Low Power and Broadband 2 X 2 Silicon Thermo-Optic Switch

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Abstract: We present a 2X2 silicon thermo-optic switch which requires a switching power of only ∼12.5 mW and has a response time of 5.4 μs. The measured extinction ratio of the switch is >∼20 dB across the C and L communications bands.

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1. Introduction

Optical switches are critical components for optical networks. The ability to reconfigure switches with low power is highly desirable. Furthermore switches with a small footprint are critical for space and satellite and flight based applications. Silicon has a relatively large thermo-optic coefficient of $1.86*10^{-4}\,{}^{\circ}K^{-1}$, additionally the large refractive index difference between silicon and its oxide (∼2) allows for extremely compact optical guided wave devices in silicon [1]. Typically thermo-optic devices in silicon are fabricated with metallic thin film resistive heaters [2, 3]. Due to the low thermal conductivity of oxide and the separation of the metal resistive heating element and silicon waveguide required for low optical loss these devices require switching powers which are on the order of 100 mW, moreover the low thermal diffusivity of oxide results in devices with response times which are typically ∼100 μs [4]. We recently presented a thermo-optic band-pass switch [5] which was based upon a second-order resonant filter design, here we present a broadband silicon thermo-optic 2 X 2 switch with a switching power of 12.7 mW a response time of 5.4 μs and a total device footprint of 311 μm x 14 μm. The key to the low switching power and fast response time of this device is direct resistive heating of the silicon waveguide by means of an integrated n-type silicon resistor.

2. Device Design and Fabrication

The device consists of a thermo-optic phase modulator on each arm of a Mach-Zehnder interferometer with differential input/output ports. The 3 dB splitters in this device were designed to be adiabatic, the designed dimensions of the adiabatic splitters can be seen in Fig. 1 (a). Unlike directional coupler or multimode interference splitters, adiabatic 3-dB splitters can have a uniform 50-50 split over very large wavelength bands with very little wavelength dependent loss and are therefore ideal for broadband switching applications [6].

In order to improve upon previously reported silicon thermo-optic switches we directly heat the silicon waveguide with an integrated n-type silicon resistor, as illustrated in Fig 1 (b). The difficulty in directly heating the silicon waveguide lies with the prevention of excess optical scattering created from electrical contact of the resistive heating element. In order to prevent scattering from the electrical contacts we use a design based upon previously reported adiabatic waveguide tapering which allows for reduced scattering from electrical contact regions [5, 7].

In our adiabatic design the waveguide is bent in a 6 μm diameter arc, the width of the guide is 400 nm at the beginning of the arc and 1 μm in the middle, its widest point. The tapering of the width is elliptical and symmetric through both halves of the arc. The theoretical calculation of the transfer efficiency through the phase-shifter arc was performed using the frequency-domain finite-element package COMSOL Multiphysics and is shown in Fig. 2 (a) and (b). The computation was carried out using two-dimensional field simulation under the effective index approximation. The effective index of the oxide-embedded 220 nm thick silicon slab was determined using the slab-waveguide dispersion equation and was found to be 2.872 at 1550 nm. This index was then assumed as the material index for the 2D field calculation. For the adiabatic phase-shifter, the transfer efficiency found using the above procedure was 98.39
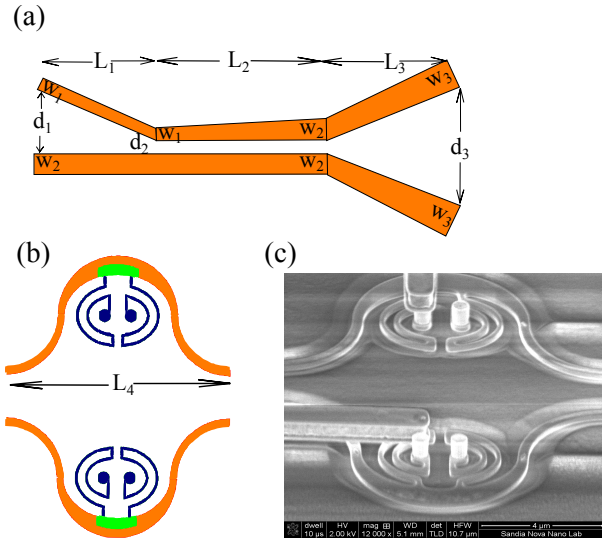
(a)

(b)   (c)

Fig. 1. (a) Adiabatic 3 dB splitter fabricated in silicon and clad by oxide where $w_1 = 280$ nm, $w_2 = 320$ nm, $w_3 = 400$ nm, $d_1 = 2.1\mu m$ $d_2 = 280$ nm, $d_3 = 2.0\mu$m, $L_1 = 25\mu$m, $L_2 = 100\mu$m and $L_3 = 25\mu$m (b) Thermo-optic phase modulators, an n-type resistor (green) contacted by tethered n^+ (blue) to silicided contacts with a total length of $L_4 = 11.2\mu$m. The optical waveguide is tapered in the region of the electrical contacts in order to prevent scattering. (c) Scanning electron micrograph (SEM) of fabricated thermo-optic phase modulators.

%. For a uniform arc with contacts, the efficiency was 85.86 % which demonstrates the efficiency of our adiabatic approach. Note that the loss represented by these numbers is the sum of the bending loss and the scattering loss.
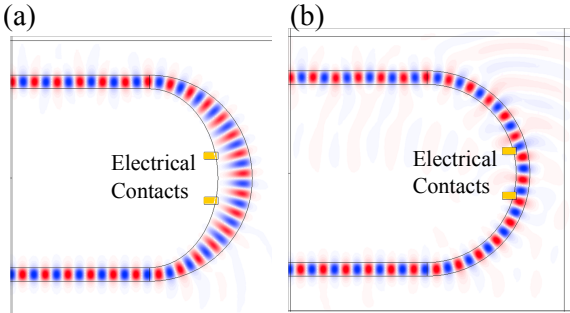
(a)   (b)

Fig. 2. (a) Simulation of optical transmission through an adiabatic waveguide bend with electrical contacts present, resulting in 98.39 % transmission. (b) Simulation of the optical transmission through a simple waveguide arc of width 400 nm with electrical contacts present resulting in 85.86 % transmission.

The thermo-optic switch was fabricated on a six-inch diameter silicon on insulator (SOI) substrate with 250 nm of silicon on 3 μm of buried oxide. The waveguide was patterned with an ASML Deep Ultra-Violet (248 nm) laser scanner and subsequently etched with reactive ion etching. The silicon layer was then oxidized down to a total thickness of 220 nm. The n-type resistor was formed by implanting $4 * 10^{13} cm^{-2}$ arsenic (Ar) using 380KeV directed from the four cardinal wafer direction at a seven degree tilt to minimize ion channeling in the silicon lattice. The electrical contact area was doped using $2 * 10^{15} cm^{-2}$ Phosphorus (P) again using a quad seven degree wafer tilt at an energy of 40KeV. Electrical contact was then made using standard 500nm wide tungsten plugs through an ~0.9 μm deposited tetra-ethyl oxy-silicate (TEOS) oxide layer. Aluminum lines and pads were subsequently defined and etched. Final passivation was performed with phospho-silicate glass (PSG). A scanning electron micrograph (SEM) of the fabricated thermo-optic phase modulators is shown in Fig. 1 (c).

3.   Experimental Results

The switching power and response time were measured and are shown in Fig. 3 (a). The switching time τ from the exponential decay $e^{-t/\tau}$ was measured to be 5.4 μs and was limited by the time required to cool the waveguide, the time constant for heating the device was measured to be 2.2 μs. The power required to switch from full power in the Bar port to full power in the Cross port was measured to be 12 .7 mW. Finally, the response of the switch was measured across the C and L bands (1535 nm- 1605 nm), demonstrating an extinction ratio of greater than $\sim$ 20 dB across the entire bandwidth and is shown in Fig. 3 (b).
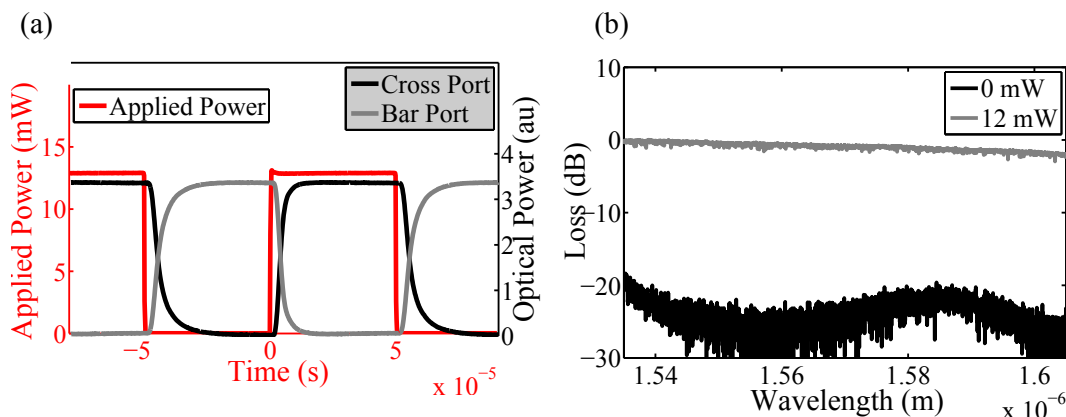

Fig. 3. (a) Measured response for power applied to the integrated heater for the optical Cross and Bar ports. The measured time constant was $\tau = 5.4\,\mu$s, limited by the cool down time. (b) Measured wavelength response of the switch across the C and L bands showing better than $\sim$20 dB extinction.

4.   Conclusion

We have demonstrated a 2 X 2 silicon thermo-optic switch with a low switching power of 12.7 mW, fast response time of 5.4 μs with a compact footprint of 311 μm x 14 μm and broadband operation across the C and L bands with greater than 20 dB extinction. This device was enabled by an adiabatic design which prevents optical scattering from the electrical contact of the integrated n-type silicon resistor.

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