WC5 (Invited)
18:00 – 18:30

Silicon Photonic Crystal Waveguide Modulators

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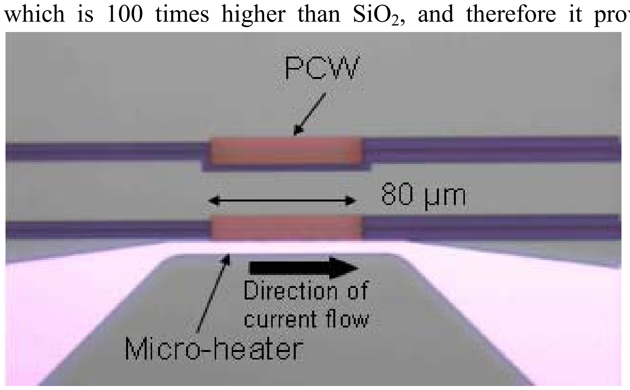
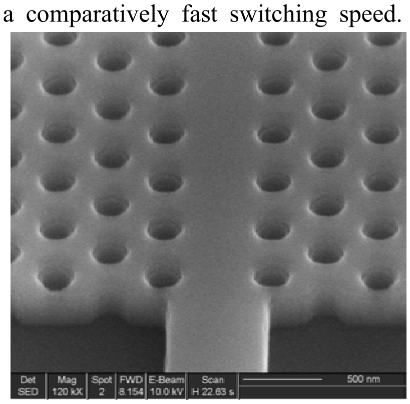
Abstract
Ultra-compact silicon-photonic-crystal-waveguide-based thermo-optic and electro-optical Mach-Zehnder interferometers have been proposed and fabricated. Thermal and electrical simulations have been performed. Experimental results were in a good agreement with the theoretical prediction.

Introduction
The driving force behind the development of silicon photonics is the monolithic integration of optics and microelectronics. Silicon remains the dominant material for microelectronics ever since the invention of the integrated circuit. Silicon-on-insulator (SOI) has been identified as a promising material for integrated optoelectronics. CMOS circuits fabricated on SOI benefit from reduced parasitics and absence of latch-up problem, which enable high-speed and low-power operations. SOI also provides strong optical confinement for the telecommunication wavelengths serving as an ideal platform to realize the guided-wave micro- and nano-photonic devices. Silicon microelectronic devices have undergone numerous generations of feature size reduction. However, there has been little progress made in the miniaturization of the silicon based optical components. Photonic crystal provides a promising platform to build ultra-compact and high-performance photonic devices [1]. It has been demonstrated that the light propagation in a photonic crystal waveguide (PCW) can have much slower group velocity than that in the conventional waveguides [2]. Such a slow-photon effect greatly enhances the interaction between the light wave and the wave-guiding materials, namely, it amplifies the optical response of materials to the external fields, such as thermal and electrical fields. It thus potentially leads to a significant reduction in size and power consumption. In this paper, we present the simulation and experimental results for ultra-compact silicon-PCW-based thermo-optic (TO) and electro-optical (EO) Mach-Zehnder interferometers (MZIs).

Results and discussion
For low-cost and low-frequency applications, the TO effect is considered an attractive alternative to the free-carrier EO effect for realization of optical switching and modulation [3, 4]. Silicon is an ideal material for implementing TO MZIs operating at 1.5μm mainly because: (1) silicon is transparent at this communication wavelength, (2) the TO coefficient is high in silicon, which is approximately 1.86 $X10^{-4}$ K^{-1} , two times greater than polymers and twenty times greater than SiO_2 and Si_3N_4; (3) the thermal conductivity of silicon is also high, which is 100 times higher than SiO_2, and therefore it provides a comparatively fast switching speed. The



(a)



(b)

Fig. 1 (a) Microscope image of the TO MZI;
(b) Scanning electron microscope (SEM) image of a PCW at the 45° viewing angle.

microscope image of the fabricated silicon-PCW-based TO MZI is shown in Fig. 1 (a). This device was fabricated on a SOI wafer with a 220 nm-thick top silicon layer and a 2 μm-thick buried oxide layer. The pitch size of the hexagonal photonic crystal lattice is a = 400 nm. The normalized air hole diameter is designed to be

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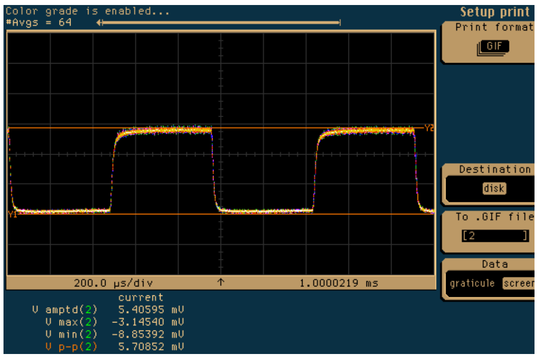
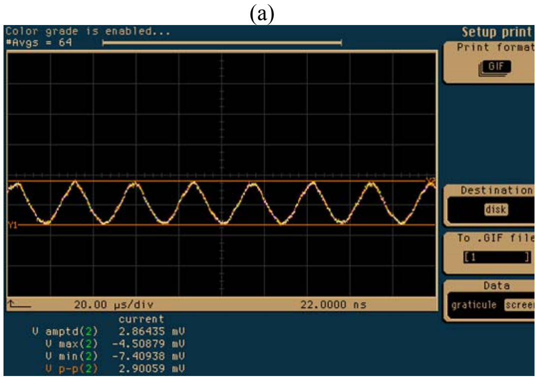
d/a = 0.53. Details of the fabrication were published in [5]. A Scanning electron microscope (SEM) image of the 45^o-view of the PCW in conjunction with an input strip waveguide is shown in Fig. 1 (b). The length of photonic crystal waveguides is 80 µm. An aluminum thin-film micro-heater with the dimension of 8µm X100 µm was deposited on the silicon layer. It was on one side of the active arm of the MZI. A static thermal analysis of such a device was performed using a finite element modeling software, ANSYS. The simulated temperature profile across the device showed a temperature rise of 9^{o}C in the line-defect region under an input ohmic heating power of 70 mW. It can be calculated, in a conventional silicon TO MZI, it requires an active region at least of 460 µm to obtain the π phase shift of the optical signal at 1.55 µm for a 9 ^{o}C temperature increase. Details of the calculation were previously reported [5]. However, in the PCW based MZI, the required length of the active region could be reduced significantly due to the amplification of TO effect in photonic crystals, which is intrinsically associated with the high-dispersion property of the PCW. We have experimentally demonstrated a size reduction of the silicon-PCW-based MZI by almost one order of magnitude compared with conventional TO MZIs [6].



(a)



(b)

Fig. 2 Modulation curves at (a) 1 kHz and (b) 30 kHz.

The modulation measurements were performed on a fully-automated Newport Photonics Alignment/ Packaging Station. The input and output lensed fibers can be accurately aligned with silicon waveguides by two five-axis high-precision stages with computerized control. TE waves were used for the optical measurements. We chose wavelength at 1548nm, which is at the edge of the defect mode, for the switching property characterization. Switching characteristics were obtained through a digital communication analyzer. The measured 3dB bandwidth was 30 kHz, which is a typical value of a TO switch. The modulation curves at 1 kHz and 30 kHz are shown in Fig. 2 (a) and (b), respectively. The rise (10% to 90%) time and fall (90% to 10%) time were measured to be 19 µs and 11 µs, respectively. It was one order of magnitude faster than that was reported in a conventional structure with the micro-heater placed on the top of the PCW region [7]. The maximum modulation depth of 84% was achieved at the switching power of 78 mW. The power consumption can be reduced by optimizing the heater geometry. It was previously shown by the ANSYS thermal simulation, a small temperature variation of 9 ^{o}C was obtained in the PCW region with a supplied heat power of 70 mW. It would require an active region at least 460 µm to achieve π phase shift in a conventional rib or strip waveguide based silicon TO MZI. Our experiments demonstrated almost a one-order of magnitude reduction in the length of the device active region, which obviously benefited from the slow group-velocity of the PCW.

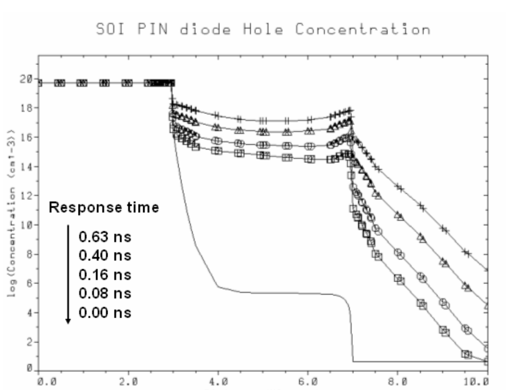


Fig. 3 Transient free-carrier distributions along lateral distance of the p-i-n diode.

The main drawback of the TO modulator is its comparative low switching speed. A feasible way to realize high-speed optical modulation in the GHz domain is to utilize the EO effect instead of the TO effect. Most EO silicon modulators operate based on plasma dispersion effect. The relation between the variation of the refractive index and perturbation of free-carrier concentration was studied by Scorf [8]. Here, we propose a lateral p-i-n configuration for a PCW based EO MZI, which has a different structure from as previously reported [9]. In this device, index tuning was achieved using a forward biasing voltage to inject free carriers into photonic crystal region of the active arm. The switching speed of such a p-i-n diode based device is usually determined by the carrier recombination time or carrier transit time depending on which one is larger. The transient characteristics of the p-i-n diode were simulated using a

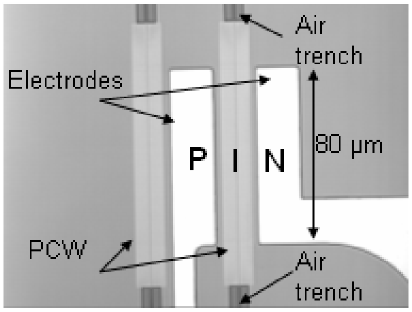


Fig. 4 Microscope image of the top view of a p-i-n diode based photonic crystal silicon MZI.

two-dimensional semiconductor device simulator MEDICI. The simulated p-i-n device has an n-type background doping concentration of 10^{15} /cm^3 in the i region, whereas a uniform doping concentration of 2X10^{19} /cm^3 was assumed for both p^+ and n^+ regions. The lateral electrodes were defined on top of the p^+ and n^+ regions, separated by 2μm from the PCW line defect. It is clearly shown in Fig. 3 that the minority carrier injection in the intrinsic region, which is also the PCW region, is fairly uniform. A carrier concentration perturbation of around 3X10^{17} /cm^3, which induced a real refractive-index change of silicon about -0.001, was predicted within 0.63ns under a forward biasing voltage of 2V. Further decrease of response time can be achieved by reducing the separation distance between the two lateral electrodes. For an index variation about 0.001, it usually requires one-half to several millimeters active region to obtain the required π phase shift in the conventional rib waveguide based MZIs [10]. However, in our proposed PCW based MZI modulators, an active PCW region with a few tens of microns in length is long enough to achieve sufficient phase shift [9]. The microscope image of the fabricated p-i-n diode based silicon PCW MZI is shown in Fig. 4. As shown in Fig. 4, the p^+ and n^+ regions were carefully designed to avoid electrical breakdown at the fragile edges of photonic crystal waveguides and the advantages of such a design have been demonstrated in experiments. Extensive electrical and optical measurements is currently under investigation. More detailed experimental results will be presented at the conference.

Summary

In summary, we have proposed and fabricated ultra-compact silicon-PCW-based EO and TO MZIs. Device configurations were carefully designed based on the thermal and electrical simulations. The size of the silicon modulators was significantly reduced by incorporating the PCW into to MZIs. Both TO and EO devices have been fabricated and characterized.

Acknowledgements

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