Silicon-organic Hybrid Electro-optic Modulator Based on One-dimensional Photonic Crystal Slot Waveguides

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Abstract: A silicon-organic hybrid electro-optic (EO) modulator based on one-dimensional photonic crystal slot waveguides is proposed and demonstrated. Effective EO coefficient up to 490 pm/V is observed as a result of the slow group velocity in the proposed structure.

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Integrated silicon electro-optic (EO) modulators are important building blocks in high-performance optical interconnects. Most silicon EO modulators rely on the plasma dispersion effect, in which the refractive index of silicon is changed by varying free carrier concentrations [1]. The bandwidths and modulation efficiencies in these modulators are therefore limited by the free carrier dynamics [2]. In silicon-organic hybrid EO modulators, the EO effect (Pockels effect) is realized in EO polymer materials when the guided wave interacts with polymer claddings. This type of EO modulators enable small voltage-length products and large modulation bandwidth simultaneously. Silicon-organic hybrid EO modulators based on various phase shifter designs have been reported in recent years. These structures include slot waveguide [3], 2D slot photonic crystal (PC) waveguide [4] and 1D PC waveguide [2]. Improved modulation efficiency has been achieved due to the use of slot waveguide (large mode volume overlap with EO polymer) and PC waveguide (slow light effect). Here we propose a silicon-organic hybrid Mach-Zehnder interferometer (MZI) modulator based on one-dimensional photonic crystal slot waveguide structure in hopes of combining the advantages of slot waveguides and photonic crystal waveguides to further enhance the photon-matter interaction and improve the performance.

The schematic of the proposed MZI modulator is shown in Fig.1(a). The device consists of a MZI formed by two 1x2 multi-mode interferometer (MMI) couplers. One of the two arms is loaded with 1D PC slot waveguide with length L=200 μm. Light is coupled in and out of the modulator through subwavelength grating couplers [5] at both ends. The low-loss high-EO coefficient polymer SEO 125 is coated on the 1D PC slot waveguide. The electric field needed for the poling of the EO polymer and the modulation signal is applied to the polymer through the metal electrodes. The gap W between the electrodes is 4.3 μm.

The structure of the 1D PC slot waveguide phase shifter is shown in Fig. 1(b). The PC slot waveguide is formed by conventional silicon slot waveguide and periodic rectangular teeth on the two rails. The parameters of the 1D PC slot is optimized to achieve slow group velocity around the optical wavelength of 1550 nm. The slot waveguide has a slot width (S_w) of 150 nm and a rail width (R_w) of 100 nm. The period (P) of the rectangular teeth is 415 nm. The width (a) and length (b) of the teeth are 124.5 nm (0.3P) and 300 nm, respectively. The whole structure sits on buried oxide layer and is infiltrated with EO polymer. Fig.1(c) shows the band diagram of the transverse electric (TE) modes for the silicon PC slot waveguide with EO polymer top cladding. The band diagram is calculated by 3D plane wave expansion method. There are three bands below the light line of the EO polymer. The nearly flat region of the

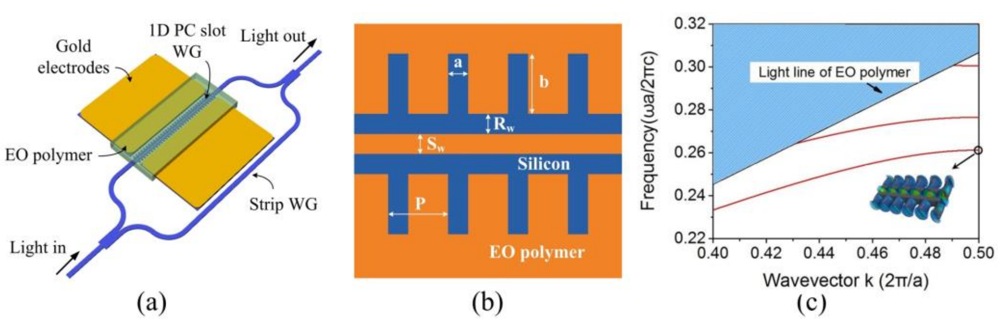

Fig. 1. (a) Schematic of the proposed MZI modulator based on 1D PC slot waveguide; (b) Layout of the 1D PC slot waveguide structure; (c) Band diagram of the 1D PC slot waveguide, inset shows the mode profile at the band edge of the lowest band.

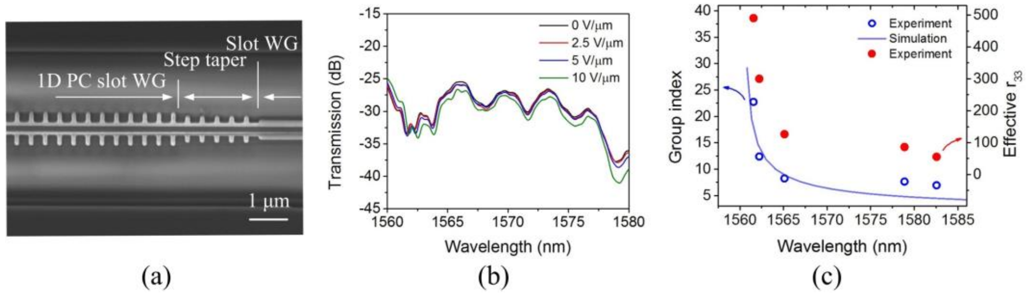

Fig. 2. (a) SEM image of the 1D PC slot waveguide connected to regular slot waveguide through step taper; (b) Transmission spectra of the MZI modulator with different electric field applied on the electrodes; (c) Group index and effective r_{33} as a function of wavelength.

lowest band is chosen as the operating range. It supports propagation mode in the PC slot waveguide and has a group index (n_g) as high as 25. The electric field intensity distribution of the mode at the band edge is shown in the inset of Fig.1(c). The ratio of the optical power in the EO polymer region is therefore calculated as $\sigma = 0.35$. To compensate the mode mismatch and improve coupling efficiency at the interface of regular slot waveguide and 1D PC slot waveguide, a short (5 periods) step taper [6] is designed.

The device was patterned by e-beam lithography on a silicon-on-insulator wafer with 250 nm top silicon layer. The pattern was then transferred onto the silicon layer through reactive ion etching. Au metal electrodes were formed along the 1D PC slot waveguide by photolithography, e-beam evaporation, and lift-off process. Finally, EO polymer SEO 125 (Soluxra, LLC.) was coated on the PC slot waveguide. Fig.2(a) shows the scanning electron microscope (SEM) image of the fabricated silicon PC slot waveguide before applying the EO polymer. Before device testing, the EO polymer is cured under vacuum at 80 °C and then poled near the glass transition temperature of 150 °C with an external electric field of 100 V/μm.

Transmission spectra of the fabricated device were obtained from a testing platform using a broadband amplified spontaneous emission (ASE) source (1510nm-1630nm) and an optical spectrum analyzer. Light from the ASE source was guided through a polarizer to subwavelength grating couplers and excites the fundamental TE mode of the on-chip strip waveguides. Fig.2(b) shows the transmission spectra under different electric fields generated by DC bias. The spectra show the oscillations due to group velocity difference between the two arms of the MZI and the period of the oscillation changes with wavelength as the group velocity in the 1D PC slot changes. The group index therefore can be estimated from the oscillation patterns.

To characterize the device performance, electric field was applied through the electrodes. The spectra show red shifts with increasing electric field, as shown in Fig.2(b). The phase shift induced by the applied electric field can be estimated by the equation $\Delta\varphi = 2\pi\Delta\lambda / FSR$, where FSR is the free spectral range of the oscillations in the MZI spectrum. The half-wave voltage is then estimated according to the wavelength shift Δλ when $\Delta\varphi = \pi$ and the relationship between applied voltage and wavelength shift obtained from the spectra. EO modulation efficiency ($V_\pi L$) of 0.91 Vcm has been observed at 1561.6 nm. The effective EO coefficient of the EO polymer, r_{33eff}, can be estimated by $r_{33eff} = \lambda W / (n^3 V_\pi \sigma L)$, where n=1.63 is the refractive index of the EO polymer. The estimated r_{33eff} at 1561.6 nm is 490 pm/V. This high r_{33} value is a result of the enhancing effect of slow group velocity of the waveguide mode. Fig.2(c) shows the group index and effective EO coefficient as a function of wavelength in the same diagram. The increasing r_{33eff} with increasing group index confirms that the effective EO coefficients and thus modulation efficiencies are enhanced by the slow light effect in our proposed PC slot waveguide.

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