Photonic-crystal-waveguide-based Silicon Mach-Zehnder Modulators

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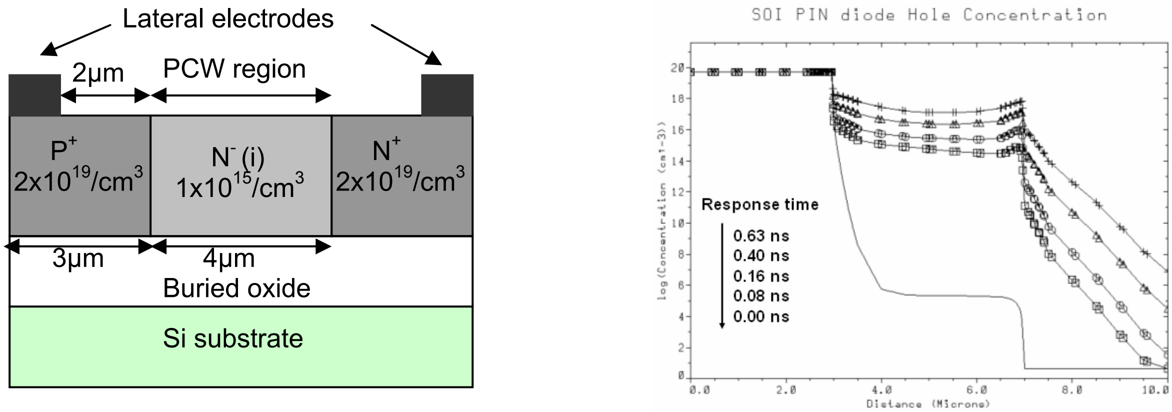
Abstract: An ultra-compact photonic-crystal silicon Mach-Zehnder modulator is proposed based on the plasma dispersion effects. Transient time response of the device is simulated using semiconductor device simulator MEDICI. An efficient optical modulation has been experimentally demonstrated.

OCIS codes: (250.7360) Waveguide modulators; (230.2090) Electro-optical devices

Silicon nano-photonics is anticipated to play a critical role in future ultra-compact system integration due to the maturity of silicon complementary metal-oxide-semiconductor (CMOS) technology. Silicon is transparent in the range of optical telecommunication wavelengths, and it has high refractive index that allows for the fabrication of high-index-contrast nano-photonic structures. In photonics, nano-scale structures, particularly photonic crystals [1], 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 a few orders of magnitude larger dispersion than conventional waveguides [2]. Such an extraordinary dispersion capability has a profound impact on the phase velocity change over a segment of photonic crystal waveguides [3].For optical intensity modulator, Mach-Zehnder interferometer (MZI) structure that converts a phase modulation into an intensity modulation is widely used. When photonic crystal waveguides are incorporated in a MZI, they lead to a significant enhancement of the phase modulation efficiency, which in turn allow us to reduce the modulator electrode length by several orders of magnitude.

Most silicon electro-optic modulators operate based on plasma dispersion effects [4, 5], 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. 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 a 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



(a) (b)

Fig. 1 (a) Schematic cross section of the simulated p-i-o diode based on SOI wafer;
(b) Transient free-carrier distributions along lateral distance of the p-i-n diode.

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 silicon-on-insulator (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. 1(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 2X10^{19} /cm^3 for both p^+ and n^+ regions is assumed. The lateral electrodes are defined on top of the p^+ and n^+ regions, separated by 4μm from the PCW line defect. It is clearly shown in Fig. 1(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 3X10^{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.

An ultra-compact silicon electro-optic modulator has been experimentally demonstrated based on silicon PCWs. The schematic structure and SEM images of a 2-dimentional PCW based silicon MZI is shown in Fig. 2. The MZI modulator consists of PCWs, waveguides, Y-junctions, electrodes, and electrode pads. PCWs are used in both arms of the MZI modulator to ensure the two arms have the same optical loss and dispersion; otherwise the modulation depth suffers a reduction due to disparity. In the lower arm of the MZI structure, a photonic crystal waveguide of 80 μm in length is located between two electrodes. The thickness of the silicon core layer is t = 215 nm. The top cladding is air and the bottom cladding is a buried oxide layer of 2 μm thick. The pitch size of the hexagonal photonic crystal lattice is a = 400 nm. The normalized air hole diameter is designed to be d/a = 0.53. Extensive experimentation with various processes was conducted to determine the optimized process parameters. A proper pre-offset of the hole-size in e-beam pattern design is used so that the hole size can be controlled with an accuracy of 5%. Details of the fabrication were previously reported [6].

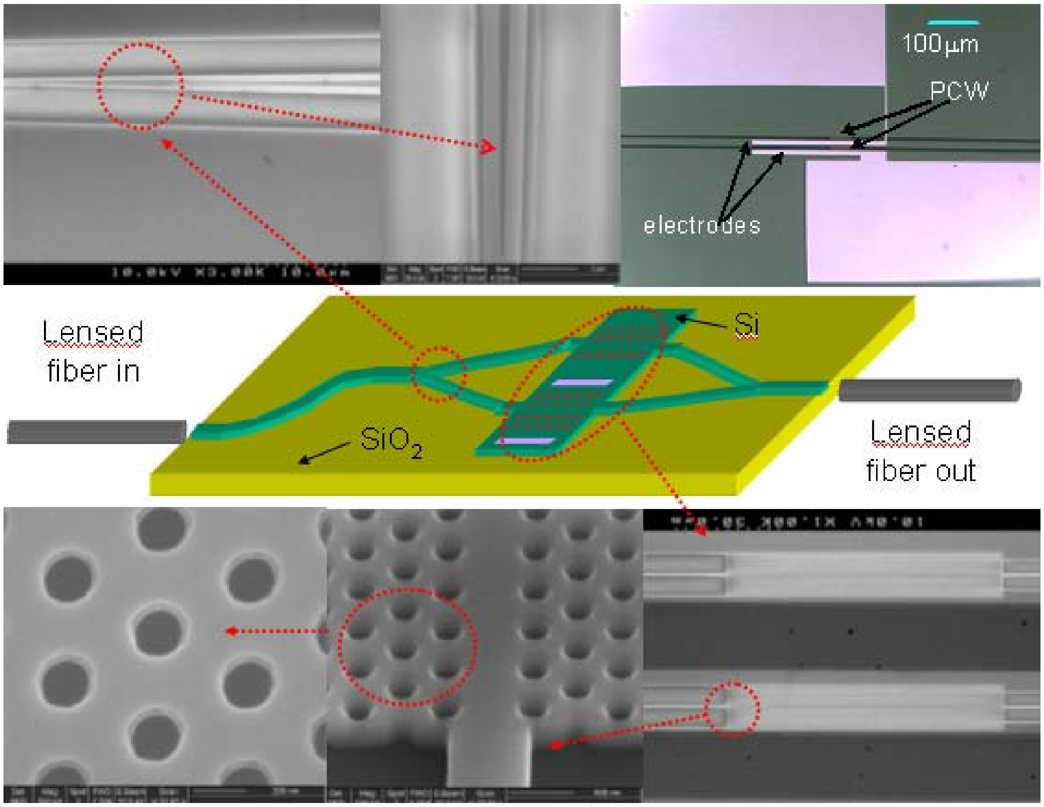
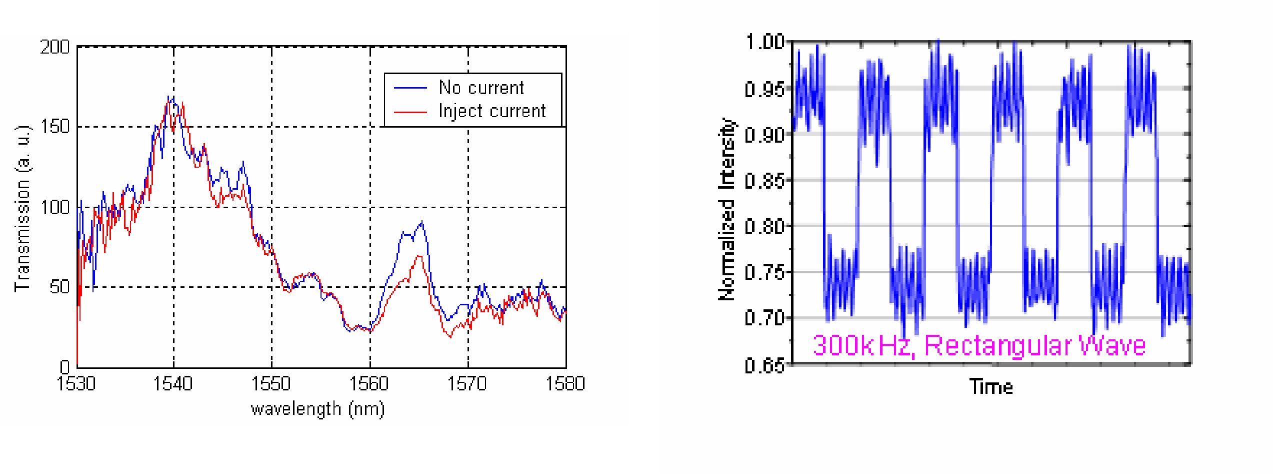


Fig. 2 Schematic and SEM images of the PCW based MZI.

The transmission spectra of the Mach-Zehner modulators were measured. For a given injection current, deeper reduction of the optical power means higher modulation efficiency. The typical measured result of the optical power reduction for PCW Mach-Zehnder modulator is shown in Fig. 3(a). It is clearly seen that the optical modulation is wavelength dependent. In this specific device structure, the great enhancement of the modulation efficiency appeared between 1561 and 1571nm. The modulation depth of 90% was experimentally achieved. Note that to our knowledge, active waveguide regions no less than a few hundreds of microns in length are generally required to obtain such an efficient modulation in conventional silicon MZI modulators [7]. Clearly, the introduction of highly dispersive PCWs into MZI modulators significantly reduces the active region and thus lowers the power consumption of the device. A typical modulation trace is shown in Fig. 2 (b). Further result on speed measurement will be presented in the conference.



(a)

(b)

Fig. 3. (a) Transmission spectra of a PCW based MZI with (red) and without (blue) current injection;

(b) Modulation trace of 300 kHz rectangular wave.

In summary, we have proposed and fabricated an ultra-compact photonic-crystal-waveguide-based silicon Mach-Zehnder modulator. Electrical property of a p-i-n based PCW MZI was simulated preliminarily by semiconductor device simulator MEDICI. Modulation operation has been demonstrated by carrier injection into an 80 µm long silicon photonic crystal waveguide. Further improvement in devices performance is expected by optimizing the electrical and optical design of the MZI structure. Complete simulation and experimental results will be reported in the conference.

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