Silicon-On-Insulator-Based Photonic-Crystal Mach-Zehnder Interferometers

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ABSTRACT

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. Photonic crystals (PhCs) provide a promising platform for developing novel optoelectronic devices with significantly reduced device size and power consumption. The active control of photonic crystal waveguides (PCWs) incorporated in Mach-Zehnder interferometers has been investigated in this paper. We designed and fabricated a PCW based silicon thermo-optic (TO) switch operating at 1.55 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 (< 20μs) 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 84% was demonstrated for switching power of 78mW. For high-speed applications, a p-i-n structure based PCW electro-optical (EO) MZI modulator was proposed. The transient performance of such a device was evaluated using a two-dimensional semiconductor device simulator MEDICI. The simulated structure demonstrated a great potential to realize high-speed ultra-compact Si modulators in the GHz region.

Keywords: Photonic crystal (PhC), Mach-Zehnder interferometers (MZI), silicon-on-insulator (SOI), thermo-optic (TO) effect, plasma dispersion effect

I. INTRODUCTION

The cost and size reduction of optoelectronic devices in order to facilitate large-scale integration are the bottleneck to overcome. Among many existing material systems, silicon-on-insulator (SOI) is considered a top candidate to develop integrated nano-photonic devices because it allows for monolithic integration of optical and electronic devices, avoiding the use of hybrid packaging techniques. Silicon is transparent in the range of optical telecommunication wavelengths, and it has high refractive index that enables the fabrication of high-index-contrast nano-photonic structures [1]. Si based optical components have made little progress in miniaturization while microelectronic devices have undergone numerous generation of feature size reduction. Photonic crystal (PhC) provides a promising platform for a variety of compact and high-performance optical and optoelectronic devices due to their unique properties, such as photonic bandgap and slow group-velocity for the propagation of light [2-4]. Optical waveguides based on photonic crystal line defects, the so-called photonic crystal waveguides (PCWs), have been demonstrated to provide a few orders of magnitude larger dispersion than conventional waveguides [5-7]. Such an extraordinary dispersion capability has a profound impact on the phase velocity change over a segment of photonic crystal waveguides [8-9]. By locally controlling the external fields such as thermal and electrical fields in the PCW region, a tremendous amplification of optical response to the material property variation could be achieved. It in turns results in a significant reduction in the size and power consumption of the PCW based the optoelectronic devices. Optical switches and optical amplitude modulators are key components for photonic integrated circuits. Mach-Zehnder interferometer (MZI) structure that converts a phase modulation into an intensity modulation has been widely employed to develop optical switches and modulators. When PCWs are incorporated into a MZI structure, they lead to a significant enhancement of the phase modulation efficiency, which allows for the potential reduction in device size by several orders of magnitude. In this paper, we present some simulation and experimental results of our newly developed silicon thermo-optic (TO) switch and electro-optical (EO) modulator based on the PhC MZI structure.

II. SOI THERMO-OPTIC SWITCHS BASED ON THE PHOTONIC CRYSTAL MZI STRUCUTRE

The high-speed Si EO modulator working in the GHz regime has been demonstrated [10]. However, 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 [11-13]. Si is a great material for implementing TO MZIs operating at 1.5μm because: (1) Si is transparent at this communication wavelength, (2) the TO coefficient is high in Si, which is approximately $1.86 \times 10^{-4} K^{-1}$, three times greater than in normal TO material; (3) the thermal conductivity of Si is also high, which is 100 times higher than SiO_2, and therefore it provides a comparatively fast switching speed; (4) the fabrication cost is low due to the maturity of silicon very large-scale integration (VLSI) technology.

A TO MZI based on 2D-Si PhCs has been recently reported by Tao [14]. The length of their device was about one order of magnitude shorter than conventional-waveguide-based MZI optical switches owing to the slow photon effect in PCWs. However, its switching speed is comparatively slow, which is around 120μm. Such a long response time is believed to be associated with the oxide buffer layer sandwiched between the thin-film micro-heater and silicon wave-guiding layer. For a conventional SOI based TO MZI, schematically illustrated in Fig. 1(1), an oxide layer is usually deposited or grown on top of waveguide core layer, supporting the micro-heater and preventing the metal absorption loss. However, this buffer layer could possibly introduce two problems. First, the deposited SiO_2 will partially block the air holes of the PCW, which may change the designed transmission property and increase the propagation loss of the PhC device. Second, the SiO_2 is an undesirable thermal buffer layer between the heater and Si PCW. It may degrade the device performance in terms of switching speed and the power consumption. To overcome these problems, we proposed a novel structure that a micro-heater is placed on the side instead of on the top of the PCW region. The direct contact between the micro-heater and silicon core layer, as shown in Fig.1 (2), allows a more efficient heat transfer between the heat source and actively controlled PCW region, compared with conventional oxide buffered top-structure, where the oxide layer has 100 times smaller thermal conductivity than silicon layer. On the other hand, the buried oxide (BOX) layer of SOI wafers functions as a vertical thermal barrier to further enhanced the efficiency of the lateral heat exchange. This novel design may bring various advantages such as faster speed, lower loss and easier fabrication process.
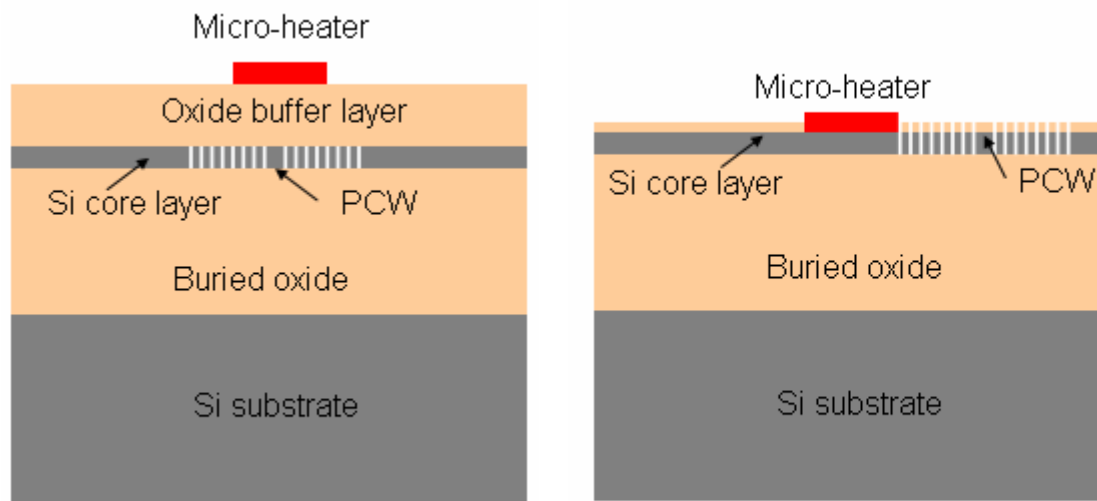

Fig. 1 (1) Conventional top-structure;   (2) Proposed side-structure.

In the proposed side-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. 2 shows the magnetic field density profile of the PCW mode. It is obvious that most energy is confined within the line defect and becomes evanescent into the photonic crystal. A more than 40dB decrease of optical energy is obtained at the location 1.5 μm away from the line-defect on each side of the PCW. This simulation indicates optical loss owing to the
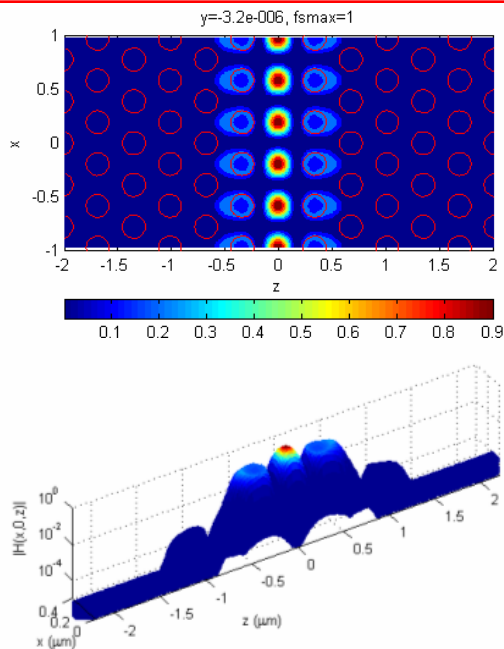
Fig.2 Magnetic field density profile of the PCW mode simulated by the plane wave expansion method.

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 static thermal analysis of the proposed structure was performed using a commercial finite element modeling software, ANSYS. The cross-sectional view of the simulated structure is shown in Fig.1 (2). The device was simulated based on a SOI wafer with a top silicon core layer of 0.22 μm and a bottom cladding buried oxide (BOX) layer of 2μm. The thickness value of the top oxide cladding layer was chosen as the same dimension of the real devices we fabricated, which was 0.08 μm. Si substrate was set to 20 μm thick to assure the room temperature boundary condition valid at the backside of the SOI wafer. An aluminum thin-film micro-heater was designed with the dimension of 8μm X100 μm, which generated a 70mW ohmic heating power to actively control the TO MZI. To perform a 2D analysis, the simulated structure was simplified by ignoring the air holes in the PCW region. We believe this model simplification would not have substantial effect on the accuracy

of the computation results for the steady-state thermal analysis. ANSYS smart-sizing algorithm was used to mesh the whole simulated structure. The calculated temperature profile across the device is given in Fig 3. It is clearly seen there is a temperature rise of 9ºC in the line-defect region, 5.2 μm away from the right end of the micro-heater. The simulation also confirmed that the BOX layer provided a good thermal isolation of the waveguide from Si substrate, which enhanced the capability of later heat exchange between the source and the PCW active region.
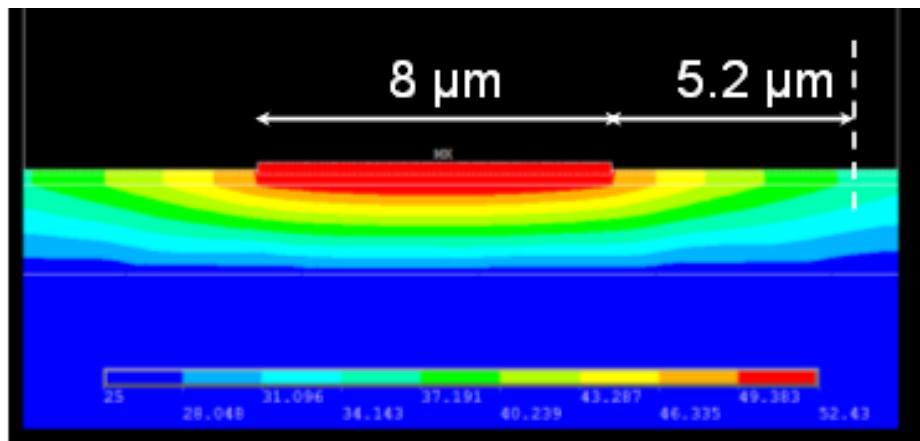

Fig. 3 Steady-state temperature profile across the TO MZI calculated by ANSYS.

The phase shift of the MZI is described by

$$\Delta\phi = \frac{2\pi}{\lambda}(\frac{dn_{eff}}{dT}) \, \Delta TL \qquad\qquad [1]$$

where λ is the operating wavelength, n_{eff} is the effective refractive index of the waveguide mode, ΔT is the temperature variation and the L is the length of the active region of the MZI. For conventional waveguide, dn_{eff}/dT is approximately equal to the material TO coefficient, which is $1.86 \times 10^{-4} K^{-1}$ in Si. We can do a simple calculation, for a 9 ºC increase in

temperature, it requires an active region at least of 460 μm to obtain the π phase shift of the optical signal at 1.55 μm. 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 PhC, which is intrinsically associated with the high-dispersion property of the PCW. We have experimentally demonstrated a size reduction of the PCW based MZI by almost one order of magnitude compared with conventional TO MZIs [12, 13, 15]. Details of the fabrication and measurements are presented as follows.
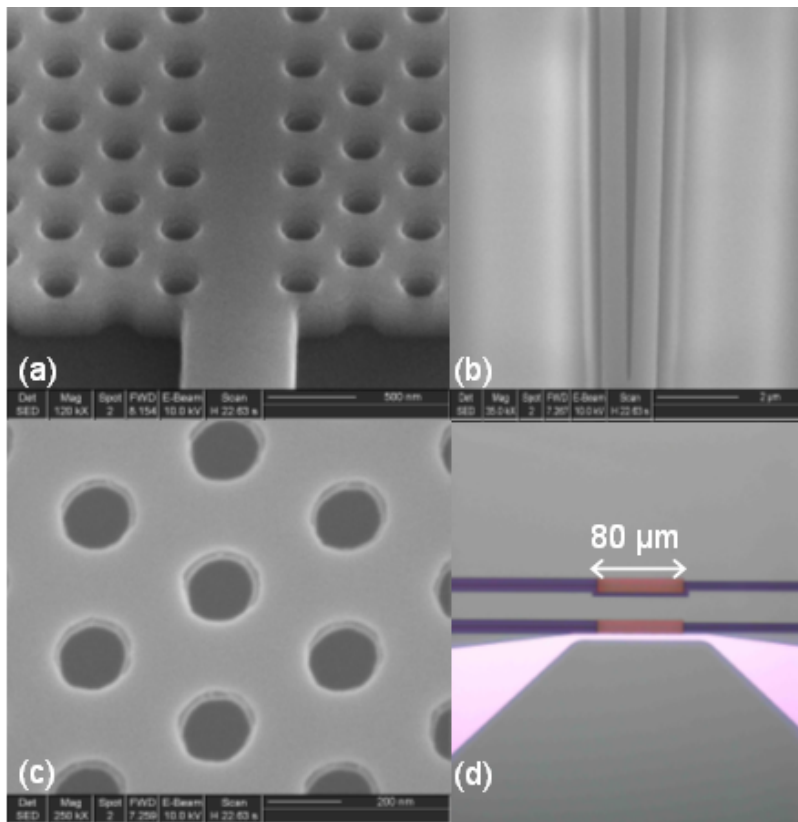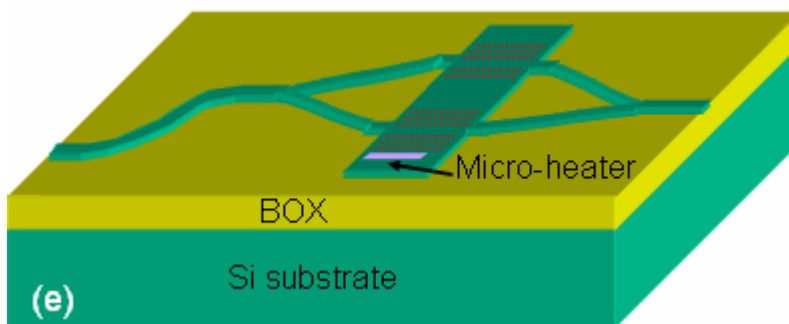

Fig.4 Scanning electron microscope (SEM) images and charge-coupled device (CCD) pictures of the SOI PCW based TO MZI

(a) 45° view picture of PCW in conjunction with input strip waveguide ;
(b) Y-junction of MZI;
(c) Top view of PhC hexagonal lattice;
(d) CCD picture of the device;
(e) Schematic diagram of the PCW based TO MZI switch, an S-bend is used at the input to suppress the stray light collected at the output.

The schematic diagram, canning electron microscope (SEM) images and charge-coupled device (CCD) pictures of the developed PCW based TO MZI are shown in Fig. 4. The TO MZI consists of two PCWs, an input S-bend strip waveguide, an output straight strip waveguide, two Y-junction 3 dB splitters and a thin-film micro-heater. The S-bend strip Si waveguide was used at the input to suppress the stray light collected at the output. The device was fabricated on a Unibond SOI wafer. A thermal oxide layer of about 80 nm was grown, at 850 °C by wet oxidation, on the surface of silicon core layer serving as an etching mask as well as the top cladding of the Si waveguides. The whole structure of the device was defined using e-beam lithography followed by the reactive ion etching (RIE). The thickness of the silicon core layer was $t = 220$ nm. The bottom cladding was a buried oxide layer of 2 μm thick. The pitch size of the hexagonal photonic crystal lattice was $a = 400$ nm. The normalized air hole diameter was designed to be $d/a = 0.53$. Two 80 μm-

long PCWs were formed by removing the central row of air-holes in the Γ-K direction. An air trench was added between two PCW waveguides to achieve a good thermal isolation between the signal arm and reference arm of the MZI. As the last step of whole process, an 8 X100 μm^2 Al micro-heater with the thickness of 250 nm was formed by e-beam evaporation and a lift-off process. The resistance of the metal heater was 20 Ω.
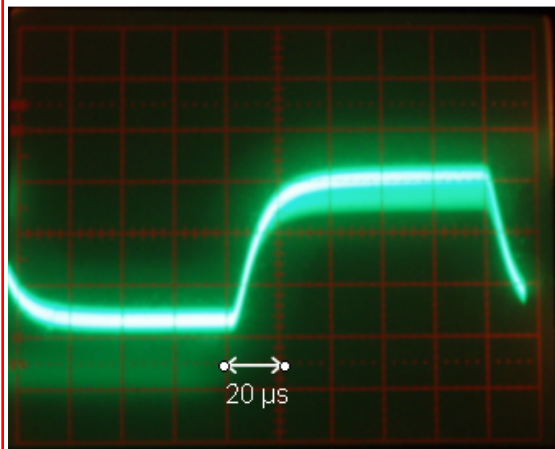

Fig. 5 Switch characteristic of TO MZI in the time domain.

Optical measurement was performed on a fully-automated Newport Photonics Alignment/ Packaging Station. The transverse electrical (TE) wave (electric field vector is predominantly in plane) from a wavelength tunable laser was launched to the input Si strip waveguide through a single mode lensed fiber. The output optical signal was collected by a multi-mode lensed fiber which has much larger numerical aperture (NA) than the input fiber. We measured TO MZI switch operating at 1548nm. A 5-kHz rectangular-wave voltage signal was applied to micro-heater by a function generator. The measured switching characteristic was shown in Fig. 5. The rise (10% to 90%) time and fall (90% to 10%) time was measured to be 19 μs and 11 μm, respectively, which is 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 [14]. 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. Another feasible way for the power reduction is to add some air trenches on the Si core layer in the surrounding area of micro-heater. These air trenches would act as thermal barriers to reduce the lateral power dissipation [16]. It was previously shown by the ANSYS thermal simulation, a small temperature variation of 9 °C was obtained in the PCW region with a supplied heat power of 70mW. As calculated by equation [1], in the ideal situation, it requires an active region at least 460 μm to achieve π phase shift in a conventional rib or strip waveguide based Si TO MZI. Our experiments demonstrated almost a one-order of magnitude reduction in the length of the device active region, which clearly benefited from the slow group-velocity of the PCWs.

III. SOI ELECTRO-OPTICAL AMPLITUDE MODULATORS BASED ON THE PHOTONIC CRYSTAL MZI STRUCUTRE
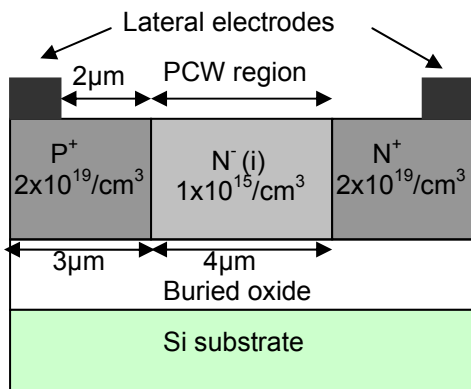
(a)
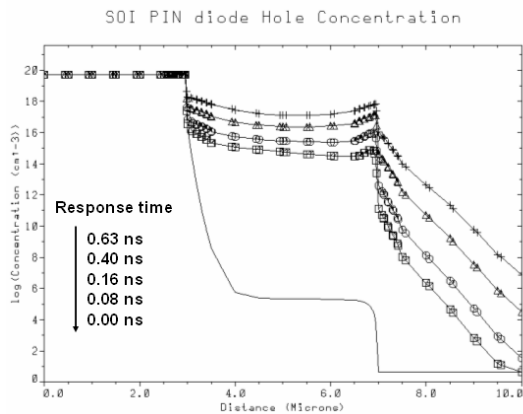
(b)

Fig. 6 (a) Schematic cross section of the simulated p-i-n diode based on SOI wafer; (b) Transient free-carrier distributions along lateral distance of the p-i-n diode.

Most silicon electro-optic modulators operate based on plasma dispersion effects [17], through which free carrier concentration perturbation results in refractive index change. Carrier injection and capacitive coupling through the metal-oxide-semiconductor (MOS) field effect are two major methods to introduce the free carriers into silicon [10, 18, 19]. In MOS structure based silicon modulator, the overlap between the optical field and carrier perturbation area is usually small because the efficient free-carrier concentration variations only presents within the thin silicon layer beneath the insulated gate region. However, in a p-i-n configuration, overlap between the optical field and electrical field can be maximized since the free carriers will be uniformly injected into a comparative large intrinsic area that covers the whole wave-guiding region. Considering the above issue, we proposed a lateral p-i-n configuration for a PCW based MZI where the forward biasing voltage is applied to inject carriers into the wave-guiding region. The switching speed of such a p-i-n diode based device is usually determined by the carrier recombination time and carrier transit time. The response time of the carrier concentration perturbation of a SOI based p-i-n diode was evaluated using the semiconductor device simulator MEDICI. The schematic of the simulated structure and the simulated transient free-carrier distributions are shown in Fig. 6 (a) and (b).The 0.22μm-thick silicon layer has an n-type background doping concentration of 10^{15} /cm^3, whereas a uniform doping concentration of 2×10^{19} /cm^3 for both p$^+$ and n$^+$ regions was assumed. 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. 6(b) that the minority carrier injection in the intrinsic region, where is also the PCW region, is fairly uniform. A carrier concentration perturbation of around 3×10^{17} /cm^3, which induces a real refractive-index change of the Si about -0.001, is 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 a 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, 18, 19]. However, in our proposed PCW based MZI devices, an active PCW region with a few or a few tens of microns in length is long enough to achieve sufficient phase shift. Extensive experimental work has been carried out and some important results will be reported in a journal article in the near future.

IV. CONCLUSION

PCW based TO and EO MZIs operating at 1.55 μm on SOI wafers have been investigated. The steady-state thermal analysis and optical simulations have been performed to design a PCW based TO MZI switch. We have proposed a novel structure to improve the switching speed of the TO switch. Such a PCW based TO MZI has been experimentally demonstrated with switching time shorter than 20 μs. The length of the active region of our newly developed TO MZI is almost one order of magnitude shorter than that of the conventional rib and strip waveguide based Si MZIs. The maximum modulation depth of 84% was achieved with 78mW switching power applied to the micro-heater. Power consumption may be reduced by an optimized thermal design. We have also proposed a p-i-n structure for PCW based EO MZI. Electrical simulation predicted a carrier concentration perturbation of around 3×10^{17} /cm^3, which induces a real refractive-index change of the Si about -0.001, could be achieved within 0.63ns under a forward biasing voltage of 2V. It provides an attractive and feasible method to realize high-speed ultra-compact Si modulators.

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