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Abstract. An electro-optic polymer waveguide modulator based on both Pockels and Kerr effects has been demonstrated. A conjugated polymer, poly (9,9-dioctyl-2,7-fluorene-co-benzo [c][1,2,5]thiadiazole-co-9-hexyl-3,6-carbazole), which has the delocalization of p-electrons and a push-pull structure along the main conjugated chain, exhibits the Pockels effect and still maintains the Kerr effect after corona-poling. By applying a direct current (DC) bias, the optical output of the modulator is roughly linearly to a modulation voltage, and the modulation depth is improved with the DC bias at fixed modulation voltage. The proposed modulator achieves a 2.18% modulation depth with 5 V p-p modulation triangular voltage and 90 V DC bias at 100 kHz by employing both the Pockels effect and Kerr effect. [DOI: 10.1117/1.OE.52.4.044601]

Subject terms: waveguide modulator; Pockels effect; Kerr effect; direct current bias voltage.

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1 Introduction

Polymer-based electro-optic (EO) modulators have been investigated and demonstrated because of their applications in many optoelectronic fields, such as optical communication system, optical signal processing, and optical measurement.[1,2] EO polymers are well known for their low dielectric constants and excellent velocity match between optical-wave and modulation microwave.[3,4] Waveguide modulators based on EO polymers are of great interest in view of their relatively simple and potentially low-cost fabrication procedures.[5] Perhaps the most unique feature of EO polymer devices is their compatibility with a variety of substrates, such as Si, GaAs, or plastic.[6] Most of EO polymer modulators are based on the Pockels effect instead of the Kerr effect, as the quadratic electro-optic (QEO) coefficient is usually relatively much smaller than the Pockels coefficient.[7] In this paper, we report on an EO polymer waveguide modulator based both on the Pockels effect and the Kerr effect. By applying a direct current (DC) bias, the optical output of the device is roughly linearly to a modulation voltage, even though both the Pockels effect and Kerr effect are employed. A special feature of the proposed device is that the modulation depth is improved through increasing the DC bias without changing the modulation voltage. By utilizing the prism-waveguide configuration, the fabrication of the proposed modulator is very simple, in which only the spin coating technique and the vacuum sputtering technique are needed.

2 Theory

The schematic diagram of the waveguide electro-optic polymer modulator is shown in Fig. 1, which employs a prism-waveguide configuration, consisting of:

- a ZF-7 prism with refractive index n_1
- a thin gold film with relative dielectric constant ε_2 and thickness d_2 as the coupling layer and one electrode
- an electro-optic polymer film serving as the guiding layer
- a buffer layer, and
- another gold film electrode.

When a laser beam (TM-polarized) is incident upon the base surface of the prism with resonance angle θ where the resonance condition is satisfied, the energy of the incident light is coupled into the waveguide and the intensity of reflected light decreases, forming a resonance dip on the reflective spectrum. An applied electric field E across the guiding layer along the z-direction modulates the refractive index of the electro-optic polymer film, changing the propagation constant of the guided mode, shifting the resonance dip along the angular direction, and thus resulting in modulation of the reflected light. The refractive-index change of the electro-optic polymer film is related to the electric field E by:

$$\Delta n_{33} = -\frac{1}{2} n_3^3 (\gamma_{33} E + s_{33} E^2), \tag{1}$$

where n_3 is the refractive index of the electro-optic polymer without the applied electric field, γ_{33} is the component of the Pockels coefficient and s_{33} is the component of the QEO coefficient, and Δn_{33} is the change in refractive index of the electro-optic polymer with electric field. At the midst of the fall-off of the resonance dip, where good linearity is observed, the alternation of reflected light intensity ΔI is given by Ref. 8:

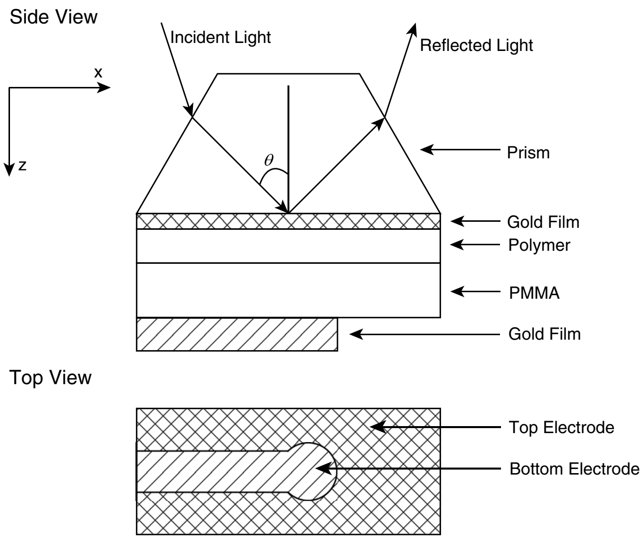

Fig. 1 The schematic diagram of the waveguide EO polymer modulator.

$$\Delta I = k \cdot \frac{1}{n_1 \cos\theta} \cdot \Delta n_{33}, \tag{2}$$

where $k = \Delta I/\Delta\theta$ is the slope of the linear area of the fall-off at the midst of the resonance dip. Substituting Eq. (1) into Eq. (2), the relation between the alternation of reflected light intensity ΔI and applied electric field E is obtained:

$$\Delta I = -k \cdot \frac{1}{2n_1 \cos\theta} n_3^3(\gamma_{33}E + s_{33}E^2). \tag{3}$$

The applied electric filed across the guiding layer is:

$$E = E_{\mathrm{DC}} + E_S \sin\omega t, \tag{4}$$

where E_{DC} is the DC bias; $E_s \sin\omega t$ is the modulation electric field, E_S is the amplitude of the modulation field. Substituting Eq. (4) into Eq. (3) yields:

$$\Delta I = -k \cdot \frac{n_3^3}{2n_1 \cos\theta} \cdot [(\gamma_{33}E_{\mathrm{DC}} + s_{33}E_{\mathrm{DC}}^2) + (\gamma_{33} + 2s_{33}E_{\mathrm{DC}})E_S \sin\omega t + s_{33}E_S^2 \sin^2\omega t]. \tag{5}$$

It is can be seen from items in brackets in the right-hand side of Eq. (5) that:

1. When the DC bias E_{DC} is fixed, the first item $(\gamma_{33}E_{\mathrm{DC}} + s_{33}E_{\mathrm{DC}}^2)$ is a constant, having no influence on the modulation of the reflected light ΔI.
2. The last item $s_{33}E_S^2 \sin^2\omega t$ is a quadratic term of the modulated electric field, which can be omitted if $\left|\frac{\gamma_{33}}{s_{33}} + 2E_{\mathrm{DC}}\right| \gg E_S$.
3. The middle item $(\gamma_{33} + 2s_{33}E_{\mathrm{DC}})E_S \sin\omega t$ is linearly proportional to the modulation electric field, and the proportional coefficient $(\gamma_{33} + 2s_{33}E_{\mathrm{DC}})$ is determined both by the Pockels coefficient and the QEO coefficient.

Thus the modulated reflected intensity is rewritten as:

$$\Delta I_m = -k \cdot \frac{n_3^3}{2n_1 \cos\theta} \cdot (\gamma_{33} + 2s_{33}E_{\mathrm{DC}})E_S \sin\omega t. \tag{6}$$

Therefore, the modulated reflected intensity ΔI_m, the optical output of sample, is proportional to the modulation electric field under the conditions of fixed DC bias E_{DC} and

$$\left|\frac{\gamma_{33}}{s_{33}} + 2E_{\mathrm{DC}}\right| \gg E_S,$$

and ΔI_m is increased with the DC bias.

3 Experiment

A conjugated polymer, poly (9,9-dioctyl-2,7-fluorene-co-benzo[c][1,2,5] thiadiazole-co-9-hexyl-3,6-carbazole) (PF8-BT-CZ), was employed in the experiment. The delocalization of p-electrons along the PF8-BT-CZ's main conjugated chain contributes a large susceptibility, which is the origin of the QEO effect. After corona-poling, the push-pull structure in the main conjugated chain was oriented and formed a more ordered structure along the poling electric field, yielding a noncentrosymmetric arrangement, which is required to obtain the linear electro-optic (LEO) effect. Therefore, the poled PF8-BT-CZ layer exhibits both linear electro-optic effects and QEO effects.

The sample was prepared on a triangular prism. A 40-nm-thick gold film was sputtered on the ZF-7 prism (the refractive index $n_1 = 1.783$ at 832 nm). The dielectric constant of the gold film was $\varepsilon_2 = -20 + 1.5i$ at 832 nm, which was determined by the double wavelength method.[9] The polymer PF8-BT-CZ was dissolved in methylbenzene, and then was spin-coated onto the gold film to serve as guiding layer. The thickness of the polymer film was $d_3 = 1.02\ \mu$m and the refractive index was $n_3 = 1.590$ at 832 nm, which were measured by the traditional m-line method. Corona poling is used to obtain the molecular orientation for removing the centrosymmetric structure of PF8-BT-CZ.[10] For yielding large areas of high-quality poled films, the larger poling field is 4.1 kV which close to the dielectric breakdown of nonlinear polymer. The PF8-BT-CZ film was heated to the glass–rubber transition temperature (Tg) 105°C, corona-poled in the air for 25 min with an interelectrode distance of 20 mm and cooled down to room temperature with the electric field still applied. A buffer layer with thickness $d_4 = 3.27\ \mu$m and an refractive index $n_4 = 1.483$ was fabricated by spin-coating the poly(methyl methacrylate) (PMMA) layer onto the EO polymer film. Finally, another 300-nm-thick gold film was deposited on the PMMA buffer layer by the sputtering technique to serve as the other electrode.

The experimental setup is shown in Fig. 2. A collimated p-polarized beam of a 832 nm laser was incident on the sample and the intensity of reflected light was measured by a PIN photo detector. The angular scan was performed by a $\theta/2\theta$ computer-controlled goniometer. The computer-collected experimental attenuated total reflection (ATR) spectrum is shown in Fig. 3. The working angle is chosen at the midst of the fall-off of the resonance dip of TM_1 mode. A triangular electric field was applied across the two gold electrodes of the sample. The oscilloscope traces of the

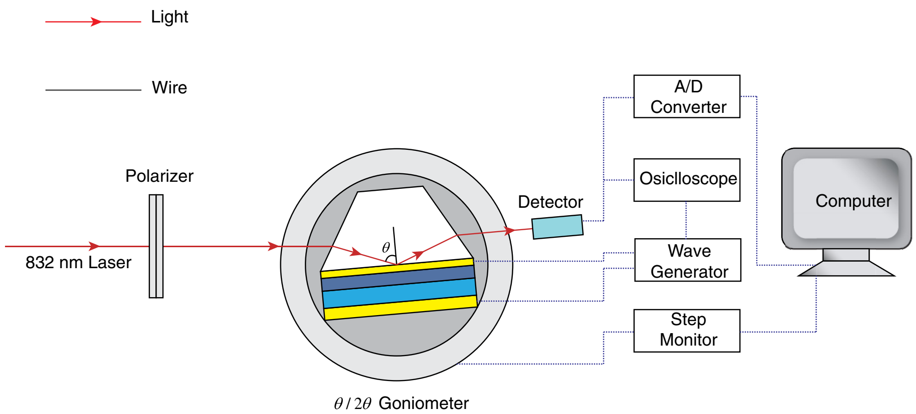

Fig. 2 the experimental setup.

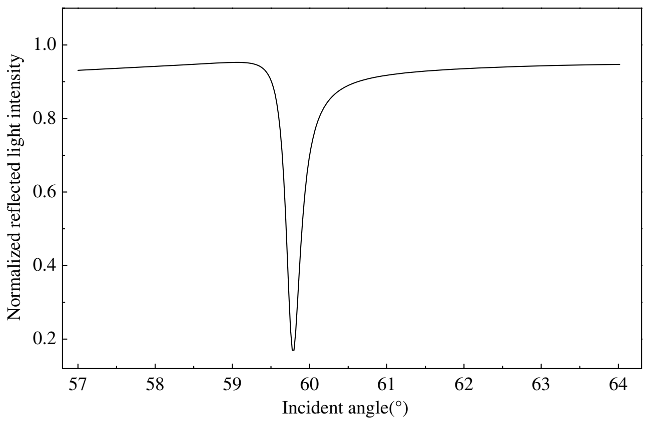

Fig. 3 The experimental ATR spectrum of TM1 mode.

applied electric field and the alteration of reflected light intensity versus time are shown in Fig. 4. With the linear increase or decrease of the applied field, the alteration of reflected light intensity exhibited an unsymmetrical parabolic curve which was displayed as a function not only of E but also of E^2, resulting from the combined action of LEO and QEO effects. Measured by the method (e.g., see Ref. 11), the Pockels coefficient component of PF8-BT-CZ film is $\gamma_{33} = 4.05 \times 10^{-14}$ m/V and QEO coefficient component is $S_{33} = 6.89 \times 10^{-21}$ m^2/V^2.

In order to achieve a linear modulation, a DC bias E_{DC} is also applied across the EO polymer film. The peak-to-peak value of modulation voltage of triangular electric field is 4.97 V with frequency of 100 kHz. The DC bias voltage was increased gradually to avoid damaging the polymer by a step of 10 V. The alteration of reflected light is linearly

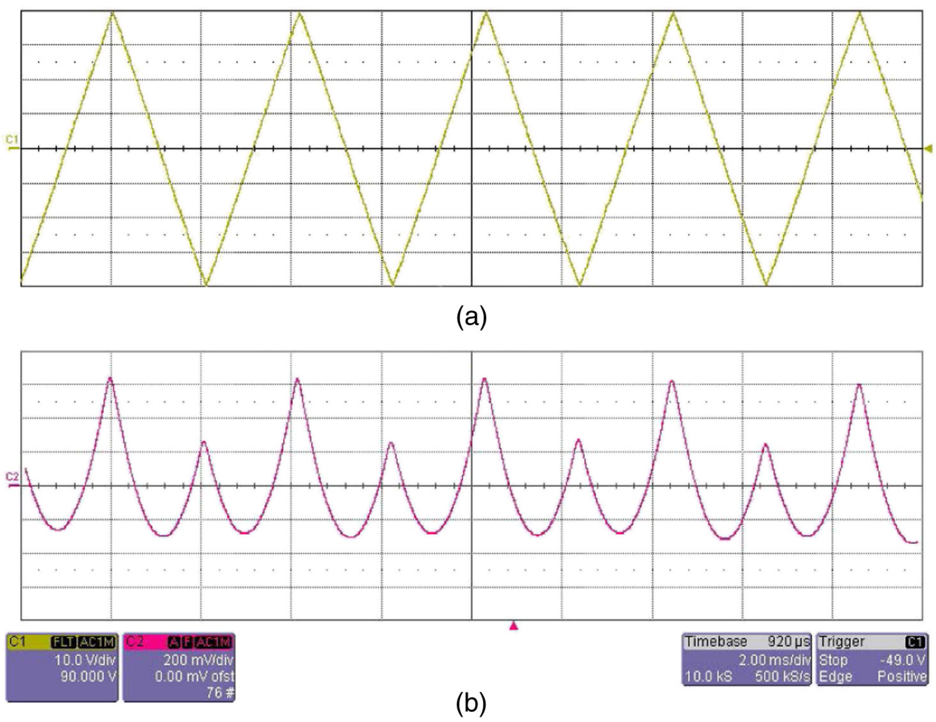

Fig. 4 Oscilloscope traces of applied voltage versus time (a) and the reflected intensity versus time (b) with the operation angle selected at TM1 resonance dip at 832 nm. The applied voltage was attenuated to be 10% of its original value before input in the oscilloscope.

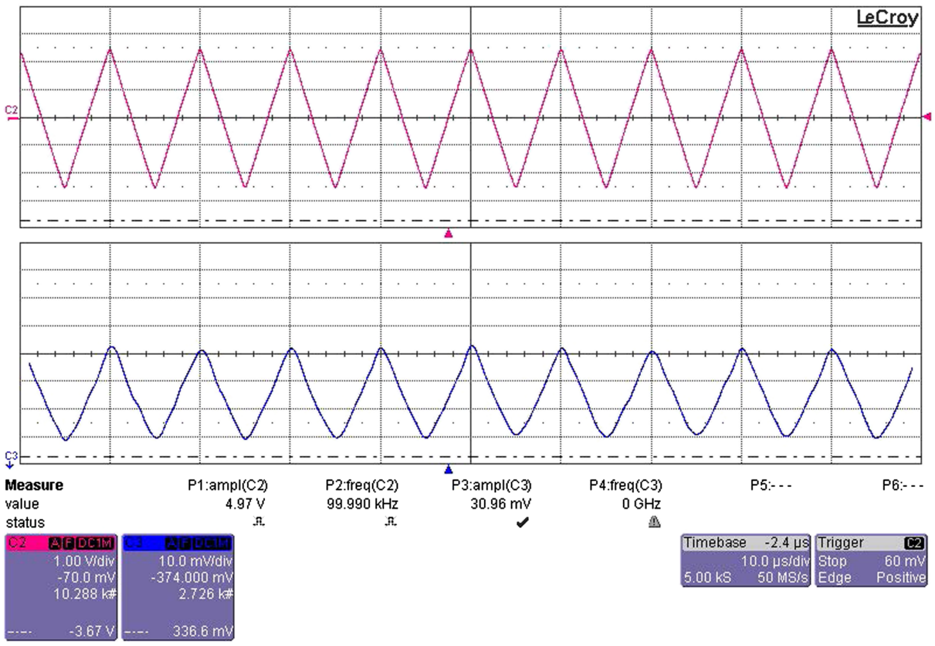

Fig. 5 The oscilloscope traces of the alteration of the reflected light with 90 V DC bias at fixed modulation voltage.

proportional to the applied modulation voltage with applying a DC bias of 90 V, and then increased with the DC bias voltage under the fixed modulation voltage as showed in Figs. 5 and 6. From Eq. (1), the refractive index change induced by modulation voltage is 4.72×10^{-8} in both Figs. 5 and 6, and that induced by DC bias are 3.37×10^{-7} and 3.74×10^{-7} in Figs. 5 and 6, respectively. The modulation depth is improved from 2.18% with a 90 V DC bias to 3.20% with a 100 V DC bias with fixed modulation triangular voltage 4.97 V p–p. It is the DC bias which causes the alteration of reflected light intensity, and then improves the modulation depth. Table 1 gives the modulation depth and the refractive index change induced by difference DC bias with 9.9 modulation voltage at 100 kHz. The refractive index change induced by modulation voltage is 9.39×10^{-8}. It can be seen that the modulation depth of the sample is improved with the DC bias at fixed modulation voltage because the increase of DC bias change the refractive index of waveguide layer and shift the resonance dip along the angular direction.

The Pockels coefficient and QEO coefficient of the polymer used in this paper are relatively small, which leads to a low modulation depth. However the PF8-BT-CZ polymer system can be further optimized and will have even higher molecular polarizability, the better experimental results in this work, such as lower modulation voltage and DC bias,

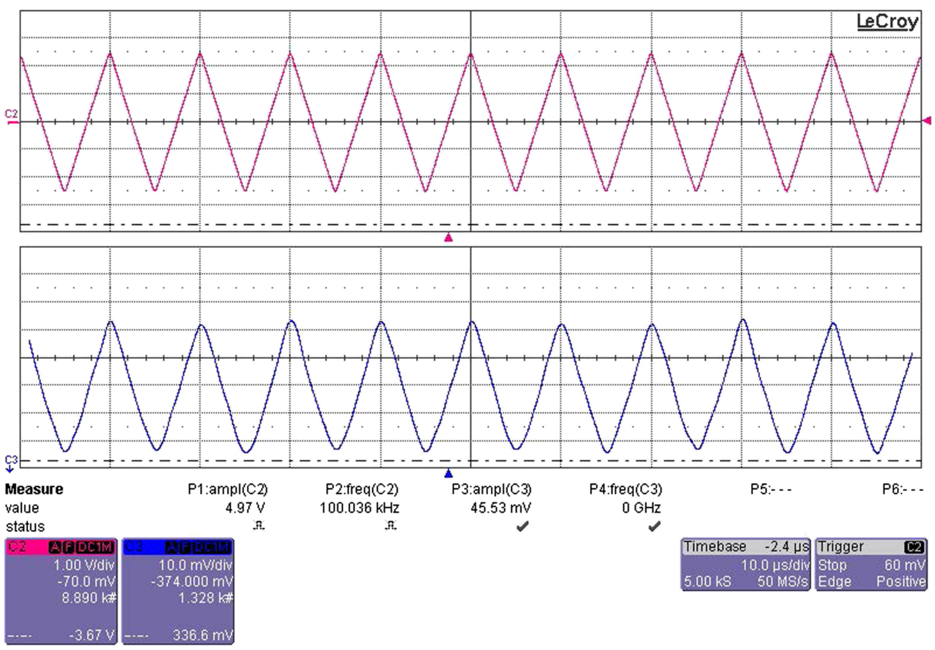

Fig. 6 The oscilloscope traces of the alteration of the reflected light with 100 V DC bias at fixed modulation voltage.

Table 1 Modulation depth and the refractive index change induced by difference DC bias with 9.9 V modulation voltage.

Frequency (kHz)	Modulation voltage (V)	DC bias (V)	Modulation depth (%)	The refractive index change induced by DC bias (10^{-7})
100.0	9.9	90.0	4.37	6.70
		100.0	7.54	7.45
		110.0	15.86	8.19
		130.0	16.54	9.68

higher modulation depth, are expected in the future. The modulation working angle is chosen at the resonance dip of TM_1 mode, so the modulator is TM polarization dependence. Although the modulator was performed at wavelength of 832 nm as an example, the basic principle can be applied to the polymer with both linear and QEO effects at wavelengths from long-wavelength tail of the absorption band to the nonabsorption band. It is especially valuable at the case that the modulation voltage is relatively small.

4 Conclusion

In conclusion, 2.18% modulation depth with 4.97 V p–p modulation triangular voltage and 90 V DC bias at 100 kHz were achieved in a waveguide modulator based on EO polymer with both Pockels and Kerr effects at a wavelength of 832 nm. The special feature of the proposed device is that the EO modulation depth is improved with the DC bias at fixed modulation voltage and it is particularly useful when the modulation voltage is small. The experimental results in this work can be improved by optimizing the polymer system, and the modulator working wavelength can be expand from long-wavelength tail of the absorption band to the nonabsorption band of the EO polymer.

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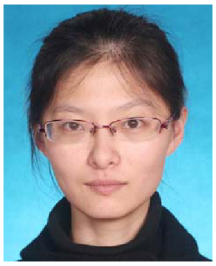

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