Invited Paper

Silicon Modulators Based on Photonic Crystal Waveguides

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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 and optical characterizations have been performed. Experimental results were in good agreement with the theoretical predictions.

Keywords: photonic crystal waveguide, silicon modulator, Mach-Zehnder interferometer, thermo-optic, electro-optical, plasma dispersion effect

1. INTRODUCTION

The physical limitations of conventional interconnects and the arguments for introducing optical interconnects have been discussed for the last few years. The field of intra-system optical interconnects is currently at a transition point between the academic research and industrial development. Optical interconnects provide many advantages over their electrical counterpart, such as high-bandwidth, low latencies and low power dissipation. These advantages call for the research on the optoelectronic integrated circuit (OEIC). For quite a long time silicon has not been considered an ideal material to realize photonic devices due to some of its intrinsic properties, such as indirect band-gap and slow carrier mobility. Currently, the primary devices in OEIC still rely on semiconductor materials from group III-V and II-VI. However, trigged by the realization of cost-effect monolithic integration of the optical and electrical devices using well established silicon-based very-large-scale-integrated (VLSI) technology, the global research interest on silicon photonics has increased rapidly in recent years. Significant progress has been made in the demonstration of silicon low-loss waveguides [1, 2], light emitters[3], lasers[4], amplifiers[5] and photodetectors. However, little progress has been made in the research on compact and large-band-width silicon electro-optical modulators. Device size of silicon modulators is traditionally large owning to the weak optical effects in silicon material. Because of its inversion symmetry, silicon does

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not have linear electro-optic (Pockels) effect. It has been studied that its refractive-index changes due to Franz-Keldysh effect and Kerr effect are also very weak [6]. These leave the thermo-optic (TO) effect and plasma dispersion effect the most efficient means to obtain the index tuning within the silicon. Nevertheless, the TO and EO coefficient of silicon is comparatively small which make the resulting phase-shift based optical amplitude modulator, such as the most intensively studied structure Mach Zehnder interferometer (MZI), stay in large size and high power consumption.

The beginning of 21st century witnesses the pervasive presence of nanostructures and nanofabrication in science and technology. In photonics, nano-scale structures, particularly photonic crystals, hold the promise of achieving the same function in a significantly reduced device size with reduced power consumption. Optical waveguides based on photonic crystal line defects, the so-called *photonic crystal waveguides* (PCWs), have been demonstrated to provide five orders of magnitude larger dispersion than conventional dispersion compensating fiber [7, 8]. This brings the exciting prospect of replacing kilometers of conventional dispersion-compensating fiber with a PCW of merely a few centimeters, among numerous other promising applications. Such an extraordinary dispersion capability has a profound impact on the phase velocity change over a segment of photonic crystal waveguides [9]. When incorporated in MZI, photonic crystal waveguides lead to a significant enhancement of the phase modulation efficiency, which in turn allows us to reduce the modulator electrode length by several orders of magnitude. For optical intensity modulators, the MZI structure that converts a phase modulation into an intensity modulation is most widely used. Consider a typical dispersion relation for a PCW mode shown in Fig 1. If the refractive index of the waveguide core material (*i.e.* silicon) varies by an amount of Δn, the dispersion curve will shift vertically by an amount $\Delta \omega_0$. For a fixed frequency of light, the propagation constant β

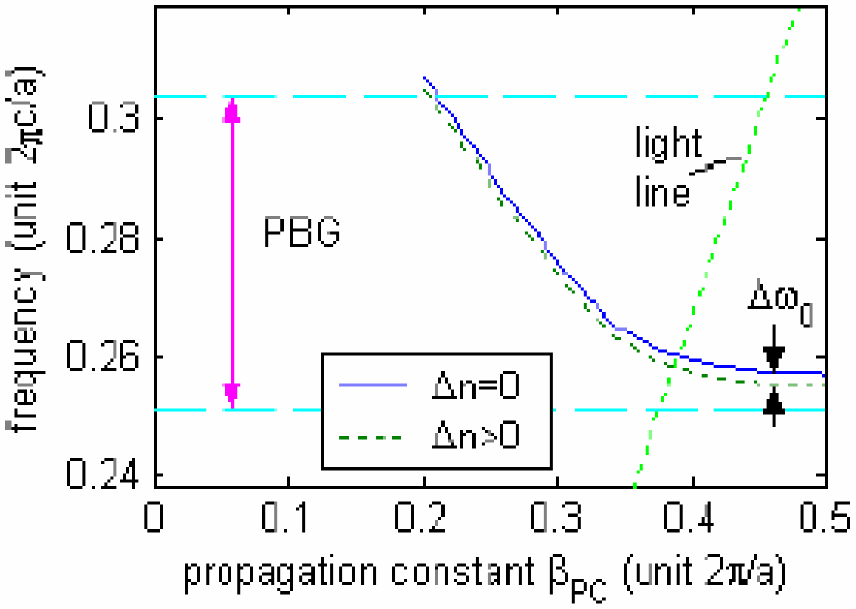


Fig. 1 Photonic crystal waveguide dispersion relation, used to illustrate the principle of enhancing modulation efficiency through highly dispersive photonic crystal waveguide

pc of PCW changes as $\Delta\beta_{pc} = \frac{d\beta_{pc}}{dw}\Delta w_0$, which grows significantly whenever the group velocity $\frac{d\beta_{pc}}{dw}$ approaches zero, e.g. on the right-most segment of dispersion curve in Fig 1 . Such an extraordinary growth of Δ β *pc* directly leads to a significant enhancement of phase modulation efficiency because the phase change is related to the change of propagation constant and waveguide length *L* as $\Delta\varphi=\Delta\beta_{pc} \times L$ [9]. Therefore, a much shorter PCW can produce the same phase change as a long conventional waveguide owing to the significant increase of Δ β *pc*. The short device length is a beneficial feature for many other device performance considerations. Propagation loss for PCWs has been a concern for some applications that employ a long PCW segment. With the advance of nano-fabrication technology, the propagation loss for PCWs has been controlled to below 1dB/mm. The proposed device has a short PCW of a few tens of microns in length, which results in a low propagation loss. Note that in the proposed device, the dimension shrinkage is achieved by enhancing the modulation efficiency through a new mechanism rather than through condensing high injection current into a small area (i.e. increasing the injection current density or power density). As the area density of power consumption in the proposed device remains about the same as a conventional device, the power dissipation of the proposed ultra-compact modulator is expected to be close to two orders of magnitude lower owing to the considerably shorter electrode length. In this paper, we studied device performance of PCW based thermo-optic (TO) and electro-optical (EO) silicon Mach-Zehnder interferometers (MZIs). Both theoretical predictions and experimental results are presented.

II. RESULTS AND DISCUSSIONS

PCW BASED THERMO-OPTIC SILICON MODULATORS

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 [10, 11]. 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 1.86×10^{-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 schematic of proposed PCW based TO MZI is shown in Fig. 2.

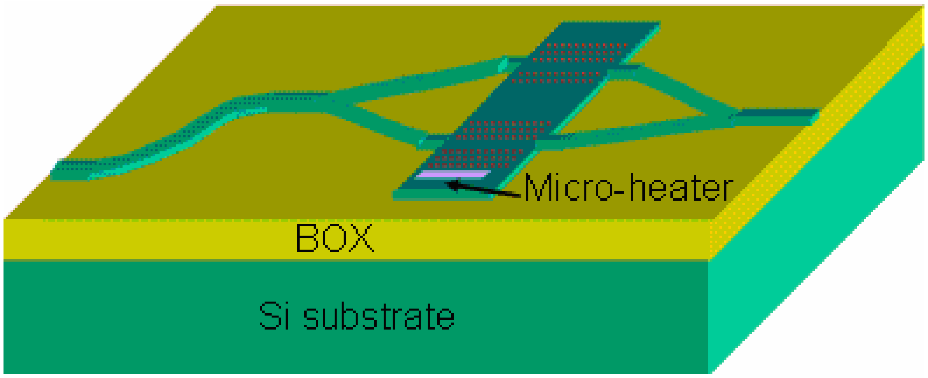


Fig. 2. The schematic of the proposed PCW based TO MZI.

In the proposed structure, decreasing the lateral distance between the heat source and the optical confinement region will largely facilitate the heat exchange. However, a large amount of absorption loss occurs when the optical field is in proximity to metal heater. The Optical mode profile of a carefully designed PCW was simulated by the plane wave expansion method. Fig. 3 shows Optical simulations of a photonic crystal waveguide. It is obvious that most energy was confined within the line defect and becomes evanescent into the photonic crystal (PhC) region. A more than 40dB decrease of optical energy was obtained at the location 1.5 μm away from the line-defect of the PCW. This simulation indicates the optical loss owing to the metal absorption is negligible as long as the metal heater is separated from the line-defect region by a distance larger than 1.5 μm. In our designed structure, 15 columns of air-holes with diameter of 400 μm are defined on each side of the line-defect to achieve a great optical confinement. An aluminum metal heater was designed to be placed on one side of the active PhC region, which is around 5.2 μm away from the central position of the line-defect.

(a)

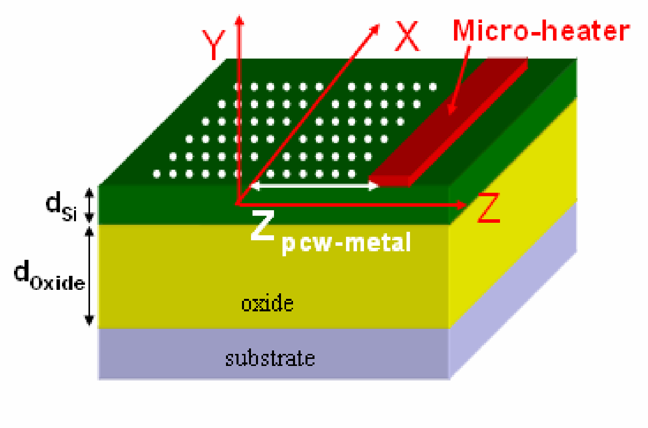
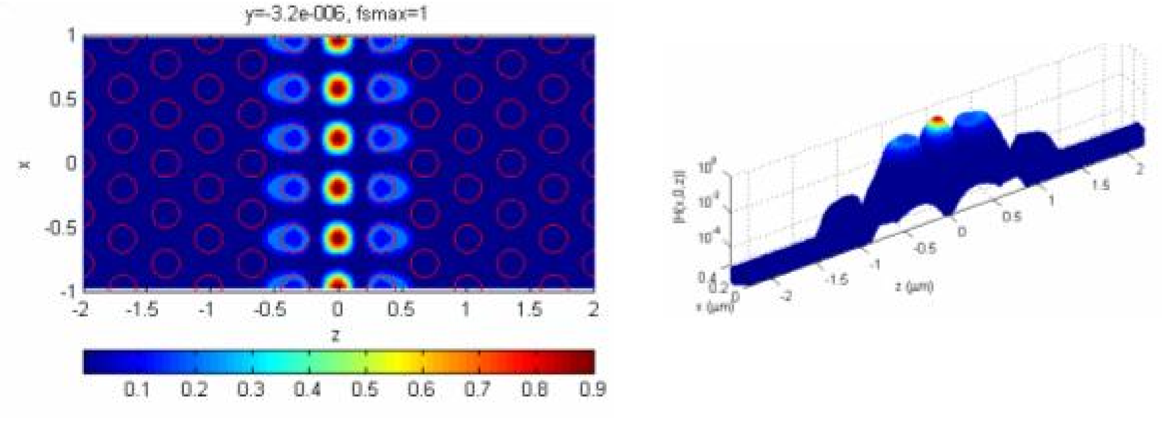


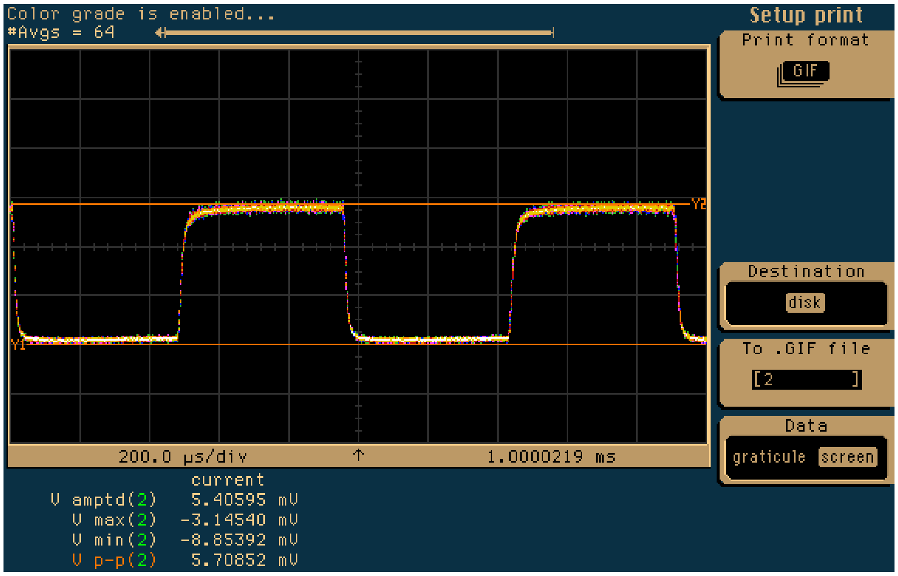
Fig. 3 Optical simulations of a photonic crystal waveguide (a) The device structure; (b) Top view of the mode field (contour plot) in the x-z plane; (c) Surface plot the mode field in the y-z plane.

(b) (c)



The real device was fabricated on a SOI wafer with a 220-nm-thick silicon top layer and a 2-µm-thick buried oxide layer. The pitch size of the hexagonal photonic crystal lattice was a = 400 nm. The normalized air hole diameter was designed to be d/a = 0.53. Details of the fabrication were published in [12].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°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 °C temperature increase. Details of the calculation were previously reported. However, in the PCW based MZI, the required length of the active region could be reduced significantly due to the enhancement of the 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.

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 under a 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



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V amptd(2)    5.40595 mV
  V max(2)   -3.14540 mV
  V min(2)   -8.85392 mV
  V p-p(2)    5.70852 mV
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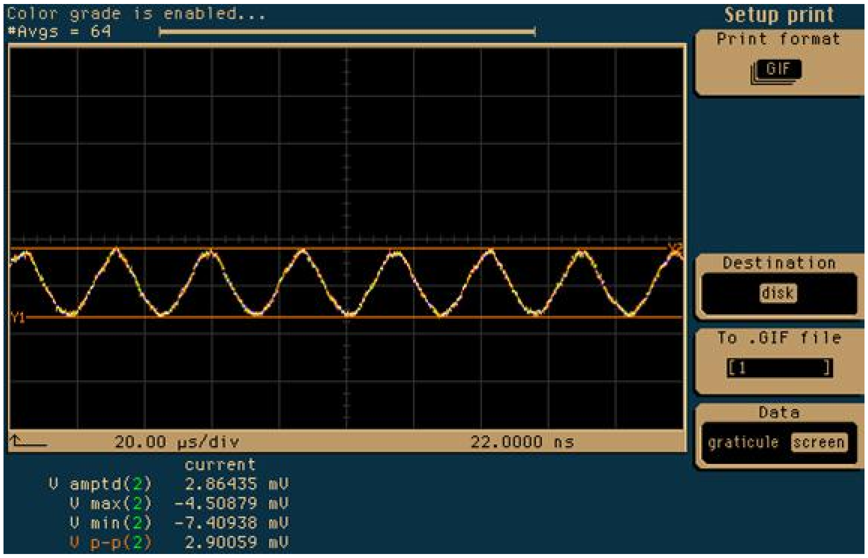
(a)



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  V max(2)  -4.50879 mV
  V min(2)  -7.40938 mV
  V p-p(2)   2.90059 mV
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(b)

Fig. 4 Modulation curves at
(a) 1 kHz and (b) 30 kHz.

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 [13]. 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. From the ANSYS thermal simulation, a small temperature variation of 9 ^{o}C was predicted 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 reduction in device length by one-order of magnitude [14, 15], which obviously benefited from the slow group-velocity of the PCWs [5, 16, 17].

PCW BASED ELECTRO-OPTICAL SILICON MODULATORS

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 [6]. Here, we propose a lateral p-i-n configuration for a PCW based EO MZI, which has a different structure from as previously reported [12]. 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 generation and/or recombination time. The transient characteristics of the p-i-n diode were simulated using a 2D semiconductor device simulator MEDICI. The simulated 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. 5 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 long active region to obtain the required π phase shift in the conventional rib waveguide based MZIs [18, 19]. 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. The schematic and SEM images of the fabricated p-i-n diode based silicon PCW MZI is shown in Fig. 6. Extensive electrical and optical measurements have been performed. Details about the optical and electrical characterization of our devices will be reported in some journal publications soon.

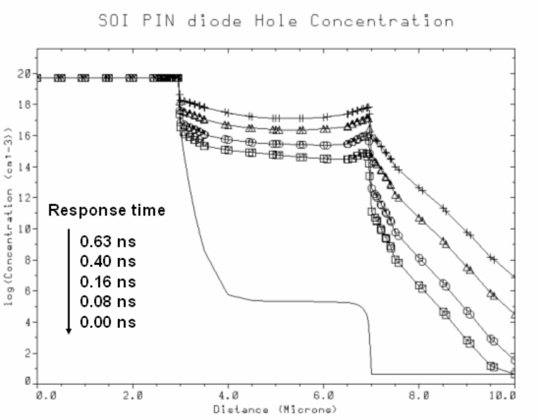

Fig. 5 Transient free-carrier distributions along lateral distance of the p-i-n diode.

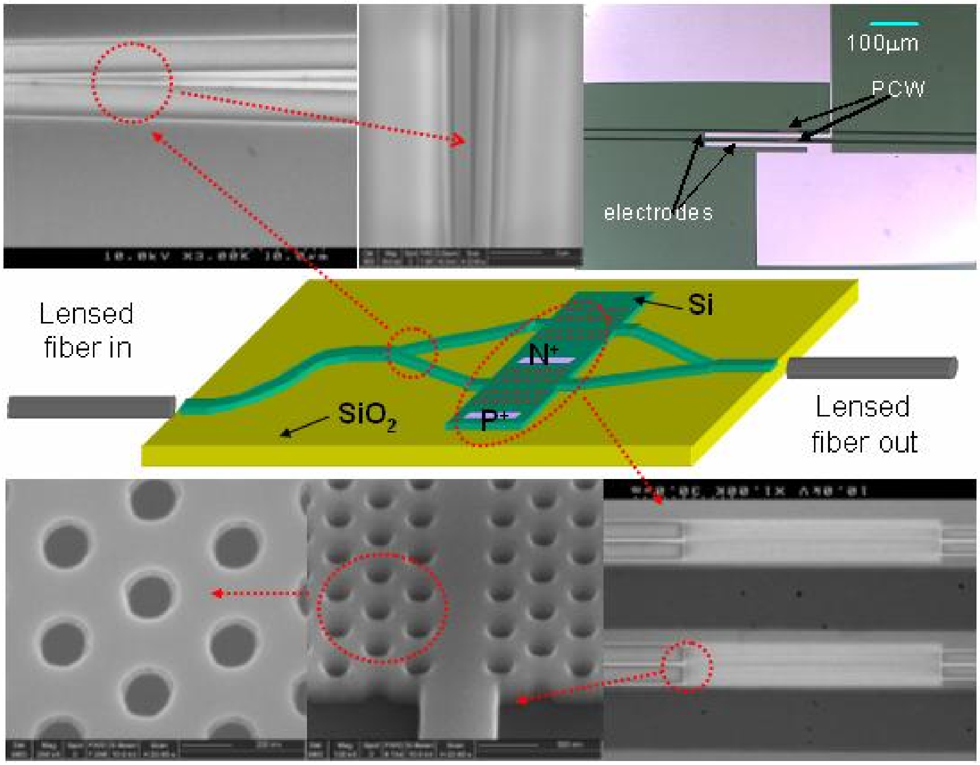

Fig. 6 The schematic and SEM images of the fabricated p-i-n diode based silicon PCW MZI.

SUMMARY

In summary, we have proposed ultra-compact silicon-PCW-based TO and EO MZIs. Device configurations were carefully designed based on the thermal, electrical and optical simulations. Device 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.

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