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Che-Yun Lin, Xiaolong Wang, Swapnajit Chakravarty, Beom Suk Lee, Weicheng Lai, Jingdong Luo, Alex K.-Y. Jen, and Ray T. Chen

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Electro-optic modulation in slotted resonant photonic crystal heterostructures
Electro-optic polymer infiltrated silicon photonic crystal slot waveguide modulator with 23 dB slow light enhancement

Che-Yun Lin,1(a) Xiaoalong Wang,2(b) Swapnajit Chakravarty,2 Beom Suk Lee,1 Weicheng Lai,1 Jingdong Luo,3 Alex K.-Y. Jen,3 and Ray T. Chen1,c

1Department of Electrical and Computer Engineering, University of Texas at Austin, Austin, Texas 78712, USA
2Omega Optics Inc., Austin, Texas 78759, USA
3Department of Materials Science and Engineering, University of Washington, Seattle, Washington 98195, USA

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A silicon/organic hybrid modulator integrating photonic crystal (PC) waveguide, 75 nm slot, and electro-optic (EO) polymer is experimentally demonstrated. Slow light in PC waveguide and strong field confinement in slot waveguide enable ultraefficient EO modulation with a record-low $V_{\pi} \times L$ of 0.56 V mm and an in-device effective $r_{33}$ of 132 pm/V. This result makes it the most efficient EO polymer modulator demonstrated to date. The modulated signal shows strong wavelength dependence and peak enhancement of 23 dB near the band edge of defect mode, which confirms the signature of the slow light effect. © 2010 American Institute of Physics. [doi:10.1063/1.3486225]

Silicon has long been the optimal material for microelectronics. Building photonic devices in silicon bears the advantage of being compatible to complementary metal-oxide-semiconductor fabrication technology, which can lead to monolithic integration of microelectronic and photonic devices on a single silicon chip. However, due to its centrosymmetric crystal structure, silicon shows no Pockels effect. Electrically driven optical modulation in silicon photonic devices typically relies on free carrier injection or depletion, where the achievable modulation bandwidth is limited by time constants related to removing or injecting free carriers to the modulation arm.

By contrast, EO polymers offer very high Pockels coefficient ($r_{33} > 300$ pm/V)3 with extremely fast response speed in the terahertz range.4 Ultrahigh bandwidth5 and subvolt half-wave driving voltage ($V_{\pi}$)3,5 have been demonstrated in EO polymer modulators. However, the size of these devices is limited by conventional waveguide structures with millimeter to center meter interaction length. Compared to conventional waveguides, silicon PC waveguide offers slow light-enhanced light-matter interaction, which can shrink the interaction length down to 80 μm8 and a reduced index change of $4.2 \times 10^{-3}$ to achieve switching in a silicon-based structure.9 Photonic devices based on silicon/EO polymer hybrid material system combine strong optical confinement abilities of silicon with superior EO modulation efficiency of polymers. Compared with conventional EO polymer photonic devices, this hybrid approach requires no cladding polymer layers. This should lead to higher poling efficiency and lower driving voltage with fabrication simplicity. Slot waveguide infiltrated with EO polymers in Mach–Zehnder modulators (MZM) have reported half wave voltage of 0.25 V, and $V_{\pi} \times L$ of 5 V mm.10 A more advanced design using silicon PC slot waveguide can exploit slow light effect from the defect mode close to the photonic band edge,11 thus even lower $V_{\pi} \times L$ can be expected. Compared with PC devices without slot,8,9 integrating EO polymer in slot PC waveguide offers better potential for high speed operation.5 In this paper, we present the design and experimental demonstration of a MZM based on EO polymer infiltrated silicon PC slot waveguide with slow light enhanced EO modulation.

Figure 1(a) shows the schematic of the PC slot waveguide. Input and output waveguides are conventional silicon strip waveguide, which connect to PC slot waveguide with optical mode converter12 for better mode-matching. The PC waveguide is a W1 waveguide formed by replacing a row of air holes with a narrow slot of width $w=75$ nm, which provides good optical confinement and modulation efficiency without compromising the feasibility of EO polymer infiltration. The modulation region, with slot nanostructures, is formed in a hexagonal lattice PC slab with lattice constant $a=385$ nm and hole diameter $d=217$ nm, which has a total length of 308 μm. Silicon PC regions including air holes and slot are fully covered by EO polymer with strong EO coefficient (AJ-CKL1/APC).13 Refractive index of infiltrated polymer is 1.63 at 1.55 μm. Dispersion diagram of the guided mode is shown in Fig. 2(a), which is calculated by

![Image](https://example.com/image.png)

FIG. 1. (Color online) Schematic of the input strip waveguide, optical mode converter, PC taper, and modulation region.
The group refractive index $n_g$ of the guided mode as a function of wavelength is shown in Fig. 2(b), which shows that $n_g$ can exceed 100 when the wavelength is tuned close to the band edge of 1569 nm. The optical intensity profile of the guided mode at $n_g=100$ is shown in inset of Fig. 2(b). Figure 2(b) also shows in-slot optical power weight ($\Gamma$) in the total guided mode power. It should be noted that integration of 75 nm slot waveguide into photonic crystal (PC) waveguide causes light with low group velocity within the defect mode spectrum remain concentrated in the slot, which will otherwise penetrate to second or third row of holes without the presence of a slot. With lightly doped silicon functioning as electrode, huge electric field can be induced with small driving voltage. This design enables ultraefficient electro-optic (EO) interaction within EO polymer infiltrated slot. To effectively couple light into slow light region, a PC taper from W1.08 to W1.0 is designed to minimize the group index mismatch between strip waveguide and slow light PC waveguide, as shown in Fig. 1.

The hybrid nanophotonic modulator is fabricated on a silicon-on-insulator (SOI) wafer with 230 nm lightly doped top silicon and 3 $\mu$m buried oxide. Details of fabrication are described in Ref. 15. Figure 3(a) shows the fabricated MZM structure with gold electrodes. Figure 3(b) shows scanning electron microscopy (SEM) image of the silicon PC slot waveguide. The EO polymer was processed using standard methods and poled with high electric field of 200 V/µm. Figure 3(c) shows cross sectional view of the 75 nm slot infiltrated with EO polymer. Compared to other devices with slot width over 120 nm, our narrower slot will provide higher modulation efficiency at same driving voltage.

To characterize the modulator performance, transverse electric light from a broadband source was butt coupled into the modulator with a polarization maintaining tapered lensed fiber. Transmitted light was collected by a single mode lensed fiber and analyzed with an optical spectrum analyzer. We observe a 5 nm deviation in the photonic band edge at 1569 nm compared to simulation results, which is attributed to fabrication errors. A laser source was tuned to 1564.5 nm, corresponding to the slow light region, where maximum modulation response is achieved. The modulator was biased at 3 dB point and driven by a 50 KHz triangular wave. Modulated optical signal was converted to electrical signal through a gain-switchable photodetector. Figure 4 shows that the EO polymer nanophotonic modulator has a $V_m$ of 1.8 V. The effective EO coefficient is defined as $\gamma_3=\lambda w/n^2V_mL=1565\times75\text{ nm}^2/1.63^3\times1.8\text{ V}\times0.37 \times308\text{ µm}=132\text{ pm/V}$, where $\Gamma$ is the fraction of the total power in the slot. The value of $\Gamma=0.37$ is given by simulation results in Fig. 2(b). The device also achieves very high modulation efficiency $V_m\times L=1.8\text{ V}\times308\text{ µm}=0.56\text{ V mm}$. This result is nearly one order of magnitude lower than that reported in Ref. 9.
light effect. The low $V_p \times L$ of 0.56 V mm represents the best figure of merit achieved for EO polymer modulator. Such compact and highly efficient nanophotonic modulator is an ideal candidate for on-chip optical interconnects. It should be noted that efficiency from poled EO polymer materials in silicon nanoslot is still lower compared to the best results obtained from poling of thin films. Solving issues related to high electric field poling of EO polymer in silicon could lead to ultracompact devices with extremely low power operation for applications in dense wavelength-division multiplexing, phased array antennas, and photonic analog-to-digital converters.

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