Miniature Mid-Infrared Thermooptic Switch with Photonic Crystal Waveguide Based Silicon-on-Sapphire Mach–Zehnder Interferometers

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ABSTRACT

Ultracompact thermooptically tuned photonic crystal waveguide (PCW) based Mach–Zehnder interferometers (MZIs) working in silicon-on-sapphire in mid-infrared regime have been proposed and demonstrated. We designed and fabricated a PCW based silicon thermo-optic (TO) switch operating at 3.43 μm. Both steady-state and transient thermal analyses were performed to evaluate the thermal performance of the TO MZIs. The required π phase shift between the two arms of the MZI has been successfully achieved within an 80 μm interaction distance. The maximum modulation depth of 74% was demonstrated for switching power of 170 mW.

Keywords: silicon photonics, mid-infrared, photonic crystal waveguides, modulator.

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1. INTRODUCTION

Silicon is the dominant choice of semiconductor for microelectronics. Si nanophotonics is anticipated to play a critical role in the future ultra-compact system integration due to the maturity of sub-micron silicon complementary metal oxide semiconductor (CMOS) technology. In recent years, significant potential of silicon photonics in the mid-infrared wavelengths has been realized for optical sensing and interconnect applications. Ring resonators [1], photonic crystal waveguides (PCWs) [2, 3], photonic crystal (PC) microcavities [4] operating in mid-infrared wavelengths have been demonstrated in Silicon based platform. Photonic crystals (PCs) are well known for their slow light effect, hence provide a promising platform for developing novel mid-infrared optoelectronic devices with significantly reduced device size and power consumption.

In this paper, the active control of photonic crystal waveguides (PCWs) incorporated in Mach-Zehnder interferometer (MZI) in silicon-on-sapphire has been investigated. We designed and fabricated a PCW based silicon thermo-optic (TO) switch operating at 3.43 μm. A novel device structure was proposed to enhance the heat exchange efficiency between the source and the active PCW region, which resulted in a faster switching time compared with the conventional structure. The required π phase shift between the two arms of the MZI has been successfully achieved within an 80 μm interaction distance. The maximum modulation depth of 74% was demonstrated for switching power of 170 mW. The small footprint and low power consumption provide a milestone towards mid-infrared integration.

2. DEVICE DESIGN

Figure 1 shows the schematic of the PCW based MZI. The light from external laser source is coupled into and out from the chip through a pair of subwavelength grating couplers [5]. Since the PCW we designed will only open a bandgap for the TE polarized light, we therefore design our subwavelength grating coupler to have a selection for TE light. Hence, the TE polarized light is preferentially coupled into the chip from outside. After coupling into the chip, the light passes through a 1x2 multimode interference (MMI) power splitter which is describe in Ref. [4]. A group index adiabatic taper

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is designed at both the input and output ends of the PCW, as previously demonstrated, for efficient coupling of light between strip waveguides and PCWs with low Fresnel reflection losses at the interfaces [6, 7]. After passing PCWs, the light from two arms will combine and then couple out of the chip to detector. A gold based micro-heater is closely locates adjacent to one PCW. Therefore the heat from the heater will induce the refractive index change of the adjacent PCW, and further result in the phase difference between the two arms.

The PCW we used in our modulator comprises a W1.05 PCW where the width of the PCW is $1.05\times\sqrt{3}\times a$, where a is the PC lattice constant. Fig. 2 shows the dispersion diagram of the W1.05 PCW obtained by 3D plane-wave expansion simulation. Refractive indices of silicon and sapphire were considered as 3.429 and 1.7 respectively. The radius of the PC air holes is $r = 0.225a$, which gives a 40 nm PCW guided mode bandwidth compared to a 22 nm guided mode bandwidth previously [2]. There is a group index mismatch between input strip waveguide and the PCW which will reduce the coupling efficiency, hence in order to overcome this problem we design a group index taper. Light is guided in and out of the PCW by strip waveguides with PC group index taper to enable high coupling efficiency into the slow light guided mode [6, 7].

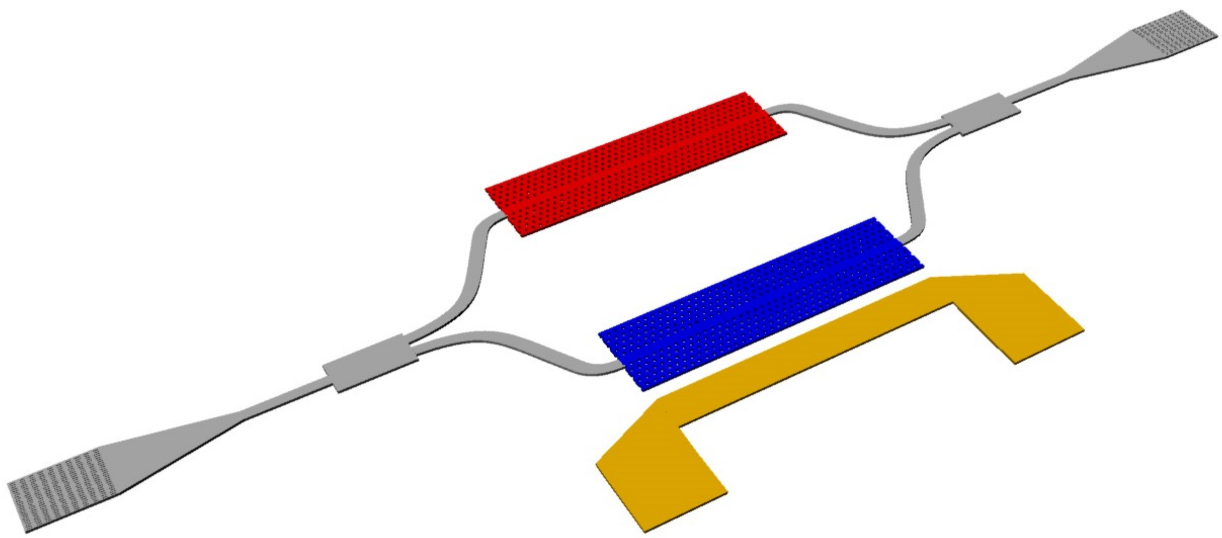

Fig. 1. A schematic of photonic crystal waveguide based MZI modulator

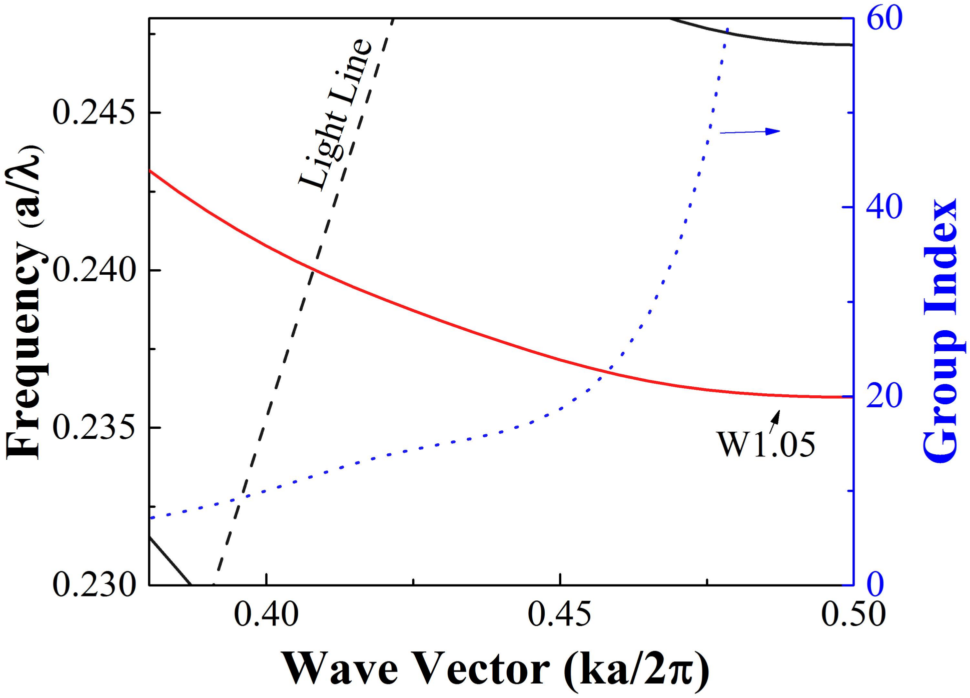

Fig. 2. 3D plane wave expansion simulation of the dispersion diagram of a silicon W1.05 PCW on sapphire substrate with air top cladding. Sapphire light line is superimposed.

3. DEVICE FABRICATION

Devices were fabricated using a combination of electron beam lithography and inductively coupled plasma etching. The process started from a SoS platform with 570 nm silicon device layer on a 500 µm thick sapphire substrate. The fabrication flow is shown in Fig. 3. A 140 nm silicon dioxide layer was first deposited on top of silicon layer using plasma enhanced chemical vapor deposition (PECVD) to serve as a hard mask for pattern transfer. All the components including grating couplers, strip waveguides, PCW were patterned in one step with JEOL JBX-6000FS electron-beam lithography tool. In order to ensure good control over the fabrication process, a thin conductive polymer (ESPACER) from ShowDenko chemicals was spin coated on the ebeam resist ZEP-520A, prior to ebeam lithography. After ebeam exposure, the devices was rinsed in DI water to remove the conductive polymer and then was developed in n-Amyl acetate (ZEP-N50) for 2 mins, and rinsed in isopropyl alcohol (IPA). The ebeam resist pattern was next transferred to silicon dioxide by reactive ion etching (RIE) using CHF_3 and O_2 at 400 V DC bias and 40 mTorr pressure for 8 mins. Following this, the pattern in silicon dioxide was transferred to silicon by inductively coupled plasma (ICP) etch using HBr and Cl_2 at 400 W ICP power, 200 W RF power, 10 mTorr pressure and 20 Torr Helium flow for backside cooling for 6.5 min. Finally, micro-heater contact windows were then opened by photolithography. Gold heaters were made by electron-beam evaporation and a subsequent lift off process.

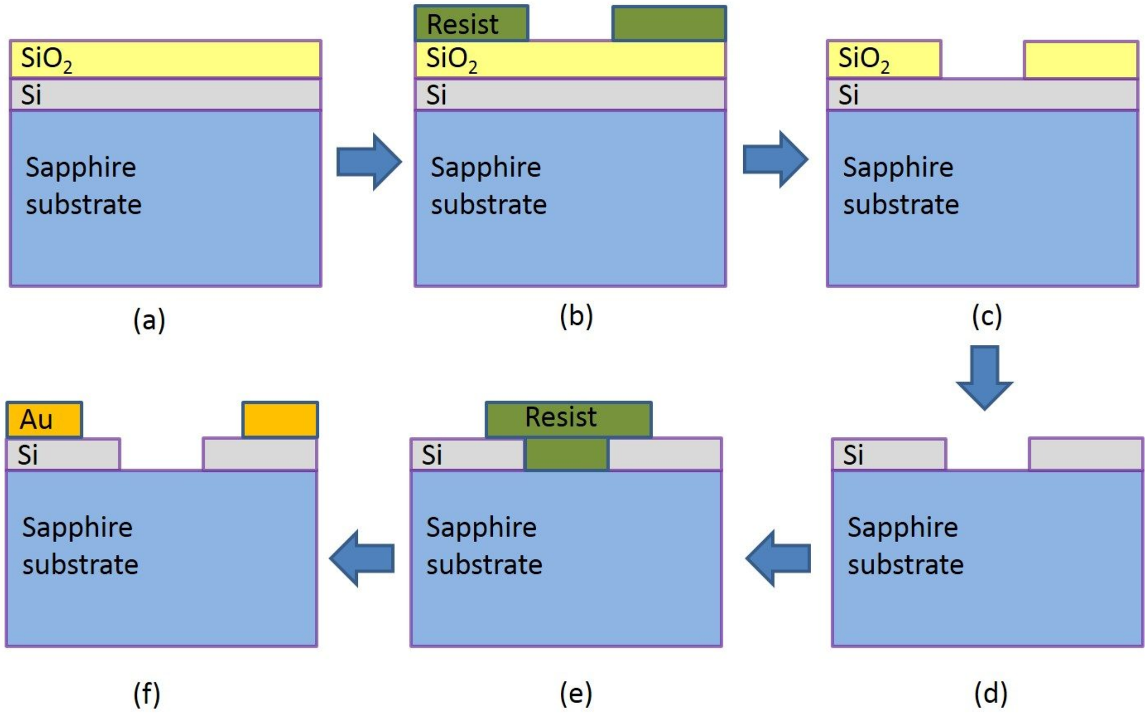

Figure 3: Fabrication steps of modulator (a) PECVD growth of oxide (b) E-beam Resist (ZEP-520A) patterning (c) Transfer of resist pattern to oxide by RIE using CHF_3 followed by resist strip (d) Transfer of pattern from oxide to Si by ICP in HBr and Cl_2 (e) heater contact windows opening (f) gold deposition and liftoff.

SEM images of the fabricated devices are shown in Figs.4 (a)-(d).

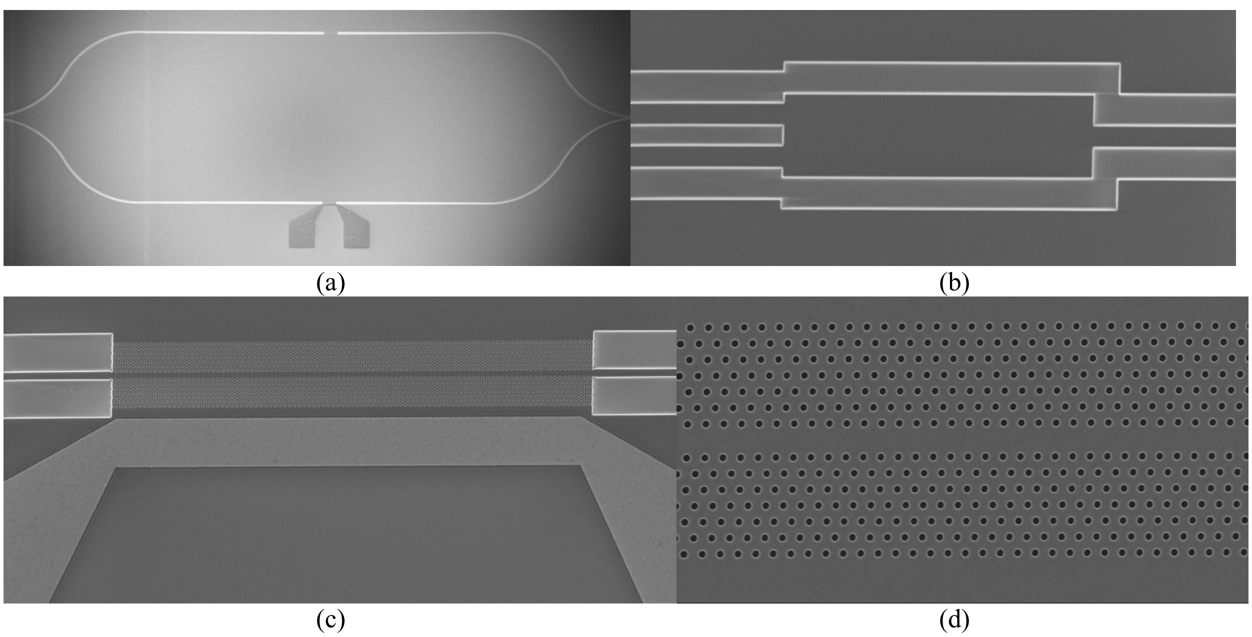

Fig. 4. (a) SEM image of the device showing the whole modulator. The dark block on one arm is a micro-heater. (b) Top view SEM image of 1x2 MMI. Magnified top view SEM images of (c) one arm of the MZI structure where the micro-heater locates. (d) PCW.

4. EXPERIMENTAL RESULTS

Devices are characterized using the setup schematically shown in Fig. 5. Light emitted from a continuous wave interband cascade laser from Thorlabs, with a fixed wavelength of 3.4 μm, is passed through a pair of ZnSe lenses and coupled into a 9 / 125 μm single mode ZrF_4 optical fiber from Thorlabs. Light from the optical fiber is then coupled into the fabricated chip via SWG couplers. The input fiber is not polarization sensitive. We make the assumption that the input light is equally split between the two orthogonal TE and TM polarizations. However the grating couplers have polarization selectivity ratio of TE to TM as 18：1. At the output end, another SWG coupler couples the light from chip to the output fiber. An InSb detector is used to measure the power from the output fiber. In order to improve the signal-to-noise ratio, a mechanical chopper is used with chopping frequency of 1 KHz, and the detected signals from InSb are demodulated by a lock-in amplifier. At a=820 nm, the probed wavelength of 3.43 μm probes the W1.05 PCW guided mode at group index around 20, as shown in our previous work [4], which translates experimentally to increasing modulation efficiency.

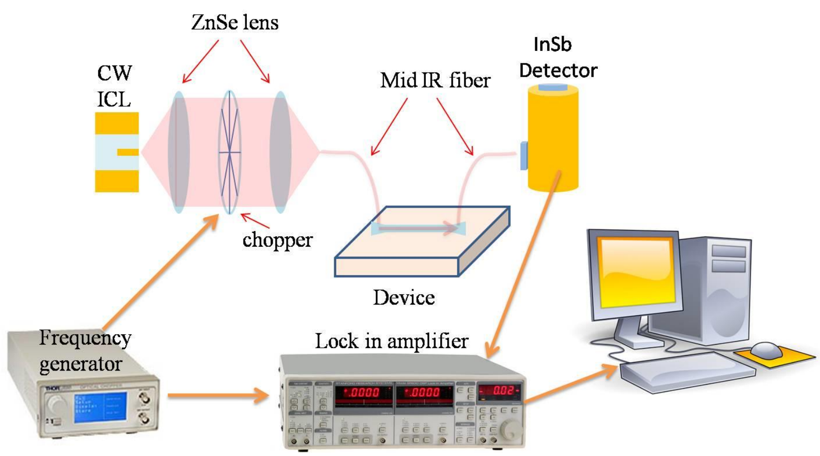

Fig. 5. Schematic of the experimental setup used to characterize our devices.

Figs. 6(a) and (b) plot the output optical intensity against the applied voltage and heating power at 3.43 μm respectively. A maximum modulation depth of 74% has been obtained for a switching power of 170 mW. A completely symmetric structure, which has micro-heaters on both the reference and signal arms of the MZI, may help increase the modulation depth through equalizing the optical intensity of two interfering beams.

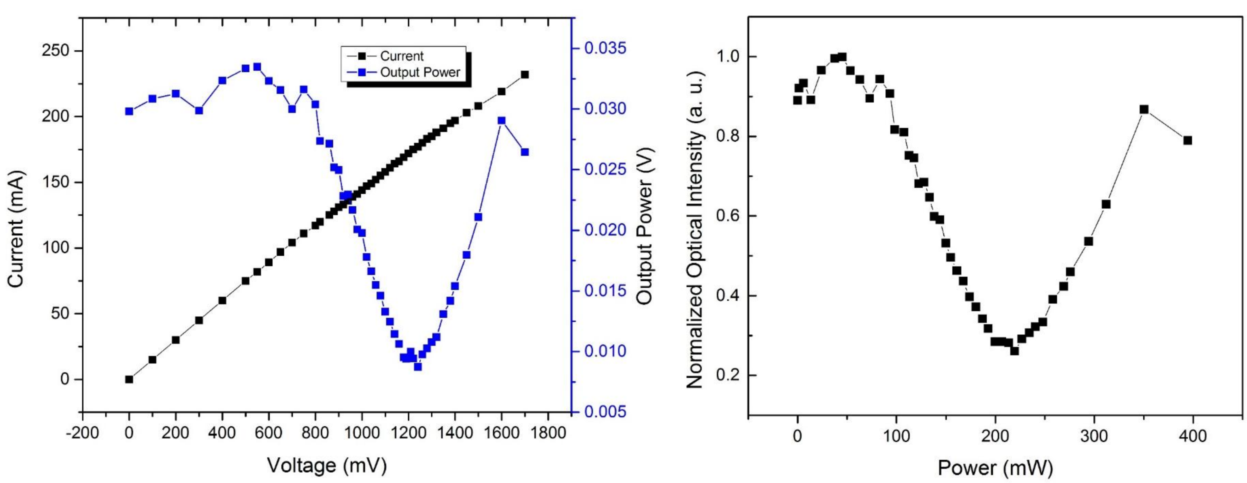

Fig. 6. (a) Applied current and output voltage of the detector against applied voltage (b) Normalized optical intensity against applied heating power at λ=3.43 μm.

5. SUMMARY

In summary, the active control of photonic crystal waveguides (PCWs) incorporated in Mach-Zehnder interferometer in silicon-on-sapphire has been investigated. We designed and fabricated a PCW based silicon thermo-optic (TO) switch operating at 3.43 μm. A novel device structure was proposed to enhance the heat exchange efficiency between the source and the active PCW region, which resulted in a faster switching time compared with the conventional structure. The required π phase shift between the two arms of the MZI has been successfully achieved within an 80 μm interaction distance. The maximum modulation depth of 74% was demonstrated for switching power of 170 mW. The small footprint and low power consumption provide a milestone towards mid-infrared integration.

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