Optical Circular-Polarization Modulator Employing Tilt-Poled Electrooptic Polymers

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***Abstract*—A polymer-based integrated circular-polarization modulator (CPM) is demonstrated in this paper. Tilted poling is adopted to achieve polarization conversion in the electrooptic (EO) polymeric waveguide and then realize the power balance between transverse electric and transverse magnetic modes. Detailed analysis and experiments on polarization conversion are presented. The tensor nature of poled polymeric materials is used to generate the phase difference. Contact poling is applied to perform tilted poling and activate the EO effect of polymeric materials. With appropriate voltage control, the polarization state of the output from the CPM can alternate between the left- and right-hand-circular states. The extinction ratios at the 45o- and−45°-tilted linearly polarized states are larger than 25 dB.**

***Index Terms*—Electrooptic (EO) modulation, integrated optics, optical polarization, optical waveguide, polymer.**

I. Introduction

THE OPTICAL circular-polarization modulator (CPM) can be employed as a source of both left-hand-circular (LHC) and right-hand-circular (RHC) lights for detecting and measuring chirality [1], [2] and can find uses in remote sensing, scanned object detection in fog, and imaging polarimetry. In optical communication systems, the CPM can also be used as a high-speed coding modulator, in which information is coded by the selection of either LHC or RHC light [3]. Another application of the CPM in optical communications is to scramble the polarization of light coupled into optical fibers. Commonly, the CPM is made by employing the bulk-optic technology with electrooptic (EO) crystals [4]. As one of the potential materials for integrated optics, the polymeric material and related planar waveguide components have attracted a great deal of attention by researchers [5]–[11]. In this paper, a monolithically integrated CPM is demonstrated using EO polymeric materials and the contact-poling technique.

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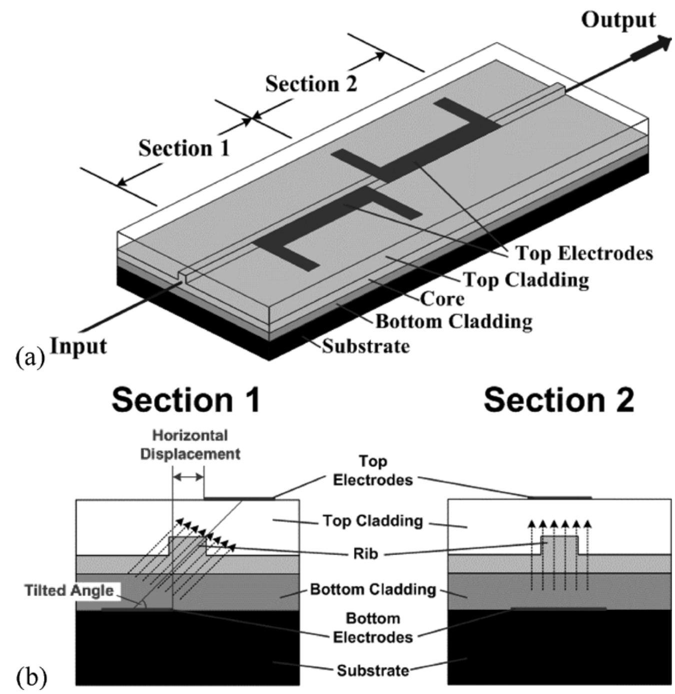
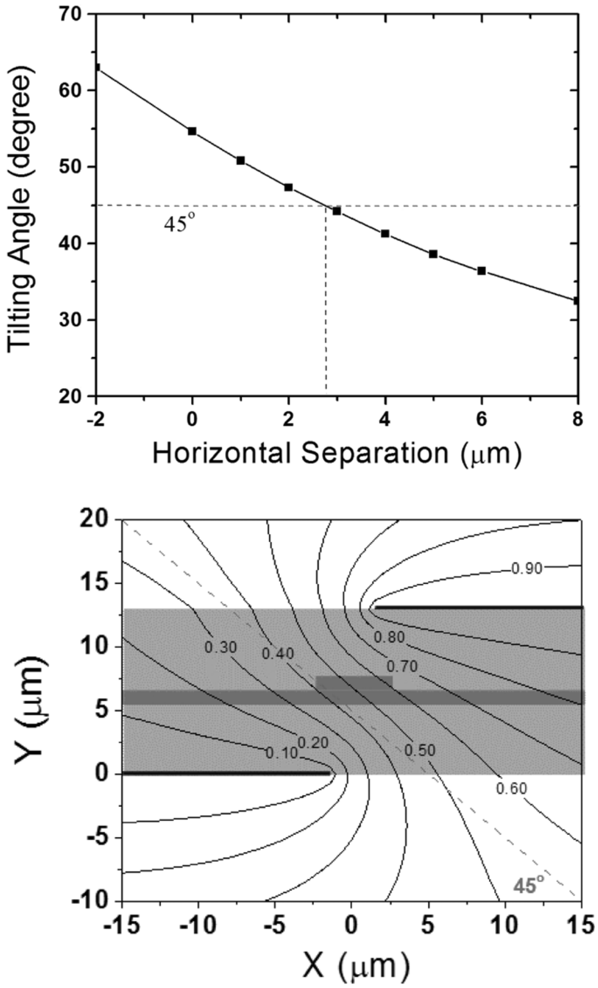


Fig. 1. Schematic diagram of the EO-polymer-based optical CPM.

The paper is organized as follows. In Section II, the operation principle and device design of the EO-polymer-based CPM are presented. Then, the CPM is fabricated with the EO polymer DR1/PMMA in Section III and characterized in Section IV. The results are summarized in Section V.

II. Principle and Design

The quality of LHC/RHC lights is determined by two factors: the power and phase differences between the two mutually orthogonal polarization components. The proposed CPM consists of two main sections: the transverse-electric/transverse-magnetic (TE–TM) polarization balancer and the TE–TM phase-difference modulator, shown by section 1 and section 2 in Fig. 1, respectively. When a linearly polarized light in the vertical or horizontal direction enters into the CPM, polarization conversion takes place in the TE–TM polarization balancer. By applying and adjusting the biasing voltage, the conversion can be controlled and the powers of the TE and TM modes will be delivered equally to the output of the CPM. Then, in the TE–TM phase-difference modulator, the variable phase difference between the TE and TM modes is generated and the polarization state of the output light is modulated. The TE–TM phase-difference modulator is the portion that actually causes



(a)

(b)

Fig. 2. (a) Tilting angle of the electrical poling field at the center point of the rib waveguide versus the horizontal displacement of the tilted-poling electrodes. (b) Contour map of the normalized electric-potential distribution of the poling field around the rib area in the designed TE–TM polarization balancer.

the circular-polarization modulation of the output light, while the TE–TM polarization balancer is a static portion of the overall waveguide device, which is needed to ensure that the powers of the two polarization components are balanced.

The TE–TM polarization balancer, in fact, follows the basic principle of the EO-polymer-based TE–TM polarization converter [12]. Since the optical principal axis of the poled EO polymer depends on the direction of the electrical field in the poling process, polarization conversion can be realized in the tilt-poled polymeric waveguides, and the conversion length can be controlled by applying a biasing voltage. To obtain the largest conversion range, a poling field that has a 45°-tilted angle with respect to horizontal direction is expected. The 45°-tilted electrical field, which is approximately uniform in the waveguide core, can always be obtained [12] by employing the configuration of the electrodes shown by the cross section of section 1 in Fig. 1(b) and setting an appropriate horizontal displacement between the top and bottom electrodes. In our experiments, this pair of the top and bottom electrodes is used as both the poling and biasing electrodes.

We analyzed the relationship of the tilting angle of the electrical field with the horizontal displacement of the electrodes in details. Fig. 2(a) presents the curve of the tilting angles of the electrical field at the center point of the rib waveguide versus the horizontal displacement. In this calculation, it was assumed that the bottom and top claddings of the polymeric waveguide were the 5.5-μm-thick UV15 and 6.5-μm-thick UV11-3 films, respectively; the core was the 2-μm-thick side-chained EO polymer DR1/PMMA [13] film; the width and height of the rib were 5 and 1 μm, respectively; and the width of the electrodes was 50 μm. UV15 and UV11-3 are the epoxy products from Master Bond, Inc. From Fig. 2(a), it can be found that the tilting angle at the center of the rib is 45° if the horizontal displacement is set to be 2.8 μm. The contour map of the normalized electrical potential induced by the 2.8-μm-spaced poling electrodes is shown in Fig. 2(b), in which the waveguide cross-section structure is also illustrated. We can find that the electrical potential is kept at an angle of 45° approximately and is rather uniform around the rib area. This configuration of the electrodes was used for 45°-tilted contact poling in our CPMs.

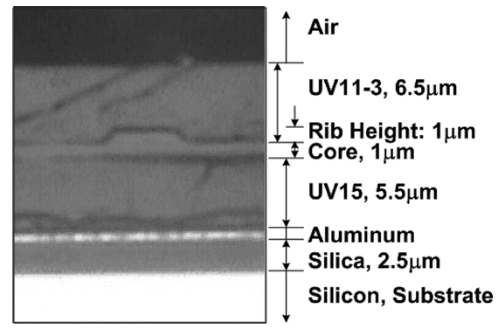


Fig. 3. Cross section of the fabricated polymeric waveguide.

The TE–TM phase-difference modulator is realized via the tensor nature of the poled EO polymer and its EO effect. Using the configuration of the poling electrodes shown by the cross section of section 2 in Fig. 1(b) and applying contact poling, the EO coefficients of the TM and TE modes, r_{33} and r_{31}, have the following approximate relationship [14]:

$$\mathrm{r}_{31} \approx \frac{1}{3}\mathrm{r}_{33} \tag{1}$$

and, with the applied modulating voltage V, the change of the phase difference between the TM and TE modes can be described as

$$\Delta\varphi_{\mathrm{TM-TE}} \approx -\frac{2\pi}{3\lambda} n_e^3 \mathrm{r}_{33} \frac{V}{d} \Gamma L \tag{2}$$

where d is the total thickness of the polymeric films between the top and bottom electrodes, L is the length of the electrodes, n_e is approximately the refractive index of the core, and Γ is the overlap integration between the modulating electrical field and the optical mode. Applying appropriate modulating voltage can generate the required phase difference $\Delta\varphi_{\mathrm{TM-TE}}$ to achieve the expected LHC or RHC state.

III. Fabrication

In our experiment, the device was fabricated on the SiO_2-on-silicon wafer. The SiO_2 layer was employed as an insulation layer. The UV15 epoxy was spin-coated and

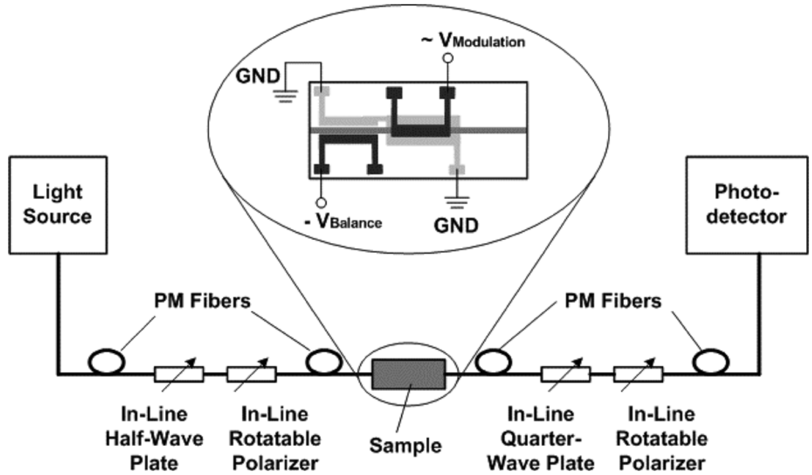


Fig. 4. Schematic diagram of the measuring setup.

UV cured as the bottom cladding layer after the bottom electrodes were patterned and etched. The thickness of the bottom cladding layer was about 5.5 μm, as designed. The DR1/PMMA powder was first dissolved in the solvent Cyclopentanone. Once filtered, the DR1/PMMA solution was coated on the UV15 film and cured at the temperature of 90 °C. The thickness of the DR1/PMMA film was about 2 μm. Oxygen was used as the reactive ion etch (RIE) gas, and the etched rib was 5 μm wide and 1 μm high. Then, a layer of the UV11-3 epoxy with the thickness of about 6.5 μm was covered on the rib waveguide as the top cladding. The top electrodes were formed by depositing and patterning an aluminum layer on the UV11-3 layer. Fig. 3 shows the cross section of the fabricated polymeric waveguide. The length of the electrode in the TE–TM polarization balancer is 1.2 cm, and the width is 50 μm. The horizontal displacement between the bottom and top electrodes is 2.8 μm, which is designed to realize the 45°-tilted poling field. The length of the electrode in the TE–TM phase-difference modulator is 1 cm.

Contact poling was applied to the device after all structure processing work was completed. Since the TE–TM polarization balancer requires tilted poling while the TE–TM phase-difference modulator should be poled in the vertical direction, the poling voltage applied to the TE–TM polarization balancer was 1200 V, slightly larger than that applied to the TE–TM phase-difference modulator, which was 1100 V. The poling temperature was 125°C, and the poling time was 30 min. The processing details of contact poling have been described in [15].

IV. Results and Discussion

The measuring system is shown in Fig. 4. A half-wave plate and a rotatable polarizer were used to control the polarization direction of the input light. The performance of the samples was quantitatively measured by properly setting the quarter-wave plate and the rotatable polarizer, which were set after the tested sample in the system. The Newport AutoAlign System was employed to realize the light coupling between the polarization-maintaining fibers and the sample. The light source was the Multi-Channel Stabilized Laser Source MSLS-1000 from E-Tek, Inc., which was at the wavelength of 1550 nm. The detecting system was the Model 2832-C optical power meter with a photodetector Model 818, both from Newport, Inc., Irvine, CA.

Since the power difference between the TE and TM modes is one of the two key factors that determine the quality of the circular-polarized output light, the TE–TM polarization balancer, which is designed to balance the power levels in the CPM, was fabricated and characterized as the independent polarization converter at first. Fig. 5(a) shows the measured near fields of the TE and TM modes at the states that the maximum TE- and TM-mode outputs are reached when the input is the TM mode. We also quantitatively measured the conversion between the TE and TM modes. Fig. 5(b) illustrates the measured conversion curve when the input light is the TE mode. With the data shown in Fig. 5(b), it can be found that the highest conversion efficiency from the TE mode to the TM mode is about 93.6%. It is also measured that about 95.1% of the input TM mode can be converted to the TE mode. Experiments show that it is very difficult to achieve complete polarization conversion. The main reason is that the poling-caused birefringence in the EO polymeric rib core leads to the mode mismatch between the TE and TM modes and limits the polarization conversion [12]. Adopting EO polymeric materials to form both the top and bottom cladding layers is the solution to eliminating the birefringence.

In the CPM, however, the function of the TE–TM polarization balancer is to balance the power levels of the TE and TM modes instead of realizing complete conversion. It means that the highest conversion efficiency of 50% is sufficient in the ideal case. In order to compensate the influences of polarization-dependent factors, especially the polarization-dependent loss, the highest conversion efficiency is expected to be larger than 50%. Using the measuring setup shown in Fig. 4, we characterized the TE–TM polarization balancer of the monolithically integrated CPM. By controlling the polarization direction of the input light, a conversion efficiency of about 90% was obtained, which was large enough to achieve the polarization power balance.

With the balanced TE and TM modes, the polarization characteristics of the output were measured when the modulating voltage was applied to the TE–TM phase-difference modulator and the inline quarter-wave plate was rotated at different angles.

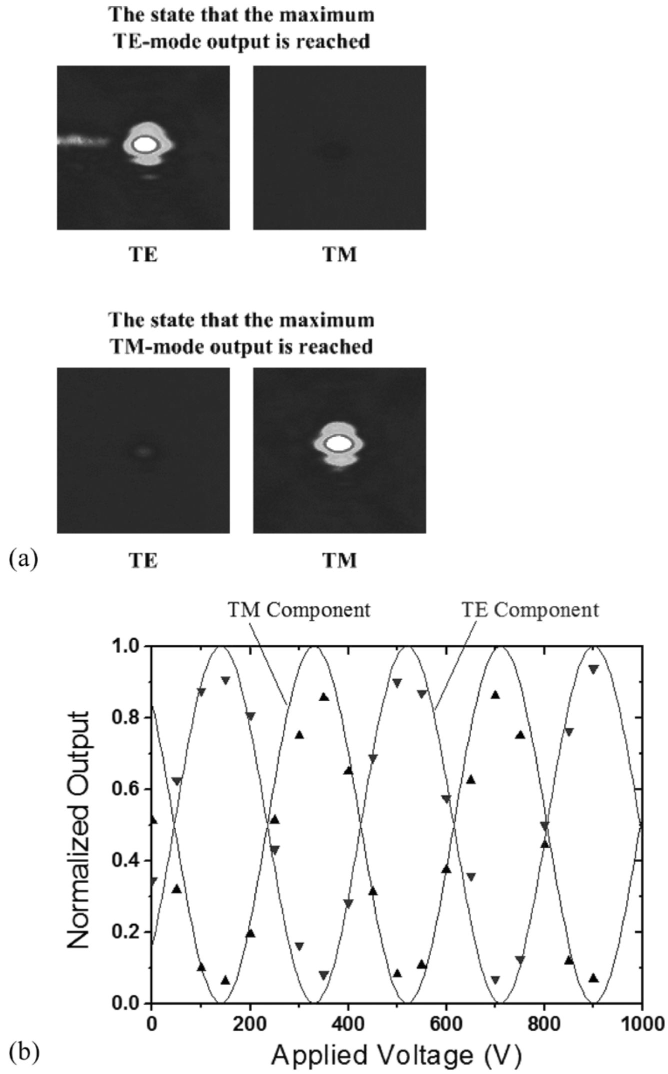


Fig. 5. (a) Near-field output intensity spots of the TE and TM modes at the states that the maximum TE- and TM-mode outputs are reached, respectively, when the input is the TM mode. (b) Measured outputs of the TE and TM modes when the input is the TE mode. ▼: TE mode. ▲: TM mode. ——: Curve of the Sine function.

With the measured data shown in Fig. 6, we can find that the polarization states of the output light at states A, B, C, and D are the 45°-tilted linear, LHC, $-45°$-tilted linear, and RHC polarization, respectively. It means that the circular-polarization state of the output light has been modulated by varying the applied voltage. The measured extinction ratios at the 45°- and $-45°$-tilted linearly polarized states are larger than 25 dB. It indicates that the power levels of the TE and TM modes are well balanced, and the output of the high-quality circular-polarized light is achieved.

The half-wave voltage of the modulating curve shown in Fig. 6 is about 96 V, corresponding to an EO coefficient r_{33} of 11 pm/V. In the TE–TM polarization balancer, the voltage change for a conversion cycle, defined as the conversion-cycle voltage, is about 230 V, which indicates that its EO coefficient arrives at 10.7 pm/V. The conversion-cycle voltage of section 1 and the half-wave voltage of section 2 are rather high in the DR1/PMMA-based CPM. However, these working voltages

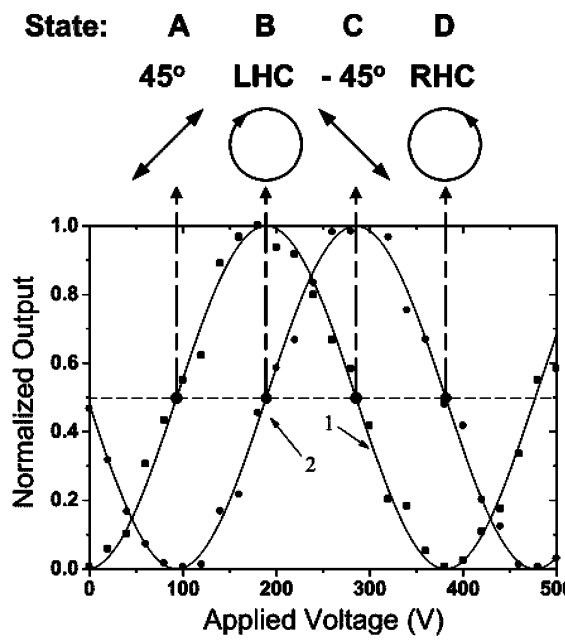


Fig. 6. Measured output of the 45°-tilted-polarization component versus the modulating voltage. ●: Principal axis of the quarter-wave plate is 45° tilted. ■: Principal axis of the quarter-wave plate is vertical. ——: Curve of the Sine function.

can be lowered if chromophores with larger EO coefficients are used, such as CLD1 [16].

V. Conclusion

In this paper, a CPM is designed and fabricated with EO polymeric materials employing contact poling. Tilted poling is employed to activate the conversion between TE and TM modes, and the tensor nature of the poled polymeric materials is applied to generate the phase difference. Detailed analysis and experiments on polarization conversion are presented. With appropriate voltage control, the outputs at the 45°-tilted linear, LHC, $-45°$-tilted linear, and RHC polarization states are achieved. The extinction ratios at the linearly polarized states are larger than 25 dB.

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