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Thin TiO_2 core and electro-optic polymer cladding waveguide modulators

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In this letter, we have fabricated a thin TiO_2 core and electro-optic (EO) polymer cladding derived rib-waveguide and demonstrated its optical modulation at 1550 nm with a $V_\pi L$ figure of merit of 3.3 V cm. We utilized the high refractive index TiO_2 to confine a large fraction of light in the relatively low refractive index EO polymer layer. Furthermore, this TiO_2 core enables the modulator to be constituted without a transparent top cladding and also can increase the EO activity to a much higher level. As a result, the waveguide has an enhanced in-device r_{33}, corresponding to a $V_\pi L$ of 1.65 V cm in a push-pull Mach-Zehnder interferometer structure. [http://dx.doi.org/10.1063/1.4809818]

Waveguide modulators based on electro-optic (EO) polymer currently play a key role in telecom, datacom, and sensing areas.[1] One of the most important characteristics of modulators is the $V_\pi L$ figure of merit required for operation, where V_π is the half wave voltage and L is the active electrode length.[2,3] This value is determined by the interelectrode gap, the integral between the applied electric field and the optical mode, and the EO coefficient (r_{33}) of the polymer.[4] In order to minimize $V_\pi L$, a great effort has been invested in the rational design and synthesis of high molecular hyperpolarizability (β) chromophores in molecular level and achieving a high r_{33} with the greatest chromophore concentration in the polymer films in macroscopic level. Generally, a polymer waveguide consists of an EO core and transparent cladding layers. The EO core must be poled in order to induce a refractive index change under an applied voltage. Recently, many types of high β chromophores have been investigated which show a large EO activity in the pristine films. However, such films exhibit a leakage current problem because of the possible electrons transfer through the π-electron chromophore at a high loading concentration. The measured electrical resistivity in the order of $10^8\,\Omega$ cm is often several orders lower than that of the cladding materials.[5,6] Consequently, it is critical to have a large voltage dropping on the EO polymer core by careful consideration and choosing suitable claddings.

Recently, researchers have explored a polymer/silicon slot waveguide and realized a modulator performance with an excellent $V_\pi L$ figure of merit for any modulator obtained to date in this structure.[7,8] This may overcome the drawbacks of traditional polymeric waveguide modulators. In the polymer/silicon slot system, two silicon ridges are separated from each other by a slot. This slot is typically ~120 nm wide and filled with an EO polymer. Because of the high refractive index contrast between silicon ($n = 3.48$) and the EO polymer ($n = 1.65$), approximately 50% of the guiding light can be concentrated in the slot of EO polymer.[9] The EO polymer has a much higher resistivity than that of silicon, so the two silicon ridges can be used as modulator electrodes.[8] As a result, the interelectrode gap is ~120 nm, and all the voltage can drop on the EO polymer. Although the in-slot r_{33} reaches only 10%–30% of the thin EO polymer film[10] and the propagation loss is still large level (35 dB/cm),[11] the waveguide demonstrated a $V_\pi L$ figure of merit of 0.5 V cm and high speed modulation in recent publication.[8] Therefore, further improvement of EO polymer devices used with high refractive index materials becomes attractive when considering such as on-chip integration with silicon photonics and the fast miniaturized components for on-chip optical interconnects.

In this work, we have fabricated a waveguide using a TiO_2 core and an EO polymer cladding. As the high refractive index TiO_2 core is thin, a large fraction of the optical TM mode extends into the cladding, which is the rationale for selecting an EO polymer cladding. As a result, our waveguide can be constituted without a transparent cladding, which makes the interelectrode gap smaller than the traditional three-layer waveguides. This TiO_2 layer also has the function of improving the poling efficiency of the EO polymer to attain a high r_{33} level, due to the blocking of excessive charge injection and the reduced the current leakage. Combining all of these merits together, the resulting fabricated waveguide exhibited a $V_\pi L$ figure of merit and propagation loss of 3.3 V cm and 3.0 dB/cm, respectively.

Figure 1(a) shows the designed cross-sectional structure of the waveguide. The thickness of EO polymer cladding is 2.4 μm. The height and width of the TiO_2 ridge is 0.1 and 2 μm, respectively. The thickness of the TiO_2 slab section is set as d_{TiO2} for the theoretical optimization. The refractive indices of our EO polymer, TiO_2, and sol-gel SiO_2 are 1.61, 2.30, and 1.44 at the wavelength of 1550 nm, respectively. Figures 1(c) and 1(d) indicate the simulated TM_0 modal pattern and power density across the waveguide with d_{TiO2} at 0.15 μm. It can be observed that there is a discontinuous mode at the boundary between the TiO_2 and the EO polymer and that more of the optical mode extends deep into the EO

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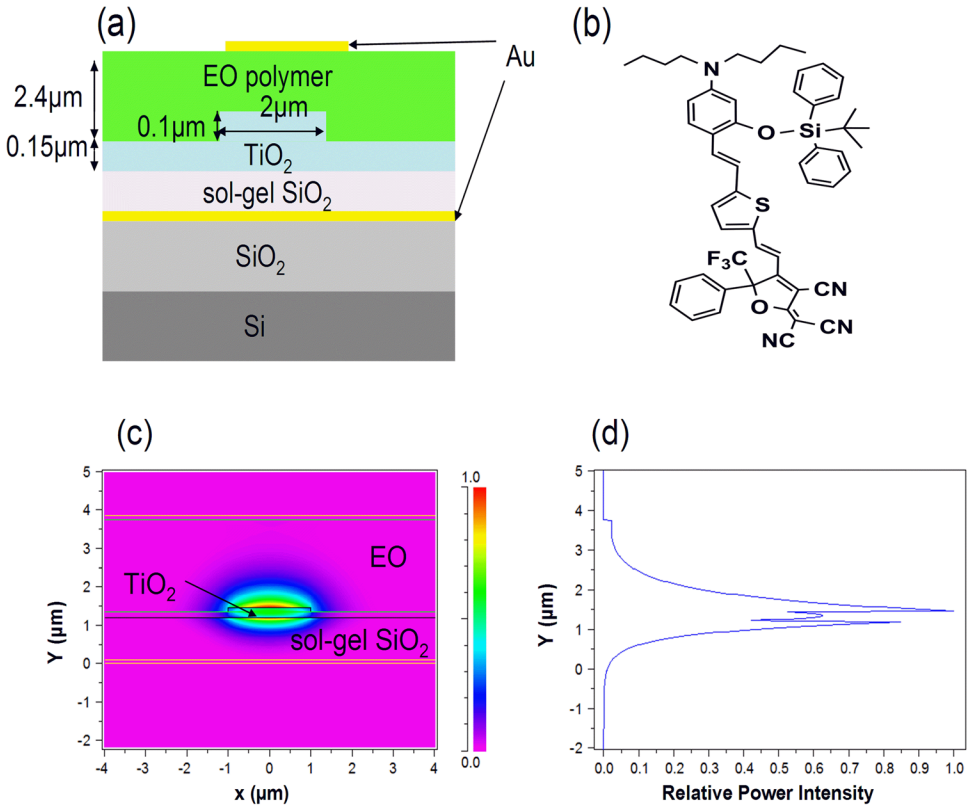

FIG. 1. (a) Designed cross-sectional structure of the TiO_2/EO polymer waveguide; (b) EO chromophore structure; (c) simulated TM_0 modal pattern; and (d) power density with d_{TiO2} at 0.15 μm.

polymer layer. This is caused by the discontinuity of the electric field at high-low refractive index contrast interfaces.[9]

Therefore, the overlap factor (Γ) indicating the integral between the applied electric field and the optical mode was calculated as a function of d_{TiO2} by using the 3D beam propagation method (BPM) of Rsoft.[12] In the calculations, the low refractive index sol-gel SiO_2 cladding is assumed thick enough, so that the absorption loss from the bottom Au electrode can be ignored. While, waveguide optical loss due to the top Au electrode is considered in the calculation. As shown in Fig. 2, there is a tradeoff between increasing Γ and optical loss within the d_{TiO2} range of 0.11–0.18 μm. In this work, therefore, we choose a d_{TiO2} of 0.15 μm to obtain an expected small optical loss as 0.7 dB/cm and Γ of 48%.

Based on these simulations, a TiO_2 core and EO polymer cladding waveguide was fabricated. A solution of sol-gel SiO_2, consisting of ethylsilicate and triethoxythysilane with a mass ratio of 30/70, was prepared for the waveguide bottom cladding. Acetic acid was used as a catalyst, and water and ethanol were the solvent. The thickness of the sol-gel SiO_2 film was 1.1 μm after spin-coating onto the Au electrode/silicon substrate and heating at 150 °C. The film was thick enough to enable the absorption loss from the bottom Au electrode to be less than 1.0 dB/cm. After preparation of the cladding, a 0.25 μm TiO_2 layer was obtained by RF sputtering technique and then patterned by photolithography and reactive ion etching. The EO material used in this work was a mixture of a high β chromophore and a PMMA host polymer as the structure shown in Fig. 1(b).[13,14] The 20 wt. % solution of this EO polymer (33 wt. % chromophore doped into PMMA) in cyclopentanone was first filtered through 0.2 μm syringe filter and then spin-coated onto the patterned TiO_2. The polymer films were baked in a vacuum condition at 85 °C for 48 h, and the film thickness was measured as 2.4 μm. Finally, the top Au electrode was sputtered onto the EO polymer.

To realize a modulator, we first poled the EO polymer in the waveguide. The poling field was set as 118 V/μm at the initial temperature of 26 °C. The poling temperature was increased to 96 °C at a rate of 5 °C/min. The sample was kept at 96 °C for 5 min and then was cooled to room temperature rapidly. During poling, the bottom electrode was contacted with the anode. Subsequently, we measured the waveguide propagation loss to be approximately 3.0 dB/cm by an end-fire coupling optical measurement.[15] To obtain the EO properties, the waveguide was observed as light intensity modulation using a cross-polarization setup. Input light

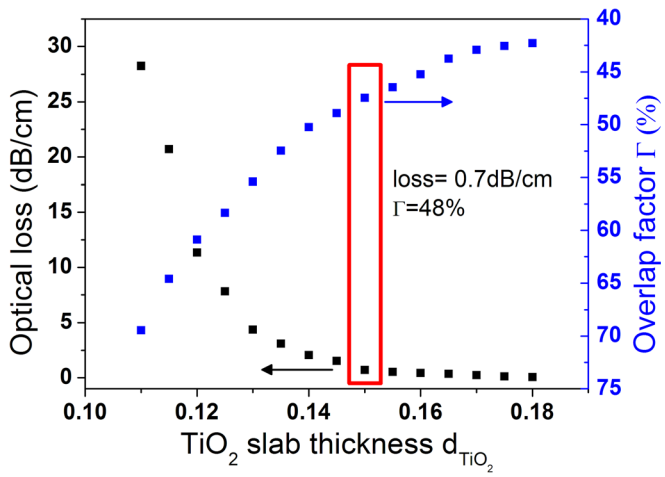

FIG. 2. Calculated overlap factor Γ and top Au electrode absorption optical loss vs the TiO_2 slab thickness d_{TiO2}.

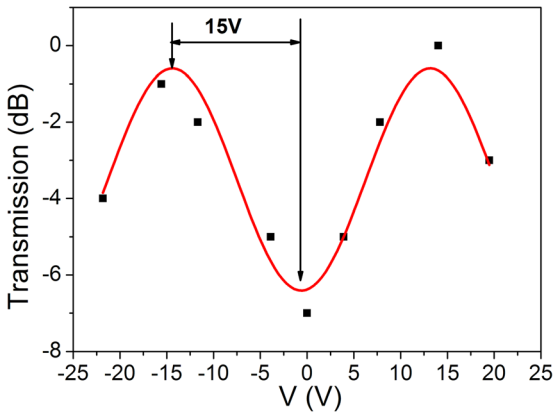

FIG. 3. Transmission through the device as a function of bias voltage.

(1550 nm) with a +45° linear polarization was coupled into the waveguide through a polarization maintaining fiber. Output light passing a −45° polarizer was collected by a photo-detector. The V_π of the modulator was obtained by measuring the relationship between the applied DC voltage and transmission.[9] Figure 3 exhibits the transmission plotted against the bias voltage. The curve was fitted by the *Sine* function according to the measured data. It can be seen that the V_π of the waveguide is ~15 V. Considering the Au electrode length of 2.2 mm, the $V_\pi L$ figure of merit is 3.3 V cm. Since this straight shape waveguide is possible for the application of a push-pull Mach–Zehnder interferometer structure, the drive voltage can be further reduced to the half voltage level. Such a $V_\pi L$ figure of merit is comparable with the previous hybrid EO polymer/sol-gel SiO_2 waveguide modulator with an in-device r_{33} of 110 pm/V.[16]

By using the measured $V_\pi L$ of 3.3 V cm, waveguide thickness of 3.65 μm (2.4 μm thick EO polymer cladding, 0.15 μm thick TiO_2 core, and 1.1 μm thick so-gel SiO_2 under-cladding), and $r_{33} = 3r_{13}$ approximation in the EO polymer film, an effective in-device r_{33} was estimated to be ~120 pm/V ($\Gamma = 48\%$). We assumed that such a large in-device r_{33} was attributed to the enhanced poling efficiency. To compare the poling efficiency, we also measured the r_{33} of a thin EO polymer film and a TiO_2/EO polymer double-layer film on ITO glass by using the Teng-Man method.[17] A laser wavelength of 1310 nm was chosen for these measurements on ITO glass substrates. The measured r_{33} was 69 pm/V for the thin EO polymer film, while r_{33} was 125 pm/V for the TiO_2/EO polymer double-layer after calibration, taking into account the multiple-reflection effects.[18,19] This ~80% overall improvement in the r_{33} value is attributed to the function of the TiO_2 layer, which has been predicted by the field distribution flattening effect in the previous reference 19. Since the sol-gel SiO_2 under-cladding has a resistivity almost the same as that of the EO polymer, an enhanced r_{33} of the EO polymer TiO_2 core can be also expected in the waveguide.

Here, it is necessary to compare the $V_\pi L$ of our waveguide (type-1) with that in the traditional EO core and transparent cladding waveguide (type-2). The effective refractive indices of type-1 and type-2 waveguides are around 1.68 and 1.58, respectively. We used the measured r_{33} values for the thin EO polymer film and it on TiO_2, and then obtained the $n^3 r_{33}$ material's figure of merit as 593 and 272 pm/V for type-1 and type-2, respectively. In type-1, the total waveguide thickness is 3.7 μm, and in type-2 typically 6.4 μm (2.4 μm thick EO polymer core and 2.0 μm thick sol-gel SiO_2 top- and under-claddings). Therefore, we evaluate a $V_\pi L$ in the type-1 waveguide which is about 40% smaller than that in the type-2 waveguide.

In summary, we have demonstrated a hybrid TiO_2/EO polymer rib-waveguide modulator with $V_\pi L$ of 3.3 V cm, corresponding to 1.65 V cm in a push-pull MZI structure. This $V_\pi L$ figure of merit benefits from the TiO_2 layer. The propagation loss is much lower than that for the previously reported EO polymer/silicon slot waveguide modulators. The fabrication of our waveguide is both simple and low-cost, which should make it amenable to industrial utilization.

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[1]Y. Shi, C. Zhang, H. Zhang, J. H. Bechtel, L. R. Dalton, B. H. Robinson, and W. H. Steier, Science **288**(5463), 119 (2000).
[2]M.-C. Oh, H. Zhang, A. Szep, W. H. Steier, C. Zhang, L. R. Dalton, H. Erlig, Y. Chang, B. Tsap, and H. R. Fetterman, IEEE J. Sel. Top. Quantum Electron. **7**(5), 826 (2001).
[3]Y. Enami, C. T. Derose, D. Mathine, C. Loychik, C. Greenlee, R. A. Norwood, T. D. Kim, J. Luo, Y. Tian, A. K. Y. Jen, and N. Peyghambarian, Nat. Photonics **1**(3), 180 (2007).
[4]R. C. Alferness, IEEE Trans. Microwave Theory Tech. **30**, 1121 (1982).
[5]R. Song, A. Yick, and W. H. Steier, Appl. Phys. Lett. **90**, 191103 (2007).
[6]F. Yi, F. Ou, B. Liu, Y. Huang, S.-T. Ho, Y. Wang, J. Liu, T. J. Marks, S. Huang, J. Luo, A. K.-Y. Jen, R. Dinu, and D. Jin, Opt. Express **18**(7), 6779 (2010).
[7]J. D. Luo, S. Huang, Z. W. Shi, B. M. Polishak, X. H. Zhou, and A. K. Y. Jen, Chem. Mater. **23**, 544 (2011).
[8]T. Baehr-Jones, B. Penkov, J. Huang, P. Sullivan, J. Davies, J. Takayesu, J. Luo, T.-D. Kim, L. Dalton, A. Jen, M. Hochberg, and A. Scherer, Appl. Phys. Lett. **92**(16), 163303 (2008).
[9]V. R. Almeida, Q. F. Xu, C. A. Barrios, and M. Lipson, Opt. Lett. **29**(11), 1209 (2004).
[10]X. Wang, C.-Y. Lin, S. Chakravarty, J. Luo, A. K.-Y. Jen, and R. T. Chen, Opt. Lett. **36**(6), 882 (2011).
[11]M. Gould, T. Baehr-Jones, R. Ding, S. Huang, J. Luo, A. K.-Y. Jen, J.-M. Fedeli, M. Fournier, and M. Hochberg, Opt. Express **19**(5), 3952 (2011).
[12]Rsoft software.
[13]X. Piao, Z. Xianmin, Y. Mori, M. Konishi, A. Nakaya, S. Inoue, I. Aoki, A. Otomo, and S. Yokoyama, J. Polym. Sci., Part A: Polym. Chem. **49**, 47 (2011).
[14]X. Zhang, I. Aoki, X. Piao, S. Inoue, H. Tazawa, S. Yokoyama, and A. Otomo, Tetrahedron Lett. **51**, 5873 (2010).
[15]F. Qiu, A. M. Spring, F. Yu, and S. Yokoyama, Appl. Phys. Lett. **102**, 051106 (2013).
[16]Y. Enami, D. Mathine, C. T. DeRose, R. A. Norwood, J. Luo, A. K.-Y. Jen, and N. Peyghambarian, Appl. Phys. Lett. **91**, 093505 (2007).
[17]C. C. Teng and H. T. Man, Appl. Phys. Lett. **56**, 1734 (1990).
[18]D. H. Park, C. H. Lee, and W. N. Herman, Opt. Express **14**(19), 8866 (2006).
[19]S. Huang, T.-D. Kim, J. Luo, S. K. Hau, Z. Shi, X.-H. Zhou, H.-L. Yip, and A. K.-Y. Jen, Appl. Phys. Lett. **96**(24), 243311 (2010).