Demonstration of Effective In-device r_{33} over 1000 pm/V in Electro-optic Polymer Refilled Silicon Slot Photonic Crystal Waveguide Modulator

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

[1]Microelectronics Research Center, Electrical and Computer Engineering Department, University of Texas at Austin, Austin, TX, 78758, US
[2]Omega Optics, Inc., 10306 Sausalito Dr, Austin, TX 78759, USA
[3] Department 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 a band engineered slot photonic crystal waveguide refilled with electro-optic (EO) polymer. The combined effects of slow-light and high performance EO polymer makes possible effective in-device r_{33} of 1012pm/V and $V_\pi \times L$ of 0.345Vmm.

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Hybrid electro-optic (EO) polymer and silicon photonic devices can benefit from the large EO coefficient, $r_{33} \geq 100$pm/V, of the polymer as well as the compact size made possible by the large index of silicon [1]. Utilizing the slow light effect, photonic crystal waveguides (PCWs) refilled with EO polymers can further reduce the device size [2]. Here, we report a symmetric Mach-Zehnder Modulator (MZM), in which the active sections consist of band engineered slot photonic crystal waveguides refilled with EO polymer, SEO125 from Soluxra, with EO coefficient, r_{33}=100pm/V. The polymer (n=1.63) is optimized for complete refilling of the PCW holes and slot. The band engineered PCW provides a low-dispersion slow-light (constant group velocity, v_g) for the MZM operation.

A schematic of the slot PCW on SOI (Si thickness=250nm, oxide thickness=3μm) is shown in Fig. 1(a). For lattice constant, a=425nm, it is found that with a hole diameter, d=300nm, s_1=0, s_2=-85nm, s_3=85nm, slot with of S_w=320nm, and dW=1.54(√3)a, we can achieve an average group index ($n_g=c/v_g$) of 20.4(±10%) over 8.2nm optical bandwidth. The band structure and the variations of n_g over the low-dispersion slow light wavelength range are shown in Figs. 1(c) and (d), respectively. In order to efficiently couple light in and out of the device, a *coupling PCW* is also designed [a=425nm, d=300nm, s_1=0, s_2=0, s_3=0, S_w=320nm, dW=1.45(√3)a], which provides n_g=6 over the same wavelength range as shown in Fig. 1(d). PCW tapers connect the input and output slot waveguides to 300μm-long high n_g PCWs and consist of 16 periods over which the design parameters parabolically change from those of the *coupling PCW* to those of the high n_g PCW. V-shaped mode converters are used to connect single mode silicon waveguides (width=500nm) and the slot waveguides. The fundamental TE mode profiles before and after the

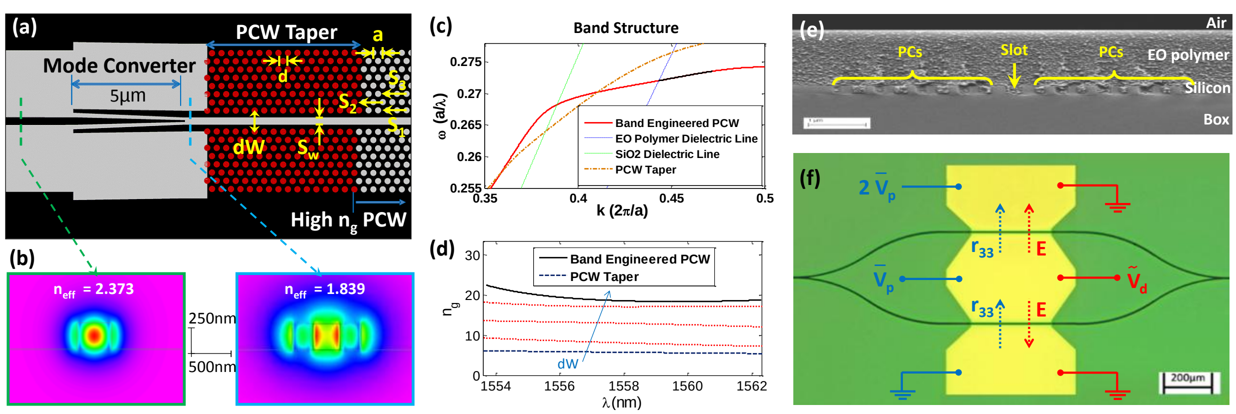

Fig. 1. (a) Actual layout of the PCW coupler (mode converter + PCW taper). The black area corresponds to un-etched silicon. (b) The fundamental mode profile (Ex) before and after the mode converter. (c) The band structure (normalized frequency v.s. normalized propagation constant, the fundamental guided defect mode) for the band-engineered PCW and the PCW taper. The black curve highlights the low dispersion slow light section of the band-engineered PCW mode. The dielectric light lines corresponding to the SiO_2 (n=1.45) and EO polymer (n=1.63) cladding layers are shown. The useful part of the mode falls below both light lines. (d) Variations of the group index v.s. wavelength for the band-engineered PCW and the PCW taper. (e) Cross-sectional SEM image of the silicon slot PCW refilled with EO polymer. PCs: Photonic crystals (f) Optical microscope image of the CPW MZM. The blue colored circuit connection indicates the push-pull poling configuration and induced r_{33} direction, and the red colored circuit connection indicates the modulation configuration. Vp: poling voltage, Vd: diving voltage.

mode converter are shown in Fig. 1(b). Multi-mode interference (MMI) couplers are used for beam splitting/combining [3]. Sub-wavelength grating (SWG) are designed to couple light into and out of the silicon strip.

The fabrication procedure starts with a SOI wafer with 250nm thick top silicon. All the photonic circuitries are fabricated using electron-beam lithography and reactive iron etching (RIE) in a single patterning/etch step, while the gold electrodes are patterned by photolithography and lift-off process. The EO polymer is infiltrated into the slot PCW waveguides by spincoating. The silicon PCW regions including holes and the slot are fully covered by EO polymer consisting of a guest/host system of 25% weight chromophore SEO125 into amorphous polycarbonate (APC), as shown in the SEM image in Fig. 1(e). A microscope image of the MZM is shown in Fig. 1(f). Next, the sample is poled by an electric field of 100V/μm in a push-pull configuration at the glass transition temperature (T_g=145 ℃) of the EO polymer. The leakage current as well as the hot plate temperature is monitored and shown in Fig. 2(a). It can be seen that the maximum leakage current density remains below 1.4×10^{-6}A/m^2 [=103μA/(300μm×250nm)]. For comparison, the leakage current density in the SEO125 data sheet is 2.36×10^{-6}A/m^2 measured in a thin film configuration. This test result is repeatable and shows that the 320nm-wide slot dramatically reduces the leakage current that is known to be detrimental to the poling efficiency [4].

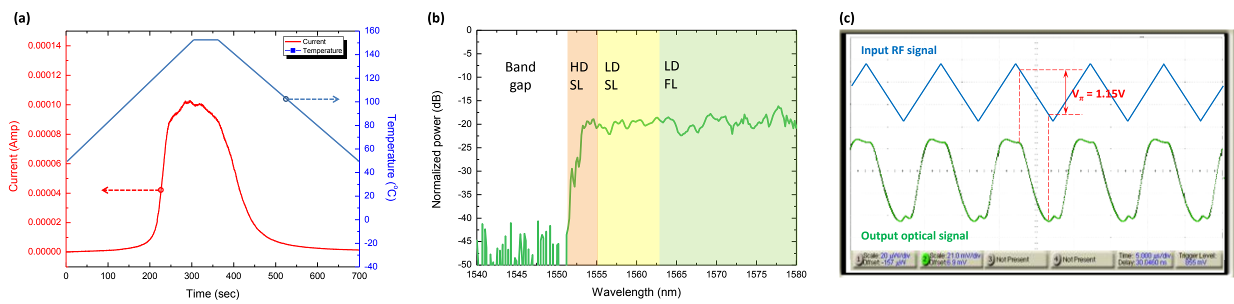

Fig. 2. (a) Temperature dependent leakage current in the entire poling process. (b) Transmission spectrum of a 300μm-Long slot PCW refilled with EO polymer. SL: slow light; FL:fast light; HD: high dispersion; LD: low dispersion. (c) Transfer function of over-modulation for determination of the V_π= 1.15V at 100KHz.

Light from a broadband ASE source is coupled into the PCW via the grating couplers. Fig. 2(b) shows the measured transmission spectrum. A clear band gap with more than 30dB contrast is observed, indicating efficient coupling into the slow-light modes of the PCW. For the modulation test, a tunable laser is used. The total optical insertion loss is 20dB, including the 6.5dB/facet coupling loss from grating couplers. The device is driven by a 100kHz triangular wave with a peak-to-peak voltage of 1.2V. The output optical waveform (at 1558nm) from a digital oscilloscope in Fig. 2(c) shows that over-modulation occurs at 1.15V, which is the V_π of the modulator. Therefore, the modulator achieves $V_\pi\times L$=1.15V×300μm=0.345Vmm. The effective in-device r_{33} is then calculated as

$$r_{33,effective} = \frac{\lambda S_w}{n^3 V_\pi \sigma L} = 1012\text{pm/V}$$

where, λ=1.56 μm, S_w=320nm (slot width), n=1.63, L=300 μm, σ=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 poling efficiency. The effective r_{33} remains over 1000pm/V over 5nm wavelength range. With the designed n_g, we estimate the in-device r_{33} to be 74pm/V, significantly more than 59pm/V in our previous work on a non-band-engineered PCW [5].

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