

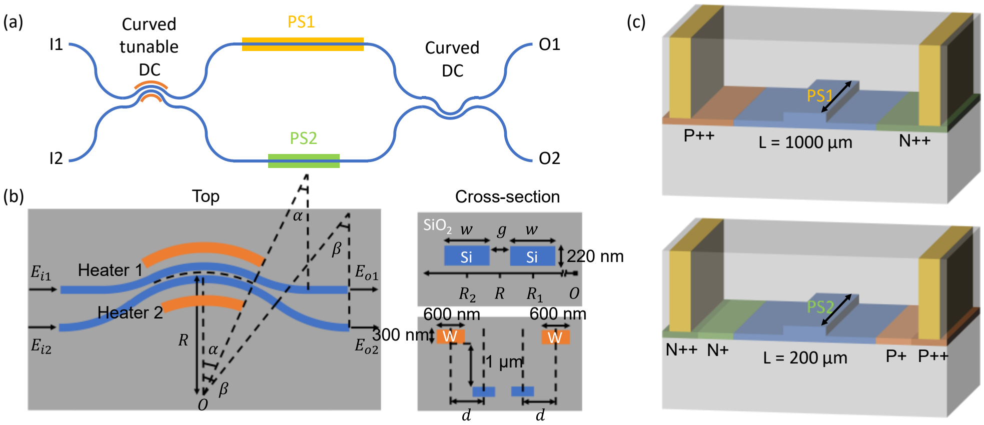

Fig. 1. (a) Schematic of the switch element. (b) Schematic of the curved tunable DC. (c) Cross-section schematic of the differential E-O phase shifters.

in effective refractive index caused by the Joule heating effectively cancels out the change caused by the carrier injection. In this manner, the two phase shifters are able to achieve a π phase difference and maintain the same insertion loss. In the following, the detailed design processes of the differential E-O phase shifter and the tunable DC are discussed successively.

Parameter design and simulations

The tunable DC employs a curved waveguide design, which enables a broad bandwidth as well as a high fabrication variation tolerance compared to conventional ones with straight waveguides. Its asymmetric nature is also suitable to work as a tunable DC. Figure 1(b) shows the schematic structure of the curved tunable DC, where w is the waveguide width, g is the waveguide separation in the coupling region, R and α are the bending radius and bending angle of the coupling region, respectively. The bottom waveguide is bent at a larger angle β to increase the separation from the top waveguide. Two tungsten (W) heaters, with a width of 600 nm and a height of 300 nm, are placed 1 μm above the silicon layer with a lateral distance d to the centre of the coupled waveguides. The structural parameters of the tunable DC are optimized using the particle swarm optimization (PSO) method [4]. The waveguide separation g was set as 300 nm to ensure a sufficient coupling length for thermal tuning and β was set to twice the value of α. The optimized design parameters are $w = 395\ nm, R = 60, \alpha = 9.4°$. The optimal position for the heater is found to be $d = 1\ \mu m$. 3D FDTD simulations were performed to calculate its coupling ratio at different heater power levels. Figure 2(a) illustrates the relationship between the power dissipated by the curved tunable DC and its cross-coupling ratio. As can be seen, it consumes only about 10 mW of power (0.55 V) to tune the coupling ratio from 0.5 to either 0.45 or 0.55. At this power level, the simulated temperature of the heater is about 169 °C. Figure 2(b) shows the wavelength dependence of the coupling ratio at different power levels. A broad bandwidth can be observed that the coupling ratio of the curved tunable DC decreases by less than 0.05 with the wavelength deviating from 1550 nm within ±20 nm.

To optimize the design of differential E-O phase shifters, we swept the structural parameters, including the doping profile of the p-i-n junction, the width of the intrinsic region, and the length of the phase shifter, and observed the relationship between the insertion loss and the phase shift at different parameters. Our simulation results illustrate that the E-O phase shifter's loss and phase shift characteristics are significantly influenced by its length. Longer phase shifters can provide the same phase shift at a lower insertion loss compared to shorter ones. Besides, phase shifters with a wider intrinsic region and a higher level of doping can also reduce the loss when providing the same amount of phase shift. Accordingly, we designed a differential EO phase shifter pair with different lengths, as detailed in Fig. 1(c). Figures 2(c) and 2(e) depict the curves of the insertion loss versus the phase shift and the I-V characteristics for the differential phase shifters, respectively. To obtain a π phase shift, the pair of phase shifters are designed to be driven by different levels of voltages (the longer phase shifter with 1.7 V while the shorter one with 0.89 V). In this case, their insertion losses keep the same at about 2 dB, while the total power consumption is around 70 mW (0.89 V × 6.6 mA + 1.7 V × 38.1 mA).

To evaluate the crosstalk performance of the proposed high-extinction-ratio E-O MZI, we perform the transfer matrix analysis. The transfer matrices between the input and output electric fields can be expressed as

$$\begin{bmatrix}E_{o1}\\E_{o2}\end{bmatrix} = C_{curved}\cdot P_{EO}\cdot C_{curved}\cdot\begin{bmatrix}E_{i1}\\E_{i2}\end{bmatrix} \qquad (1)$$

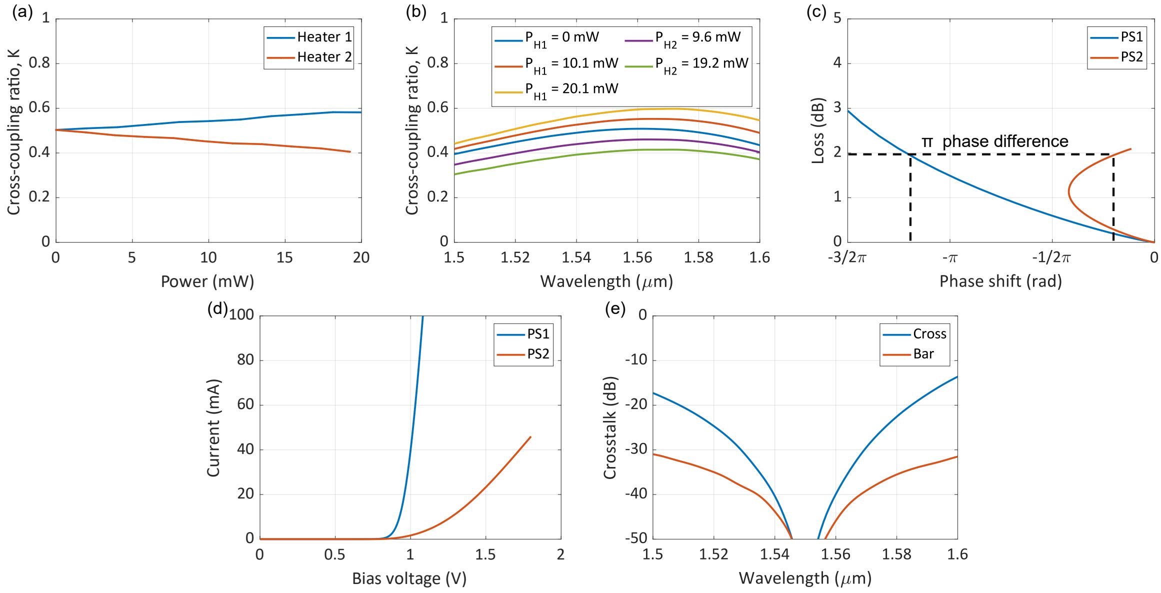

Fig. 2. (a) Cross-coupling ratio versus the power dissipated for the tunable DC. (b) Wavelength dependence of the tunable DC. (c) Insertion loss versus phase shift for the phase shifters. (d) Current versus bias voltage for the phase shifters. (e) Crosstalk versus wavelength for the proposed high-extinction-ratio switch element.

where C_{curved} is the transfer matrix of the curved coupler, and P_{EO} is the transfer matrix of the E-O phase shifter. C_{curved} is given by:

$$C_{curved} = \begin{bmatrix} te^{-j\left(\frac{\pi}{2}+\Delta\varphi'\right)} & ke^{-j\frac{\pi}{2}} \\ ke^{-j\frac{\pi}{2}} & te^{j\left(\frac{\pi}{2}+\Delta\varphi'\right)} \end{bmatrix} \tag{2}$$

where t is the straight-through coefficient, k is the cross-coupling coefficient, and $\Delta\varphi'$ is the phase difference between the two output ports of the curved DC. The transfer matrix of the EO phase shifter P_{EO} is:

$$P_{EO} = \begin{bmatrix} \alpha_1 & 0 \\ 0 & \alpha_2 e^{j\Delta\varphi} \end{bmatrix} \tag{3}$$

where α_1 and α_2 are the optical field transmission factor of the EO phase shifters. Figure 2(e) shows the crosstalk of our high-extinction-ratio E-O switch element in both cross and bar states. The crosstalk was calculated by substituting simulation data into Eq. 1. The simulated crosstalk becomes infinitesimal at 1550 nm for both states. The design good wavelength tolerance with the crosstalke below -30 dB in the range 1530 nm to 1570 nm for the cross state, whilst is it is even smaller in the bar state.

Conclusion

In this paper, we present a novel design approach of a 2×2 E-O switch element with ultra-high extinction ratio and ultra-low crosstalk. A curved tunable DC and a differential E-O phase shifter pair are employed to compensate for any fabrication imperfection and balance electro-absorption losses in the two interferometer arms. The device can completely suppress the crosstalk at 1550 nm, while keeping the crosstalk below -30 dB from 1530 nm to 1570 nm. The compact footprint and feature of high-extinction-ratio make our proposed switch element highly suitable for various switch architectures, such as the double-layer network (DLN) which is sensitive to first-order crosstalk in its middle stage. We foresee the proposed switch element to find wide applications in building high-radix silicon photonic switches with ultra-low crosstalk.

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