

Ultralow Power Consumption of 1.5nW Over Wide Optical Spectrum Range in Silicon Organic Hybrid Modulator

¹Xingyu Zhang*, ²Amir Hosseini, ³Jingdong Luo, ³Alex K.-Y. Jen, and ¹Ray T. Chen*

¹Microelectronics Research Center, Electrical and Computer Engineering Department, University of Texas at Austin, Austin, TX, 78758, USA

²Omega Optics, Inc., 10306 Sausalito Dr, Austin, TX 78759, USA

³Department of Materials Science and Engineering, University of Washington, Seattle, Washington 98195, USA

*Corresponding author: xzhang@utexas.edu, raychen@uts.cc.utexas.edu, Tel:512-471-4349, Fax: +1-512-471-8575

Abstract: We demonstrate an ultralow-power, low-dispersion and compact silicon-organic-hybrid photonic crystal waveguide modulator. RF power consumption of 1.5nW, effective in-device r_{33} of 1190pm/V and $V_{\pi} \times L$ of $0.291 \pm 0.006V \times mm$ over 8nm optical bandwidth are demonstrated.

OCIS codes: (230.4110) Modulators; (130.5296) Photonic crystal waveguides; (200.4650) Optical interconnects; (250.2080) Polymer active devices;

Silicon organic hybrid (SOH) technology has shown to enable compact and high performance integrated photonic devices [1]. Organic polymers with large EO coefficient (r_{33}) are very promising for low power consumption. Silicon photonic crystal waveguides (PCWs) refilled with electro-optic (EO) polymers can further reduce the device size due to slow light effect. One problem of PCW modulators is their narrow operating optical bandwidth of <1nm [2] due to the high group velocity dispersion in the slow-light optical spectrum range. One solution is to use lattice shifting approach to provide low-dispersion slow light (constant group velocity, v_g) over a wide optical spectrum range [3]. In this letter we report a symmetric MZI modulator based on band-engineered slot PCW refilled with EO polymer (SEO125 from Soluxra, LLC, $r_{33}=120\text{pm/V}$). Using a band-engineered EO polymer refilled slot PCW with a slot width of $S_w=320\text{nm}$, we demonstrate a slow-light enhanced effective in-device r_{33} of 1190pm/V over 8nm optical spectrum range. In addition, excluding the slow-light effect, we estimate a record high in-device material r_{33} of 89pm/V in the slot. What is more, the utilization of large slot width provides small slot capacitance, which effectively reduces the RF power consumption to 1.5nW, which is very competitive to the state-of-the-art.

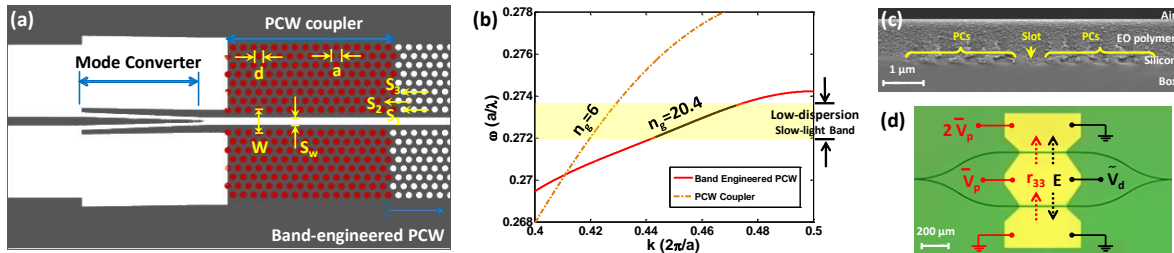


Fig. 1. (a) Layout of the PCW coupler (mode converter + PCW coupler). The black area corresponds to un-etched silicon. (b) Band diagram of the engineered slow-light PCW and the PCW coupler. (c) Cross-sectional view of the EO polymer refilled silicon slot PCW. PCs: photonic crystals. (d) Top view of fabricated slot PCW MZI modulator. The red colored circuit connection indicates the push-pull poling configuration and induced r_{33} direction, and the black colored circuit connection indicates the modulation configuration. V_p : poling voltage, V_d : driving voltage.

Fig. 1 (a) shows a schematic of the device on SOI (Si thickness=250nm, oxide thickness=3 μm). The input and output strip waveguides are connected to the device using a strip- to slot-waveguide mode converter. PCW couplers consisting of a fast-light section [4] connect the mode converters to a 300 μm -long slow-light PCW section. The slow-light PCW section is band-engineered by lateral shifting of the first three rows on the two sides of the slot [indicated by s_1, s_2, s_3 in Fig. 1 (a)] and by varying the center-to-center distance between two rows adjacent to the slot [W in Fig. 1 (a)]. For lattice constant, $a=425\text{nm}$, it is found that with a hole diameter $d=300\text{nm}$, $s_1=0$, $s_2=-85\text{nm}$, $s_3=85\text{nm}$, $S_w=320\text{nm}$, and $W=1.54(\sqrt{3})a$, we can achieve an average group index ($n_g=c/v_g$) of 20.4 ($\pm 10\%$) over 8.2nm optical bandwidth. The PCW step coupler [$a=425\text{nm}$, $d=300\text{nm}$, $s_1=0$, $s_2=0$, $s_3=0$, $S_w=320\text{nm}$, $W=1.45(\sqrt{3})a$] consists of 16 periods and is designed for low $n_g=6$ over the same wavelength range. The band diagrams of the slow-light and fast-light PCWs are shown in Fig. 1 (b).

The device is fabricated using e-beam lithography and RIE in a single patterning/etching step, while gold electrodes are patterned by photolithography and lift-off process. The EO polymer is infiltrated into the slot and holes of silicon PCW region by spincoating, as shown in the SEM image in Fig. 1 (c). A microscope image of the fabricated MZI is shown in Fig. 1 (d). Next, the device is poled by an electric field of 100V/ μm in a push-pull configuration at 145 $^\circ\text{C}$. The monitored leakage current and hot plate temperature are shown in Fig. 2(a). The maximum leakage current density is $1.4 \times 10^{-6} \text{A/m}^2$, which is comparable to that measured in a thin film

configuration ($2.36 \times 10^{-6} \text{ A/m}^2$ in data sheet). This test result shows that the 320nm-wide slot dramatically reduces the leakage current through the silicon-polymer interface which is detrimental to the poling efficiency [5].

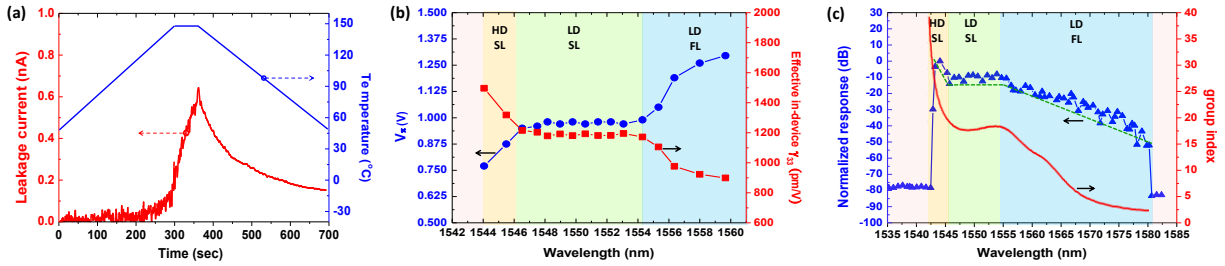


Fig. 2. (a) The temperature-dependent leakage current in the EO polymer poling process. (b) Measured V_π and corresponding effective in-device r_{33} v.s. wavelength (at 100KHz). HD SL: high-dispersion slow-light; LD SL: low-dispersion slow-light; LD FL: low-dispersion fast-light. (c) Normalized device response v.s. wavelength (at 100KHz). The green dashed line indicates the trend of the response change over different wavelength. Simulated n_g v.s. wavelength is also overlaid.

For modulation test, TE-polarized light from a tunable laser source (1550nm, 2.5mW) is coupled into and out of the device through grating couplers. RF signals are applied to the electrodes as shown in Fig. 1 (d). The modulator is biased at the 3dB point and driven by a 100KHz triangular RF wave with a peak-to-peak voltage of 1.4V. The modulated output optical signal is sent to a photodetector and then displayed on a digital oscilloscope. The V_π of the modulator is measured to be 0.973V, by observing the transfer function of the over-modulated optical signal and the input RF signal on the oscilloscope [6]. The effective in-device r_{33} is then calculated to be

$$r_{33-effective} = \frac{\lambda S_w}{n^3 V_\pi \sigma L} = 1190 \text{ pm/V} \quad (1)$$

where, $\lambda=1.55\mu\text{m}$, $S_w=320\text{nm}$, $n=1.63$, $L=300\mu\text{m}$, $\sigma=0.33$ (confinement factor in the slot) calculated by simulation. This extraordinarily high r_{33} value confirms the combined enhancing effects of slow light and an improved EO polymer poling efficiency. This modulator also achieves very high modulation efficiency with $V_\pi \times L=0.973\text{V} \times 300\mu\text{m}=0.292\text{V} \times \text{mm}$. The actual in-device r_{33} excluding the slow-light effect is also estimated to be 89pm/V, using the formula in [3], which is the highest poling efficiency demonstrated in a slot waveguide to the best of our knowledge. Furthermore, for our lumped modulator without termination, the energy consumption is dominated by the capacitive load of the slot; therefore, the RF power consumption is estimated to be

$$P = 2\pi f C V_{rms}^2 \times 2 = 1.5 \text{ nW} \quad (2)$$

Where, $f=100\text{KHz}$ (modulation frequency), $C=0.01\text{pF}$ (slot capacitance) calculated by simulation, $V_{rms}=V_\pi/2/(\sqrt{2})=0.344\text{V}$, and a factor of 2 is added due to the push-pull configuration. This ultralow power consumption benefits from the small capacitance due to large slot width and small V_π due to high EO efficiency.

To demonstrate the wide operating optical bandwidth, the optical wavelength is tuned over a wide optical bandwidth from 1544nm to 1560nm. The V_π measured at different wavelength, as well as the corresponding calculated effective in-device r_{33} , is plotted in Fig. 2 (b). It can be seen that the V_π is nearly constant, which is $0.97 \pm 0.02\text{V}$, over optical spectrum range of 8nm (low-dispersion slow-light region: from 1546.5nm to 1554.5nm), corresponding to the effective in-device r_{33} of 1190pm/V and $V_\pi \times L$ of $0.291 \pm 0.006\text{V} \times \text{mm}$. Furthermore, a small signal modulation test is done at $V_{pp} < 1\text{V}$ over a broad wavelength range. The measured wavelength dependence of the normalized optical response follows the trend of the simulated n_g , as shown in Fig. 2 (c). It can be seen that the response is almost flat in the low-dispersion slow-light region (wavelength from 1546.5nm to 1554.5nm), because the slot PCW is band-engineered to have a nearly constant n_g in this wavelength range. Details can be seen in [7].

Reference

- [1] X. Zhang, A. Hosseini, X. Lin, H. Subbaraman, and R. T. Chen, "Polymer-based Hybrid Integrated Photonic Devices for Silicon On-chip Modulation and Board-level Optical Interconnects," *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 16, pp. 3401115, 2013.
- [2] J. H. Wulbern, J. Hampe, A. Petrov, M. Eich, J. D. Luo, A. K. Y. Jen, A. Di Falco, T. F. Krauss, and J. Bruns, "Electro-optic modulation in slotted resonant photonic crystal heterostructures," *Applied Physics Letters*, vol. 94, Jun 15 2009.
- [3] A. Hosseini, X. C. Xu, H. Subbaraman, C. Y. Lin, S. Rahimi, and R. T. Chen, "Large optical spectral range dispersion engineered silicon-based photonic crystal waveguide modulator," *Optics Express*, vol. 20, pp. 12318-12325, May 21 2012.
- [4] A. Hosseini, X. Xu, D. N. Kwong, H. Subbaraman, W. Jiang, and R. T. Chen, "On the role of evanescent modes and group index tapering in slow light photonic crystal waveguide coupling efficiency," *Applied Physics Letters*, vol. 98, pp. 031107-031107-3, 2011.
- [5] X. Wang, C.-Y. Lin, S. Chakravarty, J. Luo, A. K.-Y. Jen, and R. T. Chen, "Effective in-device r_{33} of 735 pm/V on electro-optic polymer infiltrated silicon photonic crystal slot waveguides," *Optics letters*, vol. 36, pp. 882-884, 2011.
- [6] X. Zhang, B. Lee, C.-y. Lin, A. X. Wang, A. Hosseini, and R. T. Chen, "Highly Linear Broadband Optical Modulator Based on Electro-Optic Polymer," *Photonics Journal, IEEE*, vol. 4, pp. 2214-2228, 2012.
- [7] X. Zhang, A. Hosseini, S. Chakravarty, J. Luo, A. K.-Y. Jen, and R. T. Chen, "Wide optical spectrum range, subvolt, compact modulator based on an electro-optic polymer refilled silicon slot photonic crystal waveguide," *Optics letters*, vol. 38, pp. 4931-4934, 2013.