Two-dimensional design and analysis of trench-coupler based Silicon Mach-Zehnder thermo-optic switch

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Abstract: Optical switches are key components for routing of light transmission paths in data links. Existing waveguide-based Mach-Zehnder interferometer (MZI) switches occupy a significant amount of real estate on-chip. Here we propose a compact Silicon MZI thermo-optic 2 × 2 photonic switch, consisting of two frustrated total internal reflection (TIR) trench couplers and TIR mirror-based 90° waveguide bends, forming a rectangular MZI configuration. The switch allows for reconfigurable design footprints due to selected control of the optical signal being transmitted and reflected at the 90° crosses and bends. Our analysis results show that the switch exhibits a chip size of 42 µm × 42 µm, the extinction ratio of ~14 dB, the rise and fall time of 20 μs and 16 μs, and the low switching voltage and power of 0.35 V and 26 mW, respectively. This device configuration can readily scale its pattern at the two-dimensional directions, making them attractive for Silicon photonic integrated circuits.

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References and links


1. Introduction

Optical switching is one of key function for realizing light transmission path routing in optical communication networks and on-chip interconnects [1, 2]. Compact waveguide-based photonic switches are desired in large-scale photonic integrated circuits (PIC) for efficient use of silicon real estate. Silicon photonics is considered as a promising platform for on-chip optical interconnects due to its compatibility with complementary metal-oxide semiconductor (CMOS) process and capability of dense integration. To date dominant switching mechanisms include electro-optic and thermo-optic effects [3, 4]. It is well known that electro-optic modulators and switches can allow for tens of GHz and tens of fJ/bit power efficiency using free-carrier plasma dispersion effect in Silicon [5]. However, such weak electro-optic effects are often coupled with microring resonator architectures which require heaters for wavelength stabilization. This thermal tuning, in reality, limits the device speed to the sub µs range [6]. Another mechanism, the thermo-optic (TO) effect, originates from changes in the refractive index from temperature in a semiconductor material, such as the resistive heating in Silicon [7, 8]. Similar to the microring approach, the TO mechanism relies on a relatively long response time (usually > 1 µs), and requires a high energy input (>10 nJ/bit). Although having the aforementioned drawbacks, this mechanism has shown to be reliable in operational devices and sub-systems on-chip [1, 9, 10]. Interestingly, due to a rather large thermo-optic coefficient in Silicon, the formed devices are relatively compact compared to those devices built by carrier density effects (excluding nanophotonics approaches) [7, 11].

A variety of waveguide-based photonic switches were investigated based-on designs such as directional couplers, multimode interference (MMI), ring resonators, and Mach-Zehnder interferometers (MZI) [4, 12]. The MZI design is widely utilized due to the advantages of high bandwidth and ease in fabrication tolerance [13–17]. Up to now improving the integration density, reducing the power consumption, and increasing the switching speed of the thermo-optic switches are underway (Table 1). Here only the MZI based thermo-optic
switches are listed out for fair comparison with this work. Various phase-shift arm configurations of the MZI structures were reported. Note, the discussed devices in Table 1 are representative examples and shall not be taken as an exhaustive list. These novel switches show the outstanding characteristics, such as low switching power and transition time, however the devices either occupy large amounts of real estate (e.g., > 4800 $\mu$m$^2$) or possess a longer one-dimensional (1D) scale (e.g., ~1000 $\mu$m). Toward improving durability, longer waveguide phase shifters and lower operating temperature are usually adopted for a phase shift of $\pi$ in Silicon MZI thermo-optic switches. For instance, an active waveguide length as long as 6.3 mm for the spiral waveguide design is used in order to produce a temperature change of 0.7°C [13]. However, there is a trade-off between the compact footprint and the low temperature change (i.e., durability). Although a direct comparison between experimental work and numerical design analysis in Table 1 may not warrant a head-on performance comparison, it is worth to point out that the current device design predicated potential advantages over current design schemes resulting in a more compact footprint.

<table>
<thead>
<tr>
<th>Configurations of phase-shift arm in MZI switches</th>
<th>Device size $L \times W$ ($\mu$m$^2$)</th>
<th>Switching power (mW)</th>
<th>Transition time ($\mu$s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photonic crystal waveguide [8]</td>
<td>$\sim120 \times 40$</td>
<td>78</td>
<td>20</td>
</tr>
<tr>
<td>Spiral waveguides geometries [13]</td>
<td>$\sim450 \times 50$</td>
<td>6.5</td>
<td>14</td>
</tr>
<tr>
<td>Si nanowire waveguide [14]</td>
<td>$\sim700 \times 400$</td>
<td>160</td>
<td>30</td>
</tr>
<tr>
<td>Suspended phase shift arms [15]</td>
<td>$\sim1000 \times 40$</td>
<td>0.5</td>
<td>144</td>
</tr>
<tr>
<td>Adiabatic bend with embedded silicon heater [16]</td>
<td>$&gt;300 \times 20$</td>
<td>12.7</td>
<td>2.4</td>
</tr>
<tr>
<td>Asymmetric arm using periodic response [17]</td>
<td>$\sim900 \times 400$</td>
<td>36</td>
<td>-</td>
</tr>
<tr>
<td>This work (theoretical predication)</td>
<td>$42 \times 42$</td>
<td>26</td>
<td>20</td>
</tr>
</tbody>
</table>

To address the longer 1D scale, here we propose a trench-coupler based Mach-Zehnder 2 × 2 thermo-optic switch with the flexible two-dimensional design deploying the Silicon-on-insulator (SOI) platform. This novel switch consists of trench couplers operated with a principle of frustrated total internal reflection (TIR) [18] and 90° waveguide bends using TIR mirrors. The formed device exhibits a rectangular layout configuration, which can easily scale its pattern in the two-dimensional directions, avoiding the excess longer phase-shift arms in one dimension. The chip size can be significantly reduced due to the small footprint of trench couplers used. We numerically investigate the switching performance, such as transmission efficiency, extinction ratio, and switching power and time. The trade-off between the fast thermal response and the low propagation loss is attained in terms of the optimization of the oxide cladding layer thickness. Experimentally we fabricated a key component of trench-coupler with a high aspect ratio of $>16:1$ to show the feasibility of the switch device processing.
2. Switch configuration

Fig. 1. (a) Three dimensional (3D) schematic structure of a trench-coupler based rectangular Mach-Zehnder 2 × 2 thermo-optic switch on a SOI platform. The two couplers are located at the intersection of input and output ports, respectively. The 90° waveguide bends are formed by etching of TIR mirrors at the corners of the L-shape interferometric arms. (b) Cross-sectional view of the phase-shift arm (left side), showing a geometry of the single-mode SOI ridge waveguide with a large cross-section, an oxide cladding layer, and a metal heater on the top. The ridge waveguide has an etching depth of 1 µm, the total height of t_Si = 2 µm, and the ridge width of W = 2 µm, respectively. A typical TE fundamental mode intensity profile in the corresponding cross-section of the ridge waveguide at 1550 nm wavelength (right side). (c) Scanning electron microscopy image of a trench-coupler, exhibiting a ~120 nm wide trench at the “+” intersection of two ridge waveguides.

This Mach-Zehnder 2 × 2 photonic switch consists of two 3-dB optical trench-coupler (i.e., splitter or combiner) and two 90° waveguide bends, forming a rectangular layout configuration [Fig. 1(a)]. The trench-coupler is created by a single “slash” deep narrow trench...
located at the intersection of two waveguides and is aligned 45° with respect to the light propagation direction, which can be realized by etching of a deep narrow trench at the "±" intersection of the phase-shift waveguide arms. Since the trench width is comparable to the penetration length of the evanescent wave, light may tunnel and become a transmitted in addition to being reflected. Successful demonstrations of trench-based frustrated-TIR couplers can be found in SOI [19], glass [20], and quantum-well InP substrates [21]. These couplers occupy ~100-fold reduction in footprint compared to current solutions (e.g., Y-branches, directional waveguide and MMI couplers).

Figure 1 (a) shows one of the interferometric arm covered by a thin-film aluminum (Al) metal heater. The top cladding oxide layer is deposited on the waveguide patterns, forming a buffer layer between the metal heater and the waveguide. The thickness, , is a trade-off parameter in terms of thermal response and waveguide propagation loss [left side in Fig. 1(b)]. The single-mode design in a SOI ridge waveguide was performed via a commercially available FIMMWAVE software package, with a built-in finite difference method mode solver. We can verify that such a larger cross-section waveguide only support a transverse-electric (TE) fundamental mode at 1550 nm wavelength [right side in Fig. 1(b)]. Similar to the operation principle of a typical MZI switch, the output intensity can be controlled by a π phase-shift arm due to the index change through heating. For instance, as light is launched into the input port 1, the light output can be switched from the output port 1 to port 2 with a proper driving voltage.

3. Switch design

Toward analyzing the functionality of the MZI 2 × 2 thermo-optic switch, this design is divided into three steps, (i) determining the trench width for a 3-dB power splitting, (ii) determining the temperature change required for a fixed length of the L-shape interferometric waveguide arm, and (iii) designing an efficient metal heater to tune the refractive index of the interferometric arm to produce a π-phase shift.

The 3-dB trench-coupler design was performed using RSoft’s FullWAVE Ver.9.0, a commercial 3D finite difference time domain (FDTD) tool. The trench width for an equal splitting ratio is dependent on both the waveguide index and the index of dielectric material filled in the trench [18]. Our results show that an about 110 nm wide trench filled with alumina (refractive index, ~1.75 at 1550 nm wavelength) forms a 3-dB coupler for TE light polarization on SOI. A trench-coupler was fabricated by an Oxford inductively coupled plasma (ICP) etching system using SF₆ and O₂ chemistry with a gas flow ratio of 32:10 at a low temperature of ~110 °C [Fig. 1(c)]. The trench width is ~120 nm. The overall trench depth, extending through the ridge region to cover the optical mode, is 2μm. Here we can show the feasibility of processing a high aspect ratio trench of >16:1. Successful demonstration of further narrowing the trench width as small as ~100 nm can be found in [22] by using an optimized Bosch process with low frequency biased substrate in SOI platform. The coupler size is comparable to the waveguide intersection area (i.e., ~4 μm²). Alumina can be backfilled into the trench through atomic layer deposition process allowing for a conformal deposition characteristics resulting in high aspect ratio features [21]. A total efficiency of ~88% can be attained for this coupler by FDTD.

The phase shift, , in one of the interferometric waveguide arms can be evaluated by

\[ \Delta \phi = \frac{2\pi}{\lambda} \left( \frac{\partial n}{\partial T} \right) \Delta TL_H (1 + \alpha_L \Delta T), \]

where \( \lambda \) is the light wavelength, \( \frac{\partial n}{\partial T} \) is the thermo-optic coefficient of Silicon (i.e., ~1.86 × 10⁻⁴/K at 1550 nm wavelength [7]), \( \Delta T \) is the temperature change in the waveguide core, \( L_H \) is the length of the phase-shift arm, and \( \alpha_L \) is the linear thermal expansion coefficient, \( \alpha_L = 3.6 \times 10^{-6} \degree\mathrm{C}^{-1} \) for Silicon [23]. Equation (1) shows that any \( L_H \) can result in a \( \Delta T \) based on a π-
phase shift. Considering both the limited computation resources and the reasonable simulation time, the total length of L-shape phase-shift arm, $L_H = 84 \mu m$, is selected for this design for example. A reasonable temperature change of $\Delta T = 49.5 ^\circ C$, is thus required to obtain a phase shift of $\Delta \phi = \pi$. A smaller temperature change of $\Delta T = 25 ^\circ C$ can be achieved for a longer phase-shift arm, e.g., $L_H = 166 \mu m$. Here we focus on showing the novelty of this photonic switch structure, i.e., the device pattern scaled at the two-dimensional directions by using trench couplers and 90° waveguide bends.

![Fig. 2](image-url)  
Fig. 2. (a) Temperature distribution profile on the L-shape Al heater surface at various applied voltages by FEM simulation. (b) Maximum index change of the phase-shift waveguide arm as a function of temperature on the metal heater surface. (c) Temperature distribution, and (d) index change profiles on the cross-section of the phase-shift waveguide arm, respectively.

Electro-thermal Joule heating allows for a straightforward yet relatively precise and powerful option to enable localized heating in micron-scale devices. To determine a proper voltage applied for the metal heater, a finite element method (FEM) software is utilized to investigate the temperature distribution profiles along the L-shape metal heater with various applied voltages [Fig. 2(a)]. Here Al is chosen as the resistive heater material due to its larger thermal conductivity of 240 W/(m·K) and CMOS processing compatibility. The Al heater was designed to be 84 $\mu m$ in length, 2.0 $\mu m$ in width, and 0.2 $\mu m$ in thickness for heating up the entire L-shape phase-shift arm. The shallow notch observed for each curve is due to the non-uniform temperature distribution at the corner of the L-shape heater. An optimized voltage of 0.35 V is found, which may give rise to an average ~130°C temperature on the Al heater surface. This results in a temperature change of ~50°C around the ridge waveguide core region. The maximum index changes are quantitatively estimated as a function of temperatures on the heater using Rsoft Multi-physics utility tool [Fig. 2(b)]. A noticeable index change of about 1.6% is achieved at a heater temperature of ~130°C, which can be utilized for switching. However the Al heater temperature of >100 °C is beyond the thermal
budget to typical CMOS limits. To address this problem, a longer L-shape phase-shift arm can be used, e.g., $L_{H} = 166 \, \mu\text{m}$, which can enable the Al heater temperature of $< 80 \, ^\circ\text{C}$ giving $\Delta T = 25 \, ^\circ\text{C}$ based on the similar simulation method shown in Fig. 2(c). In order to visually understand the thermal diffusion process, the cross-sectional distribution profiles of the phase-shift waveguide arm are investigated, showing the uniform temperature distribution [Fig. 2(c)] and the gradual change of index profile around the waveguide core [Fig. 2(d)].

4. Results and discussion

![Fig. 3. Thermal response of the L-shape phase-shift arm at the different thickness of top dielectric SiO$_2$ layer by using a finite element method. $h$ is defined by the thickness of the top SiO$_2$ layer between the metal heater and the ridge waveguide [Fig. 1(b)].](image)

Switching time is an essential parameter used to evaluate the switch performance. A thermal response analysis allows obtaining the transient response of the thermo-optic MZI photonic switch. The generated heat by the metal pad will be conducted to the top cladding layer of SiO$_2$ first [Fig. 2(c)]. Due to the thermal conductivity of SiO$_2$ being about 100 times lower compared to Silicon, the switching time thus relies on the thickness of the dielectric SiO$_2$ layer. For instance, a thinner SiO$_2$ layer can decrease the switching time because of a faster heat spread to the Silicon waveguide core (the case of $h = 0.1 \, \mu\text{m}$, Fig. 3). However, this may increase the waveguide propagating loss due to increased metal absorption from the changed mode geometry. Therefore, a trade-off between the switching time and the insertion loss of the device exists. The simulation results show that the metal absorption loss can be neglected for a SiO$_2$ thickness of $h \geq 0.5 \, \mu\text{m}$. We thus arrive at an optimized thickness ($h = 0.5 \, \mu\text{m}$) for the device design. The resulting transient analysis gives a rise and fall time of about 20 $\mu\text{s}$ and 16 $\mu\text{s}$, respectively (Fig. 3). Here the rise (fall) time is defined as the time interval for a signal to increase (decrease) from 10 (90)% to 90 (10)% level of the steady maximum value.

The transmission spectra and extinction ratio as a function of the driving voltages were numerically simulated by using the Rsoft FullWAVE software package (Fig. 4). The extinction ratio (ER) is defined by, $ER = 10 \log \left( P_{\text{output1}} / P_{\text{output2}} \right)$. For the previously mentioned switching voltage of 0.35 V, a corresponding $ER$ of $\sim 14 \, \text{dB}$ was found for the trench-coupler based thermo-optic MZI switch [Fig. 4(b)].

Switching power is one of key performance parameters representing the power efficiency. Toward evaluating the power to switch the phase by 180 degrees, $P_{\pi}$, we utilize a modified
one-dimensional analytical treatment of heat flow considering the lateral spreading, which is expressed by [24, 25],

\[
P_\pi = \frac{\lambda \cdot \kappa_{\text{SiO}_2} \left( \frac{W_M}{t_{\text{SiO}_2, \text{top}}} + 0.88 \right)}{\frac{\partial n}{\partial T}},
\]

(2)

where \( \kappa_{\text{SiO}_2} \) is the thermal conductivity of \( \text{SiO}_2 \), and is 1.4 W/(m·K), \( t_{\text{SiO}_2, \text{top}} \) is the thickness of the top \( \text{SiO}_2 \) layer, and \( W_M \) is the width of the metal heater. We find that the calculated switching power is \( \sim 26 \) mW.

Fig. 4. Simulated switching characteristics of (a) optical transmission, and (b) extinction ratio dependency on drive voltages applied on the heater by a 3D-FDTD method. TE polarized light is launched into the input port 1 at a wavelength of 1550 nm.

The switching cutoff frequency relating to the switching power can be written by [24]

\[
f_{\text{cutoff}} = \frac{1}{\pi \lambda \rho \varepsilon_{\text{th}}} \left[ \frac{P_L}{A} \right] \left| \frac{\partial n}{\partial T} \right|,
\]

(3)

where \( \rho \) and \( \varepsilon_{\text{th}} \) are the density and specific heat of \( \text{SiO}_2 \) material, respectively, and \( A \) is the heated cross-sectional area, i.e., \( A = (2L_{\text{th}} + W)(t_{\text{Si}} + h) \) [Fig. 1(b)], \( L_{\text{th}} \) is the thermal diffusion length considering the lateral heat spreading beyond the ridge width, \( W \), which can be estimated by the temperature distribution profile on the cross-section of the phase-shift waveguide arm [Fig. 2(c)]. A thermal length of \( L_{\text{th}} = 5.0 \) μm is obtained by taking the distance where the maximum temperature laterally decreased at \( 1/e^2 \) away from the waveguide ridge. Equation (3) thus gives an estimated cutoff frequency of \( \sim 50 \) KHz.

The figure of merit (FOM) of MZI-based photonic switches can be described by incorporating an aspect ratio (AR) factor between \( x \) and \( y \) dimensions of the device,

\[
FOM = \frac{ER(dB)}{AR \cdot P_L W \cdot IL(dB)}.
\]

(4)

Conventional couplers such as Y-branches, directional waveguide couplers, and MMI-based devices are typically adopted for the MZI optical switch configuration. The aspect ratio of these devices is usually beyond at 5. In contrast this TO switch can be designed at the two-dimensional directions allowing the AR to be as small as 1, which can form a square-shape device layout enabled by the light splitters and reflectors at the 90° direction for the trench couplers and waveguide bends, respectively. The total insertion loss of the switch is estimated to be \( \sim 2.0 \) dB using a FDTD simulation method by monitoring the output power. Here the
current design can achieve the maximum $FOM$ of $\sim 270$, which is larger than that $FOM$ of $\sim 63$ and $\sim 210$ for the switches configured with spiral waveguides [13] and adiabatic bend with embedded silicon heater [16], respectively.

5. Conclusion

We have designed and numerically investigated a trench-coupler based MZI thermo-optic $2 \times 2$ switch on a SOI platform. This novel photonic switch consists of two frustrated-TIR trench couplers and TIR mirror-based $90^\circ$ waveguide bends, forming a rectangular MZI configuration. The total chip size is significantly reduced due to the small footprint (i.e., size comparable to the waveguide intersection area) of the trench couplers used. The switch allows to be flexibly designed at the two-dimensional scales due to the feature of light transmitted and reflected at the $90^\circ$ directions. The device exhibits a compact chip size of $42 \mu m \times 42 \mu m$, an extinction ratio of $\sim 14$ dB, a rise and fall time of $20 \mu s$ and $16 \mu s$, respectively, and a low switching voltage and power of $0.35$ V and $26$ mW, respectively. Experimentally, we can show the feasibility of processing a trench-coupler with a high aspect ratio trench of $>16:1$ using an ICP etching technique on SOI platform. This device configuration can readily scale its pattern at the two-dimensional directions, avoiding the excess longer phase-shift arm in one dimension, making them attractive for Silicon-based high dense PIC and on-chip optical interconnects.

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