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Electro-Optic Polymer/TiO_2 Slot Waveguide Modulators and Enhanced Electro-Optic Coefficient of 260 pm/V

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Abstract

We analyze and optimize an electro-optic (EO) polymer/TiO_2 multilayer slot waveguide modulator based on low-index EO polymer (SEO125) from experimentally obtained lower half wave voltage (V_π), compared to a hybrid EO polymer/sol-gel silica waveguide modulators without TiO_2 slot layer. We also enhanced EO coefficient to 260 pm/V for high index EO polymer (SEO100).

1. Introduction

Polymer modulators have been only one optical modulator that showed at bandwidth of >60GHz, and the widest bandwidth was 113GHz due to lower dielectric dispersion of the EO polymer [1]. We already demonstrated low half wave voltage (V_π) of 0.65 – 1.0 V [2, 3] with relatively low optical propagation loss of 5 dB/cm, based on a hybrid EO polymer/sol-gel silica waveguide modulators with in-device EO coefficient of 142 pm/V at a wavelength of 1550 nm. The $V_\pi L_e$ product (L_e : electrode length) was considered as a figure of merit (FOM) of the integrated optical modulator for an optical interconnection based on Si modulators. Only a few reports for Si modulators were focused on the optical loss for realistic applications. The combination of FOM and the optical loss can be defined as another FOM, $V_\pi Loss$ to multiple $V_\pi L_e$ [dBcm] by the optical propagation loss in the active region [dB/cm]. Our hybrid polymer modulator has $V_\pi L_e$ product of 1.56 Vcm and $V_\pi Loss$ of 7.8 VdB in the hybrid EO polymer/sol-gel silica waveguide modulator [2]. To my best knowledge, one of the best Si modulators showed the $V_\pi L_e$ product of 0.78 Vcm and 6.7 VdB [4] even though other Si modulators showed $V_\pi L_e$ product of 1-3 Vcm with $V_\pi Loss$ of >27 VdB[5, 6]. We have demonstrated EO polymer/TiO_2 multilayer slot waveguide modulator at the first time [7], and reduced $V_\pi L_e$ product to 2 Vcm and $V_\pi Loss$ product to 14 VdB using low-index EO polymer (SEO125, index of 1.621), based on enhanced conductivity of the sol-gel silica under cladding [8]. In the modulator, the enhanced conductivity of the sol-gel silica undercladding realized efficient poling of the EO polymer with selective layer of TiO_2. We also demonstrated the highest EO coefficient of 226 and 198 pm/V at the wavelength of 1.31 and 1.55 μm, respectively, for efficiently poled high refractive-index EO polymer film SEO100 deposited on TiO_2 selective layer and sol-gel silica cladding [9]. Here, we analyzed and demonstrated an advantage of EO polymer/TiO_2 slot waveguide modulators for further reduction of $V_\pi L_e$, compared to the hybrid EO polymer/sol-gel silica waveguide modulators. We also demonstrated the highest and enhanced EO coefficient of 260 pm/V and 215 pm/V at 1.31 μm and 1.55 μm for SEO100, using additional interfacial layer in the under cladding.

2. EO Polymer/TiO_2 slot waveguide modulators

EO polymer/TiO_2 multilayer slot waveguide modulators were fabricated using 300-600 nm-thick EO polymer sandwiched between two 100-nm-thick TiO_2 thin-film layers. A cross-sectional view for 4-μm-wide Mach-Zehnder type waveguide of the modulator was as shown in Fig. 1 (a), compared to standard hybrid EO polymer/sol-gel silica waveguide modulator as shown in Fig. 1. (b) [2].

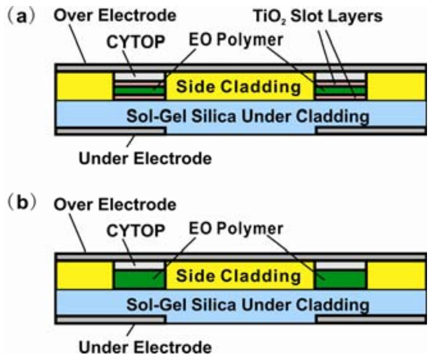

Fig. 1 Schematic cross-sectional view at the active region. (a) The EO polymer/TiO_2 multilayer slot waveguide modulator. (b) The hybrid EO polymer/sol-gel silica waveguiding modulator.

The thickness of the sol-gel silica undercladding and overcaldding was 4 μm and 1.2 μm, respectively. The refractive index of EO polymer SEO125, TiO_2, CYTOP, and sol-gel silica cladding was 1.621, 2.567, 1.328, and 1.487, respectively. At the first step, a mode overlap integral (Γ) between an electrical field driven by an applied voltage and an optical confinement in the EO polymer was calculated using three-dimensional finite differential time domain (3D FDTD) method. Next, the $V_\pi L_e$ product of the EO polymer/TiO_2 slot waveguide modulators and standard hybrid modulators was calculated for in-device r_{33} of 70 pm/V and the Γ. The dependence of $V_\pi L_e$ product for the slot waveguide modulator (see Fig. 1(a)) on the thickness of the EO polymer was obtained for 1-μm-thick and 4-μm-thick sol-gel cladding as shown in Fig. 3. The dependence of $V_\pi L_e$ product for standard hybrid modulator (see Fig. 1(b) was also obtained for the comparison.

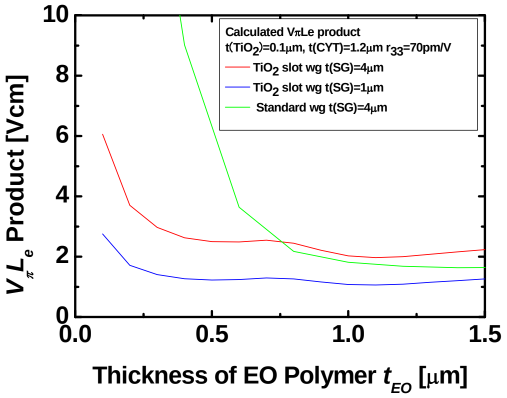

Fig. 2 $V_\pi L$ product with respect to the thickness of the EO polymer (SEO125) calculated by 3D FDTD method. The thickness of the TiO_2 and CYTOP is 0.1 and 1.2 μm, respectively. r_{33} = 70 pm/V. Red and blue lines show for EO polymer/TiO_2 slot waveguide modulator with the thickness of the sol-gel silica undercladding of 4 and 1 μm, respectively. Green line shows for standard hybrid EO polymer/sol-gel silica waveguide modulator.

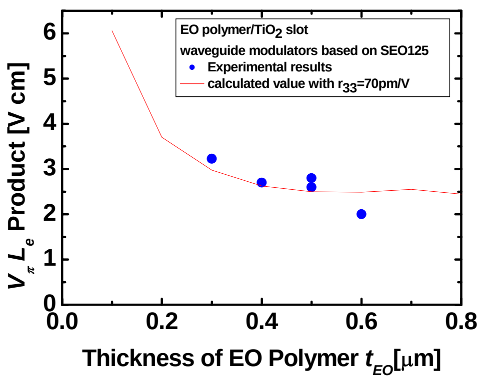

Fig. 3 $V_\pi L$ product with respect to the thickness of the EO polymer (SEO125). The blue close circles show experimental results and red line shows calculated one by 3D FDTD method. .

When the thickness of the under cladding is 4 μm, the slot waveguide modulator does not show significant advantage for >0.75 μm-thick EO polymer. In this calculation, we assumed in-device EO coefficient (70 pm/V) was same for the TiO_2 slot waveguide modulator and standard modulator. In the actual modulator devices, the in-device EO coefficient for the TiO_2 slot waveguide modulator is higher than that for the standard modulator [9] which resulted in lower $V_\pi L_e$ product. When the thickness of the under cladding was critically reduced to 1 μm, the calculated $V_\pi L_e$ product was reduced by a factor of 2, compared to other modulators. The $V_\pi L_e$ product was experimentally measured for several modulators that have different EO polymer thickness ranging from 0.3 to 0.6 μm, as shown in Fig. 3. The measured $V_\pi L_e$ product was matched with the theoretically calculated one.

For next demonstration based on high-index EO polymer SEO100, we examined to increase the poling efficiency. Thus far, the highest EO coefficient of 260 and 215 pm/V at the wavelength of 1.31 and 1.55 μm was obtained, respectively, for the SEO100 on TiO_2 and sol-gel silica, which was higher than SEO125 by a factor of 3. When we successfully employ SEO100 in this modulator, $V_\pi L_e$ product would be reduced by a factor of 6 with the reduced thickness of the sol-gel silica and enhanced EO coefficient, which will result in $V_\pi L_e$ of less than 0.3 Vcm and $V_\pi Loss$ of 2.3 VdB.

3. Conclusion

We analyzed and optimized the EO polymer/TiO_2 multilayer slot waveguide modulator from experimentally obtained $V_\pi L$. We also demonstrated the highest EO coefficient for SEO100 after the enhancement of poling efficiency.

Acknowledgements

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