

Adiabatic thermo-optic Mach–Zehnder switch

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In this Letter, we propose and demonstrate a high-speed and power-efficient thermo-optic switch using an adiabatic bend with a directly integrated silicon heater to minimize the heat capacity and therein maximize the performance of the thermo-optic switch. A rapid, $\tau = 2.4 \mu\text{s}$ thermal time constant and a low electrical power consumption of $P_\pi = 12.7 \text{ mW}/\pi$ -phase shift were demonstrated representing a $P_\pi\tau$ product of only $30.5 \text{ mW} \cdot \mu\text{s}$ in a compact device with a phase shifter of only $\sim 10 \mu\text{m}$ long. © 2013 Optical Society of America
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Recent breakthroughs in the field of silicon photonics, including the low-loss silicon (Si) waveguides [1], high-speed and low-power silicon modulators [2], Germanium detectors [3], and high-speed switches [4,5], make silicon photonics a promising technology not only for on-chip optical communications but also for switching, signal processing, sensing, and numerous other emerging applications. This Letter focuses on switch elements that previously have taken on many forms, including both resonant and nonresonant structures [4,5]. While resonant devices are important for selecting a single channel, broadband switches often are desired for rerouting terabits of data at once or when the incident wavelength is not well known. Mach–Zehnder interferometers (MZIs) typically are used for broadband applications. Although broadband Mach–Zehnder switches based on the free-carrier effect have been demonstrated [4], the free-carrier effect is a relatively weak effect (requiring long path lengths) and introduces substantial loss in the switch. Switches based on the relatively large thermo-optic effect in silicon ($dn/dT = 1.86 \times 10^{-4} \text{ K}^{-1}$) [6], however, in principle, are lossless and can be highly compact, making thermo-optic switches attractive in applications requiring a large number of phase-shifter elements (e.g., in large-scale switching arrays). However, prior demonstrations of thermo-optic Mach–Zehnder switches required over-clad heaters, which are inherently inefficient due to the inevitable thermal spreading that accompanies them [7]. To solve this problem, we recently proposed and demonstrated a high-speed thermo-optic Mach–Zehnder switch that utilizes an adiabatic bend to insert heaters directly into the Si waveguides to enable the most efficient heating of the silicon possible [8]. Here we present the results in more detail together with a rigorous analysis of the structure, which achieve a rapid switching speed with a time constant $\tau = 2.4 \mu\text{s}$, and a low electrical power consumption of $P_\pi = 12.7 \text{ mW}/\pi$ -phase shift, representing a $P_\pi \cdot \tau$ product of only $30.5 \text{ mW} \cdot \mu\text{s}$ in a compact device with a phase shifter of only $\sim 10 \mu\text{m}$ long.

In a typical broadband silicon thermo-optic switch, the switching is realized by thermally shifting the optical phase by π in one of the waveguide arms in an MZI. In most applications, achieving a rapid switching speed with minimal power is highly desired. However, these

two goals are at odds. The power consumption in the switch in the on-state is given by $P_\pi = \Delta T_\pi G$, where G is the thermal conductance of the waveguide to the heat sink (i.e., the substrate) and ΔT_π and P_π are the temperature and power consumption required to achieve a π -phase shift in one arm of the interferometer. Conversely, the thermal time constant of the switch is given by $\tau = H/G$, where H is the heat capacity of the heated arm. Therefore, if we define the power-time product as a figure of merit (FOM) for the optical switch

$$\text{FOM} = P_\pi \cdot \tau (\text{mW} \cdot \mu\text{s}), \quad (1)$$

we see that $\text{FOM} = \Delta T_\pi H$, which therefore can be improved (i.e., lessened) only by reducing the heat capacity of the switch element. It is now straightforward to understand why previous instantiations of thermo-optic switches suffered from rather high FOMs (such as $\text{FOM} = 76 \text{ mW} \cdot \mu\text{s}$ in [7]), as the over-clad heaters they employed dramatically increase the heat capacity of the switch element. The large heat capacity is a result of having to heat the waveguide, the silicon-dioxide (SiO_2) cladding, and the heater element.

A higher FOM (smaller power-time product) therefore can be achieved only by reducing the heat capacity, H , of the phase shifter through direct heating of the Si waveguide. Although direct heating of a Si waveguide has been demonstrated in an MZI structure [9], in this early demonstration, the contact geometry would be expected to introduce significant optical loss and would not be suitable for optical switch networks with cascaded optical switches. Here we do so by inserting a compact heater directly into the waveguide with the help of an adiabatic bend, an approach we recently proposed to address similar electrical connection problem in microring-based modulators and filters [10,11]. The bend shown in Fig. 1 is achieved by slowly changing the inner radius of the waveguide, stretching the width of the waveguide from a single-mode input to a multimode region where contacts can be introduced in cases in which there is little optical field. The waveguide is electrically contacted with two narrow but heavily n^+ -doped silicon leads (concentration of $9 \times 10^{19} \text{ cm}^{-3}$). In the contacted region of the waveguide part, the silicon guide is lightly n -type doped (concentration of $1.8 \times 10^{18} \text{ cm}^{-3}$), creating a resistive

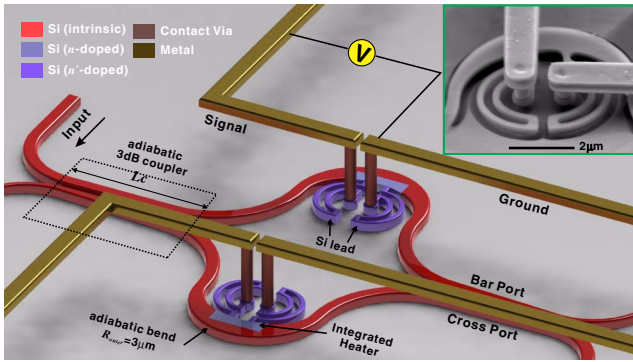


Fig. 1. (Color online) Schematics of the proposed broadband thermo-optic switch. Inset: scanning electron micrograph (SEM) of the fabricated optical switch.

heater in the waveguide. The long and narrow but heavily doped silicon leads provide low-resistance electrical connections as well as thermal isolation to prevent the metal contacts from melting at high temperatures. The calculated resistances of the heater and the leads are 5.6 and 3.2 k Ω , respectively, meaning 63% electrical power is applied on the heater.

In Fig. 2, a comparison of various waveguide bends using 3D finite-difference time-domain (3D-FDTD) simulations is provided. A 180 deg bend with an outer radius of 3 μm is adiabatically widened from an input width of ($w_0 = 0.4 \mu\text{m}$) to output widths varying from ($w_1 = 0.4 \mu\text{m}$) to ($w_1 = 1.5 \mu\text{m}$). Directly contacting a bent waveguide introduces scattering and loss [Fig. 2(a)], whereas too rapid a change in the waveguide width causes coupling between the propagating modes [Fig. 2(c)]. The simulations reveal that a moderate

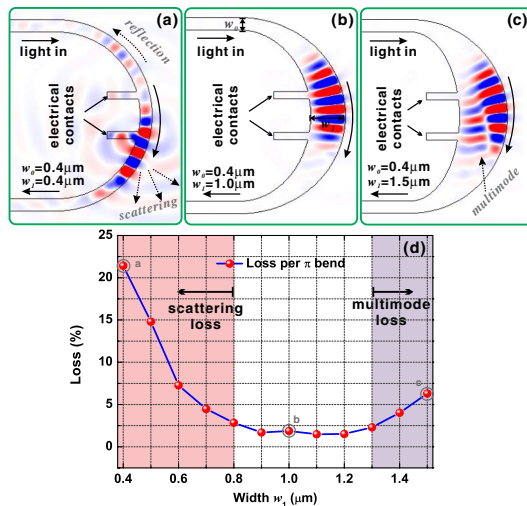


Fig. 2. (Color online) 3D-FDTD simulations showing (a) substantial optical loss due to the scattering of electrical contacts in a normal waveguide bend with $w_0 = w_1 = 0.4 \mu\text{m}$, (b) low optical loss in an adiabatic waveguide bend with $w_0 = 0.4 \mu\text{m}$, $w_1 = 1.0 \mu\text{m}$, and (c) high loss due to coupling to higher order mode in an abrupt bend with $w_0 = 0.4 \mu\text{m}$, $w_1 = 1.5 \mu\text{m}$. (d) 3D-FDTD simulations of the optical loss per π bend at different center width w_1 of the bend. At narrower w_1 , the loss is dominated by scattering loss; at wider w_1 , the loss is caused by coupling to higher order mode.

increase in the width of the waveguide prior to making electrical contact enables low-loss contact to be achieved [Figs. 2(b) and 2(d)]. At a wavelength of 1.55 μm , the optimal width of w_1 was found to be 1.0 μm . To achieve a broadband operation, an adiabatic 3 dB coupler [12] was used on both ends of the MZI with a coupling length of $L_c = 100 \mu\text{m}$. The smooth transition over the long coupling length again minimizes the optical mode coupling between fundamental symmetric mode and higher order asymmetric mode, and hence it provides equalized power splitting into both MZI arms over a large optical bandwidth.

Figure 3 shows thermal simulations of the proposed switch structure using a commercial finite element method (FEM) package (COMSOL). Figure 3(a) illustrates the temperature distribution on the waveguide when the electrical power is applied on the integrated heater. A transient thermal simulation, as shown in Fig. 3(b), also was carried out to determine the switching speed. The calculated heating and cooling time constants are $\tau_{\text{heat}} = 1.1 \mu\text{s}$ and $\tau_{\text{cool}} = 1.5 \mu\text{s}$, respectively.

The MZI-based silicon thermo-optic switch with embedded silicon heater shown in Fig. 1 was fabricated using CMOS processing techniques on a silicon-on-insulator wafer with 220 nm device layer on a 3 μm thick buried oxide layer. The whole structure was defined with an ASML deep ultraviolet (248 nm) laser scanner, followed by reactive ion etching of silicon. The embedded n -type heater was formed by arsenic (As) implantation at a dosage of $4 \times 10^{13} \text{ cm}^{-2}$, while the attached silicon leads were created by phosphorus (P) implantation at a dosage of $2 \times 10^{15} \text{ cm}^{-2}$. The silicon leads are connected to probing pads on the chip through tungsten vias and a layer of metal connection. A scanning electron micrograph of the fabricated device is shown in the inset of Fig. 1, with a compact footprint where the outer radius of the bend integrated with the silicon heater is only 3 μm . The measured resistance, including the two tungsten-silicon contacts is 11.2 k Ω , which is higher than expected due to the non-Ohmic contacts.

The fabricated chip was measured by coupling light from a cleaved fiber into the input waveguide through an inverted taper. The insertion loss of the optical switch was measured to be approximately 0.5 dB higher than a straight waveguide on the same chip, indicating a low scattering and absorption loss in the optical switch. When an electrical power of 12.7 mW was applied to

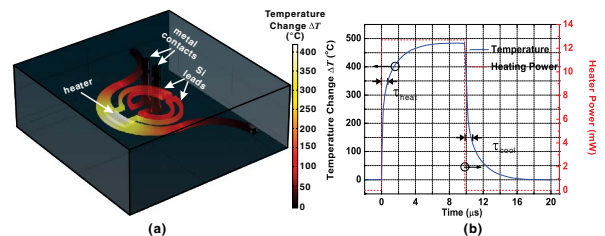


Fig. 3. (Color online) (a) FEM thermal simulation of the thermo-optic switch at steady state with applied voltage. (b) Transient thermal simulation showing the temperature change (blue) at the center of the bend when applying a pulsed heating power (red) on the thermo-optic switch, with a simulated heating time constant of $\tau_{\text{heat}} = 1.1 \mu\text{s}$ and a cooling time constant of $\tau_{\text{cool}} = 1.5 \mu\text{s}$.

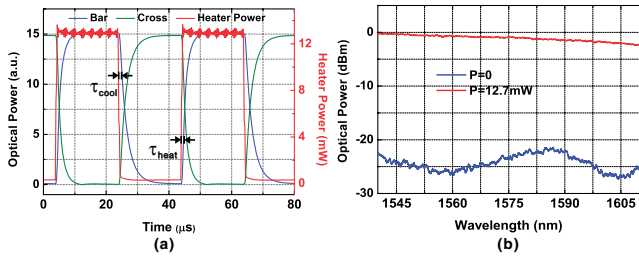


Fig. 4. (Color online) (a) Time-domain measurement of the fabricated thermo-optic switch, showing a low electrical power consumption of 12.7 mW to turn on the switch, with a cooling time constant of $\tau_{\text{cool}} = 2.4 \mu\text{s}$ and a heating time constant of $\tau_{\text{heat}} = 2.2 \mu\text{s}$. The vertical axis of the optical power is in linear scale. (b) Frequency domain measurement of the switch in the cross port showing a bandwidth of 70 nm and an extinction of >20 dB.

the heater, a π -phase shift was achieved in that arm and all the optical power switched to the bar port. The time-domain response was measured at a wavelength of $1.55 \mu\text{m}$ to determine the switching speed. A square wave was applied to the heater to turn the switch on and off, and the time-domain optical response in the bar port and the cross port was captured by an optical receiver whose electrical output was sent to an oscilloscope that is triggered by the square wave. The obtained time-domain response is shown in Fig. 4(a), with a measured cooling time constant of $\tau_{\text{cool}} = 2.4 \mu\text{s}$ and a heating time constant of $\tau_{\text{heat}} = 1.2 \mu\text{s}$, which is slightly different from simulation (Fig. 3) because the computation window was limited in simulation. Since the thermal time constant is determined by the rate of cooling, the demonstrated FOM of the proposed optical switch is $\text{FOM} = 30.5 \text{ (mW} \cdot \mu\text{s)}$. This FOM can be further improved if the high-Ohmic contact resistance can be reduced in the current fabricated device. An optical bandwidth >70 nm in C + L band from 1540 to 1610 nm was observed with a variation of less than 2.5 dB, benefiting from the broadband nature of the adiabatic 3 dB coupler, as shown in Fig. 4(b). A high extinction ratio of >20 dB also was observed across the 70 nm bandwidth.

In conclusion, this Letter defined an FOM to evaluate the switching speed and the power consumption of thermo-optic switches. A thermo-optic structure was

proposed and demonstrated in which a fast thermal time constant of $2.4 \mu\text{s}$ and a low power consumption of 12.7 mW were achieved, benefiting from the direct heating of the Si waveguide with an embedded silicon resistive heater. Broadband operation over a 70 nm optical bandwidth was demonstrated. The demonstrated low-power and high-speed optical switch is likely to find application in optical switch networks and optical signal processing applications.

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