DESIGN AND PERFORMANCE OF 2x2 THERMO-OPTIC MODE SWITCH BASED ON SOI WAFER

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Abstract: Optical switch plays a crucial role in protection switching, cross-connect, and dynamic configuration in next-generation intelligent optical networks. In this paper, we first propose to design a 2x2 thermo-optic switch based on silicon-on-insulator with high switching performance. We then investigate the performance of the proposed mode switch in terms of insertion loss (I.L) and crosstalk (Cr.T) at switch's outputs. The simulation results demonstrated that this switch can support large bandwidth of 50 nm with I.L ≥ -0.7 dB and Cr.T ≤ -25 dB for both the bar state and the cross state at two inputs. The proposed switch may find potential applications in reconfigurable optical networks.

Keywords: Mode-division multiplexing (MDM), asymmetrical directional couplers (ADCs), thermo-optic effect, 2x2 MMI coupler, Y-junction.

I. INTRODUCTION

Currently, the increasingly human demand for using the Internet has been requiring larger broadband and faster data transmission speed in any networks, especially in the next generation optical networks [1], [2]. In high-speed optical networks, not only the speed may up to Tbps but also the bandwidth, data capacity and network flexibility are required much higher values and better performances, so electrical chips gradually fail to meet those above requirements. Photonic on-chip interconnects are an effective solution proposed to replace electronic chips, in which silicon-on insulator (SOI) material platforms are preferred due to their low cost, high refractive index contrast, small footprint, and improved compatibility with complementary metal oxide semiconductor (CMOS) technology and dense integration [3].

Although the technique of wavelength division multiplexing (WDM) is widely used, it has its limit on bandwidth [4]–[6]. While the technique mode division multiplexing (MDM) can break that limitation and, therefore, have been a caught lot of interests. Furthermore, MDM has attracted attention as a way to increase further data capacity by introducing high-order modes for each single wavelength carrier. In order to construct the MDM system, many optical devices have been proposed such as mode multiplexer/de-multiplexer and optical modal switches. The optical mode switch is an important device for reconfigurable MDM networks. The reconfigurable optical network can implement data exchange between arbitrary two optical modes. Optical switch are designed for optical network because of incompatibility with high-order modes. The switchable functionality means data information carried on two optical modes can exchange or not. In additions, it is important for an advanced and reconfigurable optical network and protection, can be performed by controlling the induced phase difference.

Recently, many papers have shown their attention to the design of a switch for optical networks. Even though some optical switch structures have used multimode interference (MMI) and Y-junction with fixed phase shifter [7]–[10], or micro-ring resonators [11], those structures remain the inflexible fixed proof. Because of its natural fixedness, it can only prove the operating principle but not the performance when putting into practical production. Another class of optical modal switches using phase shift on the MMI has been proposed in [12], [13]. Nevertheless the size of the device based on polymeric material and thermo-optic effect is large (120 µm $\times$ 7000 µm) [12] and therefore this proposal is difficult to integrate in the real systems. A research has been proposed to reduce the footprint and increase the tolerance by using the MMI structure based on SOI [13]. However, the length of the MMI is long (i.e., approximately 600 µm), the bandwidth efficiency at 1550 nm is low, and the maximum of the crosstalk is high (i.e., 20 dB). In addition, a 2×2 Mach-Zehnder Interferometric (MZI) thermo-optic switch at 2-µm waveband has been demonstrated [14]. It has a large optical extinction ratio of over 30 dB for roughly 18 nm bandwidth. The studies [13]–[14] have proven that silicon platform with thermo-optic effect can realize a large tuning range and especially a tuning-independent optical loss for optical switches. This is suitable for dilated switch modules thanks to the advantages of low loss and high extinction ratio.

In this work, we propose a novel 2×2 optical switch structure based on thermo-optic and dynamic switching of modes for exchanging the payload data among multimodal channels. This device is necessary for achieving full functionality of on-chip optical networks using MDM technology. The proposed device is based on SOI working at C-band with the center wavelength of 1550 nm. This design allows simultaneous handling of two fundamental modes injected at two input ports by combining an asymmetrical directional coupler (ADC), Y-junction with a 2×2 MMI structure. This combined design is compact and easy to be integrated in optical

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networks. Here, we design a controllable phase shifter using a heat source to switch the fundamental mode (TE_0) and the first-order mode (TE_1). Also, 2×2 MMI simultaneously enables high-speed switching and de-multiplexing of two modes created from the ADC coupler. The main contribution of this work are as follow:

- Application of the phase matching condition to convert fundamental mode input into fundamental mode and first-order mode.
- Application of the phase-shifter based for thermal-optic to switch modes.
- Proposal of 2×2 optical switch structure with single mode, which makes high performance for the potential applications of high-speed communication integrated systems.

The remaining part of the paper is organized as follows. Section II describes the proposed device's structure and principle. Section III demonstrates and analyzes the device characterization. Finally, Section V summarizes the research.

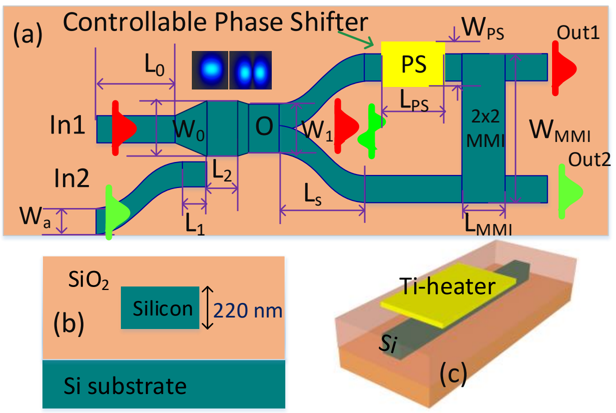

Figure 1. The proposed schematic of a two-mode switch, (a)Top View, (b)Size view, and (c) The phase shifter in the 3D sketch

II. DEVICE STRUCTURE AND PRINCIPLE

A. General Description

The schematic diagram of the device structure is shown in Figure 1(a) with a top view. The switch is based on SOI channel waveguides with 220 nm-thick top on insulator wafer illustrated in Figure 1(b). The operation wavelength λ = 1550nm and the refractive indices of the silicon core layer and the cladding silica layer are $n_r = 3.456$ and $n_c = 1.444$, respectively. In order to realize the switching function, the thermo-optic based phase-shifter shown in Figure 1(c) is used to control this switching. The phase-shifter is designed by a thin Titanium metal placed in the top of Silicon core layer. The proposed device can be fabricated by using modern methods, for instance, the whole device can be fabricated by using E-beam lithography method and dry etching technique as inductively coupled plasma (ICP) etching technique in the form of the channel waveguides.

The device is designed to support the operation of the fundamental mode in the three-dimension mechanism in the transverse electric (TE) modes polarizations states at the central wavelength of 1550 nm. EIM method is used to find out the effective index coefficients of guided the fundamental mode in the straight waveguide. It can be seen that in the Figure 2 the effective index depends on width of the waveguide. Therefore, W_a = 0.5 µm was chosen to guide the fundamental mode (TE_0).

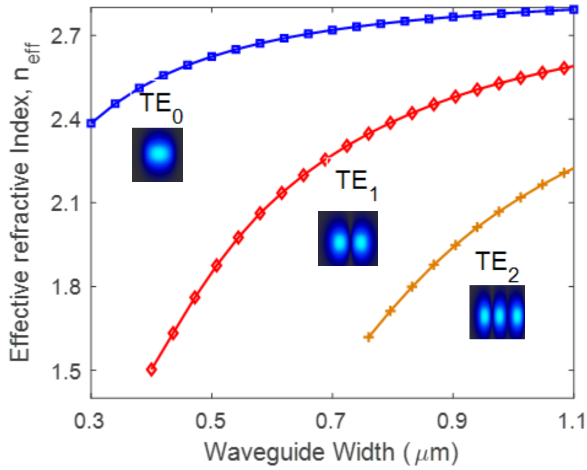

Figure 2: The effective index of the waveguide on variation of the waveguide width

Table 1: Structure parameters of the proposed device

Parameter	Dimension (µm)	Parameter	Dimension (µm)
W_a	0.5	L_1	16
W_0	1.2	L_2	100
W_1	0.9	L_S	140
W_{MMI}	2.5	L_{MMI}	24.9
W_{PS}	1.5	L_{PS}	200
L_0	60	h_{SiO_2}	0.7

The conceptual diagram of the 2×2 mode switch is used to switch between Out1 and Out2. First of all, an asymmetrical directional coupler has the function of converting single mode to multimode. Next, at Y-junction, fundamental mode and first-order mode are split equally for both branches. While the phase of TE_0 on the two outer arms is in phase, the phase of TE_1 is 180 degrees out of phase. Then, a phase shifter on one branch is used to allow these outer arms to interfere on the MMI to get the designed output state. The parameters of the switch structure are presented on Table 1.

B. Asymmetrical Directional Coupler

Multi-mode waveguides using ADC that can combine dozens of modes [15]. In this design that creates two modes, the inputs consist of a straight waveguide and a branch S-bent, which is used to combine single-mode optical signals into a multimode waveguide. This is mode mixer consisting of cascaded ADCs based on thin SOI nanowires, for which the propagation constants of the Eigen modes in the multimode bus waveguide are quite different. Therefore, it is helpful to reduce the crosstalk (Cr.T) between modes. The width for the *i*th section of the bus waveguide is determined when the waveguides satisfy the phase matching condition. Here, the phase matching occurs when $n_{eff}(W_a) = n_{eff}(W_0)$, where $n_{eff}(W_a)$ and $n_{eff}(W_0)$ are the effective indices of the TE_0 mode of the narrow access S-bent waveguide. The operation principle of ADC is demonstrated in Figure 3, and it can be seen that light is efficiently coupled from TE_0 mode in the straight waveguide passed through bus waveguide (see Figure 3(a)), while narrow access S-bent waveguide to the desired TE_1 mode is in the wide bus waveguide and very little power is left in the access waveguide (see Figure 3(b)).

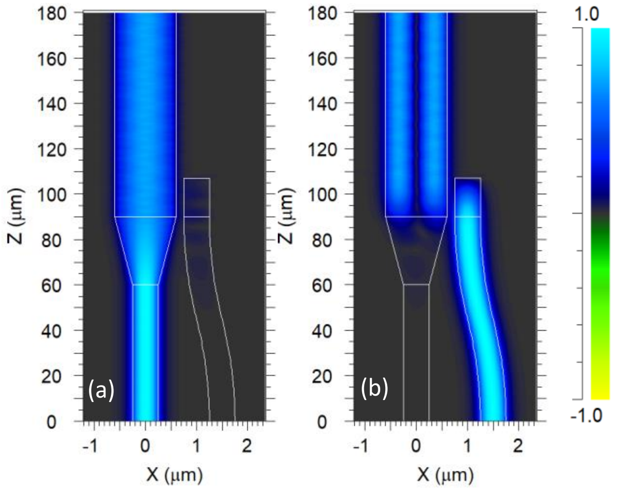

Figure 3. Simulated light propagation distribution of ADC at 1550 nm wavelength in the designed ith stage, (a) i = 1, and (b) i = 2

C. Y-junction

Because of their natural symmetry, Y-junction couplers are used as balance power splitters for each guided mode. With the width of W_a, the outer correspond to access waveguides that support the fundamental mode, whereas the wide waveguide (W_1) supports both the fundamental mode (TE_0) and the first-order mode (TE_1). By using the dimensional-beam propagation method (3D-BPM) and the phase matching condition, we choose widths in terms of stem and branch in the Y-junctions as $W_1 = 0.9$ μm and $W_a = 0.5$ μm, respectively.

D. 2×2 *MMI coupler*

Operating principle of the 2×2 MMI coupler is obeyed Talbot's effect [16]–[18]. The 2×2 MMI coupler will divide the optical input field into two equal parts (3-dB coupler) when the multimode length is equal to $L_{MMI} = 3L_\pi / 2$. Here, the length of MMI coupler (L_π) is defined as follows

$$L_\pi = \frac{4 n_{eff} W_e^2}{3\lambda}, \qquad (1)$$

where

$$W_e = W_{MMI} + \frac{\lambda}{\pi}\left(n_{eff}^2 - n_c^2\right)^{-0.5}. \qquad (2)$$

Here, W_e is the effective width of MMI region for TE mode, λ is the operation wavelength, n_{eff} is the effective index, n_c is the refractive index of the cladding layer. We use BPM simulation to optimize and characterize the length of L_{MMI} to get the desired output simulated in Figure 4. Consequently, we choose $L_{MMI} = 24.9$ μm to achieve the best output power and the power balance between the two output ports.

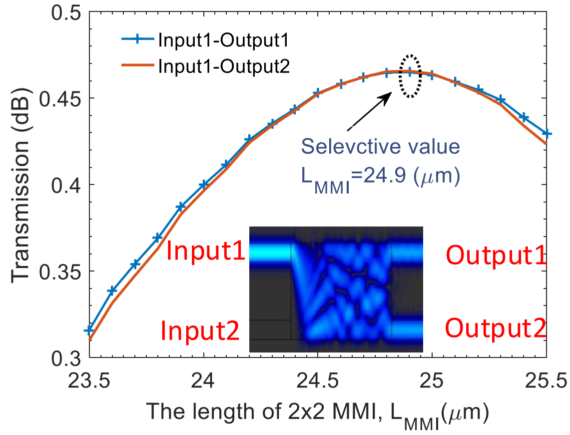

Figure 4. Simulation results to select the length of 2x2 MMI coupler

E. Controllable phase shifter

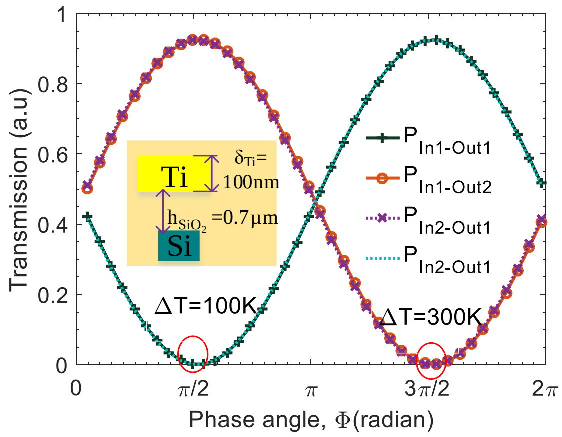

Figure 5. The transmission characteristics of the phase difference-dependent spectra for the input TE₀

In the configuration of controllable phase shifters placed at the positions in Figure 1(a) and Figure 1(b), by using 2×2 MMI coupler via simple algebra transformations, the optical fields combined at the output ports are reformed to their original modes, which are determined as follows

$$P_{a-b}(\Delta\Phi) = P_a \eta_{c,a} 10^{-\alpha L} \sin^2\left(\frac{\Delta\Phi}{2} - \frac{\pi}{4}\right), \qquad (3)$$

where *a* is symbol of input ports (In1, In2); *b* is the symbol of output ports (Out1, Out2); P_a is the input power of the fundamental mode; P_{a-b} is the reformed output power of the fundamental mode; $\eta_{c,a}$ is the accumulative coupling efficiency of the fundamental mode when propagating through device; α is the attenuation factor of the silicon core and approximate 1 dB/cm at the wavelength of 1550 nm; L is the propagation length of the device in the z-direction; $\Delta\Phi$ is the phase shift of the controllable phase shifters. Equation (3) indicates that TE_0 mode in input port In1 is switched to the bar output port Out1 if the phase difference $\Delta\Phi = \pi/2$ radian and switched to the cross output port Out2 if the phase difference $\Delta\Phi = -\pi/2$ radian, while the reverse is seen when TE_0 is excited at input port In2 as illustrated in Figure 5.

To control the phase shifter using the thermo-optic (TO) effect, we monitor the change in refractive index of the core layer caused by thermal excitation resulting in a change of the phase of the propagating light-wave. The phase and refractive index change may be calculated as [13]

$$\Delta\Phi = kL_h\Delta n = kL_h\frac{dn}{dT}\Delta T, \quad (4)$$

where L_h is the heater length to obtain the required phase shift of , $k = 2\pi/\lambda$ is the wavelength number, Δn is the total index change of the silicon material, dn/dT is the thermal coefficient for silicon 1.84×10^{-4} K^{-1}, and ΔT is the change in the temperature (degree Kelvin^{-1}).

To create a heat source, we design thermo-optic phase shifter in this proposed device shown in Figure 1(c), which consists of a thin metal. The Ti heater has a thickness of $\delta_{Ti} = 100$ nm, a width of $W_{PS} = 1.5$ µm, and a length of $L_{PS} = 200$ µm and the gap from Ti heater to Si core layer placed $h_{SiO_2} = 0.7$ µm given in Figure 5. This figure also shows the obtained results when ΔT=100K and ΔT =300K then $\Delta\Phi = \pi/2$ and $\Delta\Phi = -\pi/2$.

III. DEVICE CHARACTERIZATION

Figure 6 shows the electric field patterns under contour maps of fundamental mode in two inputs implemented by numerical simulation based on 3D-BPM for switching states in both the bar and cross direction at the wavelength of 1550 nm. The results express compatibility with the above instrument performance analysis, and a small negligible emission from the core to the clad.

In order to evaluate the performances of the proposed device in terms of topics, we consider to parameter to be Insertion loss (I.L) and Crosstalk (Cr.T) defined as

$$\text{I.L} = 10\log_{10}\left(\frac{P_{out}}{P_{in}}\right) \quad (5)$$

$$\text{Cr.T} = 10\log_{10}\left(\frac{P_{undesired-out}}{P_{in}}\right), \quad (6)$$

where P_{out} is the optical desired power at output port; $P_{undesired-out}$ is a leaked power at unwanted output port. P_{in} is input power of the In1 and In2.

Figures 7 and 8 demonstrate the transmission spectra of insertion loss and crosstalk monitored by 3D-BPM over the wavelength range from 1525 nm to 1575 nm of the C-band for the bar state (In1 to Out1 and In2 to Out2) and cross state (In1 to Out2 and In2 to Out1). Simulated I.L in the bar state is in the narrow scope from -0.7 dB to -0.3 dB for both input ports In1 and In2 with Cr.T of less than -25 dB for In1 and -28 dB for In2. This is seen similar to cross state. This performance is comparable to previous studies [9], [10] in this wavelength range. These high contrast between I.L and Cr.T (i.e., ≥ 25 dB throughout the full wavelength in question) results in good quality for the optical signal-to-noise ratio (OSNR) of the proposed 2×2 thermo-optic mode switch for optical networks with approximately 50 nm bandwidth. Our proposed 2×2 mode switch can support two directions with the size 4 µm$\times$800 µm, which is smaller than the switch size of 120 µm$\times$7000 µm that was proposed in [12].

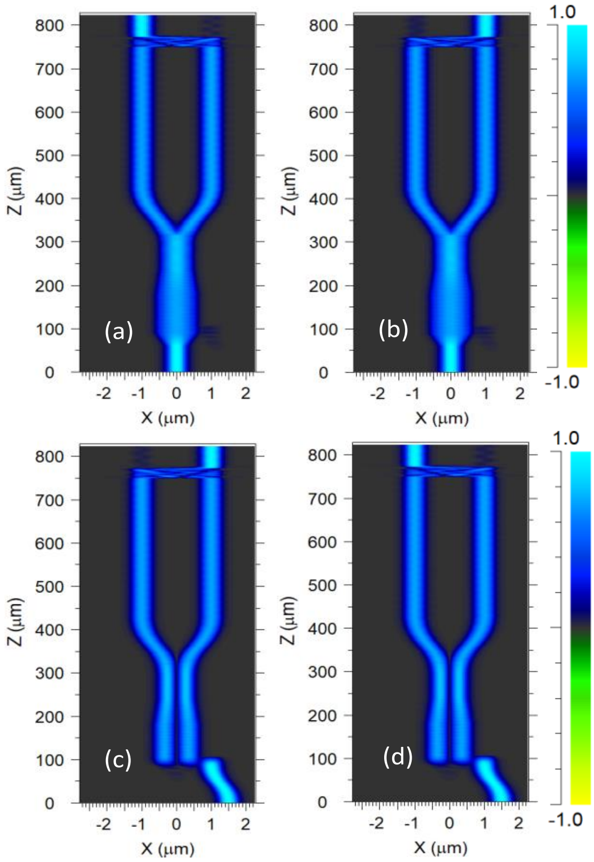

Figure 6. Simulated electric field patterns for the 2x2 mode switch (a), (c), bar sate and (b), (d) cross state

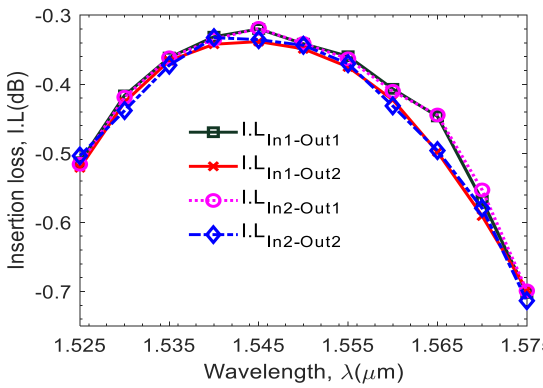

Figure 7. The optical performance characteristic of the device depends on Insertion loss, I.L(dB)

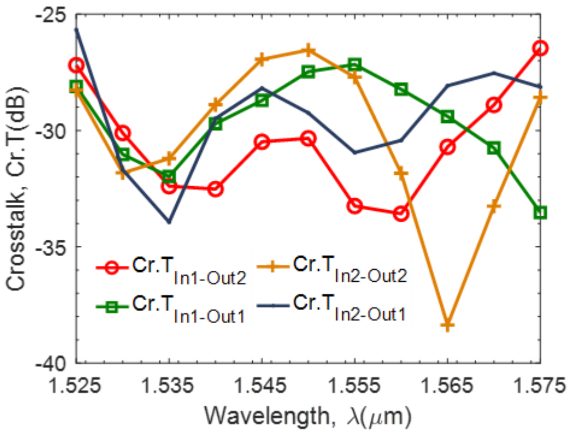

Figure 8. The optical performance characteristic of the device depends on Crosstalk, Cr.T (dB)

IV. CONCLUSION

In summary, the paper has presented a new structure of 2×2 thermo-optic mode switch based on silicon-on-insulator. The principle of the proposed structure was simply based on a asymmetric directional coupler, a Y junction and a 2×2 MMI coupler. It can flexibly switch the desired output states with high efficiency and low crosstalk in a wide range of wavelengths from 1525 nm to 1575 nm. In addition, the footprint is compact with a small size 4 μm $\times$ 800 μm, bringing a great number of potential applications in photonic-on-chip network and WDM-MDM switching systems, especially for variable optical distribution in new generation intelligent optical networks.

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THIẾT KẾ VÀ CẢI THIỆN HIỆU NĂNG CHUYỂN MẠCH QUANG NHIỆT DỰA TRÊN TẤM SILICON TRÊN CHẤT CÁCH ĐIỆN.

Tóm tắt: Bộ chuyển mạch quang đóng một vai trò quan trọng trong việc chuyển mạch bảo vệ, kết nối chéo và cấu hình động trong các mạng quang thông minh thế hệ tiếp theo. Trong bài báo này, trước tiên chúng tôi đề xuất thiết kế một bộ chuyển mạch quang nhiệt 2x2 dựa trên chất cách điện silicon với hiệu suất chuyển mạch cao. Sau đó, chúng tôi điều tra hiệu suất của công tắc chế độ được đề xuất về khả năng mất chèn (I.L) và nhiễu xuyên âm (Cr.T) tại các đầu ra của công tắc. Kết quả mô phỏng đã chứng minh rằng bộ chuyển mạch này có thể hỗ trợ băng thông lớn 50 nm với I.L ≥ -0.7 dB và Cr.T ≤ -25 dB cho cả trạng thái thẳng và chéo ở hai đầu vào. Bộ chuyển mạch được đề xuất có thể tìm thấy các ứng dụng tiềm năng trong các mạng quang có thể cấu hình lại.

Từ khóa: Ghép kênh phân chia theo mode (MDM), bộ ghép định hướng không đối xứng (ADC), hiệu ứng quang nhiệt, bộ ghép 2x2 MMI, bộ ghép nối Y.

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