Electro-optic polymer waveguide modulator based on the Pockels and Kerr effects

Haibin Yu
Lei Chen
Kangye Li
Xiaoxu Deng
Electro-optic polymer waveguide modulator based on the Pockels and Kerr effects

Haibin Yu
Shanghai Jiao Tong University
Department of Physics
State Key Laboratory of Advanced Optical Communication Systems and Networks
Shanghai 200240, China

Lei Chen
Shanghai Aircraft Manufacturing Co., Ltd.
Shanghai 200436, China

Kangye Li
Xiaoxu Deng
Shanghai Jiao Tong University
Department of Physics
State Key Laboratory of Advanced Optical Communication Systems and Networks
Shanghai 200240, China
E-mail: mrxxdeng@yahoo.com.cn

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 systems, 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 processes.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 thin gold film with relative dielectric constant ε2 and thickness d2 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:

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

where \( n_3 \) is the refractive index of the electro-optic polymer without the applied electric field, \( \gamma_{33} \) is the component of the Pockels coefficient and \( s_{33} \) is the component of the QEO coefficient, and \( \Delta n_{33} \) 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 \( \Delta I \) is given by Ref. 8:

Abstract. An electro-optic polymer waveguide modulator based on both Pockels and Kerr effects has been demonstrated. A conjugated polymer, poly (9,9-diocetyl-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. © The Authors. Published by SPIE under a Creative Commons Attribution 3.0 Unported License. Distribution or reproduction of this work in whole or in part requires full attribution of the original publication, including its DOI. [DOI: 10.1117/1.OE.52.4.044601]
Thus the modulated reflected intensity is rewritten as:

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

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

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

and $\Delta I_m$ 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
do-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 refrac-
tive 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. 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 $d_1 = 1.02 \mu m$ and the
refractive index was $n_3 = 1.590$ at 832 nm, which were mea-
sured by the traditional m-line method. Corona poling is
used to obtain the molecular orientation for removing the
centrosymmetric structure of PF8-BT-CZ. 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. 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 elect-
ric field still applied. A buffer layer with thickness
$d_4 = 3.27 \mu m$ and an refractive index $n_4 = 1.483$ was fabri-
cated 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 sam-
ple and the intensity of reflected light was measured by a PIN
photo detector. The angular scan was performed by a $\theta/20$
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

---

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

1. When the DC bias $E_{DC}$ is fixed, the first item $(\gamma_{33}E_{DC} + s_{33}E_{DC}^2)$ is a constant, having no influence on the modulation of the reflected light $\Delta I$.
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 $|\frac{\gamma_{33}}{s_{33}} + 2E_{DC}| \gg E_S$.
3. The middle item $(\gamma_{33} + 2s_{33}E_{DC})E_S \sin \omega t$ is linearly proportional to the modulation electric field, and the proportional coefficient $(\gamma_{33} + 2s_{33}E_{DC})$ is determined both by the Pockels coefficient and the QEO coefficient.
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 \( \gamma_{33} = 4.05 \times 10^{-14} \text{ m/V} \) and QEO coefficient component is \( S_{33} = 6.89 \times 10^{-21} \text{ m}^2/\text{V}^2 \).

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
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 $4.72 \times 10^{-8}$ in both Figs. 5 and 6, and that induced by DC bias are $3.37 \times 10^{-7}$ and $3.74 \times 10^{-7}$ 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 $9.39 \times 10^{-7}$. 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,
higher modulation depth, are expected in the future. The modulation working angle is chosen at the resonance dip of TM1 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.

Acknowledgments

This work is supported by the National Natural Science Foundation of China under Grant Nos. 60978056, 61178050, Fund of National Engineering and Research Center for Commercial Aircraft Manufacturing (The project No. is SAMC12-JS-15-019), and Research Fund for the Doctoral Program of Higher Education of China.

References


Lei Chen received the BS degree from the Nanjing University of Aeronautics and Astronautics, Nanjing, China, in 1992. He is currently the deputy chief engineer of Shanghai Aircraft Manufacturing Co., Ltd.

Kangye Li is currently pursuing the BS degree in the Department of Physics, Shanghai Jiao Tong University, Shanghai, China.

Xiaoxu Deng received her PhD in physics from Harbin Institute of Technology in 1999. After graduation, she worked as a post-doctoral researcher in Shanghai Jiao Tong University from 2002 to 2004. She is currently a professor in the Physics Department of Shanghai Jiao Tong University.