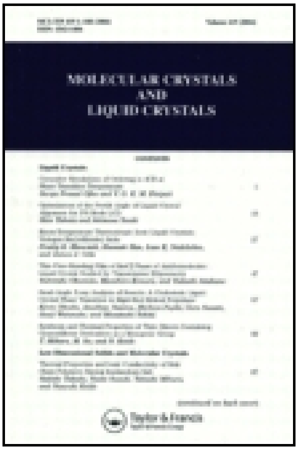


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# Mach-Zehnder Interferometry Measurement of the Elctro-Optic Effect in a Poled Polymer Film

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# Mach-Zehnder Interferometry Measurement of the Elctro-Optic Effect in a Poled Polymer Film

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**Abstract** Two different configurations, reflection and transmission, of Mach-Zehnder interferometer(MZI) are introduced for the measurement of the electro-optic coefficients in a poled polymer thin film. The MZI measurement of the electro-optic coefficients has an advantage of permitting the determination of the electro-optic tensor coefficients, $r_{13}$ and $r_{33}$, independently, when compared with the single-beam polarization interferometer. In the reflection configuration of two beam interferometric measurement, a proper consideration of the optical path change, due to the reflection angle change, is found to be critical in determining the absolute value of the electro-optic coefficients, while the transmission configuration allows the independent determination of the electro-optic coefficients in the direction of the ordinary and the extraordinary optic axes.

Keywords: Mach-Zehnder Interferometry, Electro-Optic Coefficient, Refractive Index

## 1. Introduction

Optical characterization of an electro-optic (EO) polymer can be performed through a Mach-Zehnder interferometry, which is a two-beam interferometry where the amplitude of the incident light is split into two and each beam experiences a different optical path, and recombines at the beam splitter to give a sinusoidal interference pattern.[1-2]

Mach-Zehnder interferometer (MZI) can be configured in two different ways, depending on how the thin film sample is prepared, as is well-known in that the electrode poling of EO polymer can be achieved in two different electrode structures, namely, parallel-plate (PP) and coplanar (CP) electrode geometries.[3-6] In the case of the PP electrode geometry the thin film serves as a reflection mirror in the sample arm of the MZI, while the laser beam at the sample arm passes through the film for the CP electrode geometry.[7]

In this paper MZI is applied to the EO polymer thin film to determine the EO coefficient, in both reflection and transmission configurations. As a complete optical characterization of the EO polymer film, the modulated light intensity of MZI is investigated as a function of the optical bias in the reference arm, the modulation voltage applied to the film, the polarization angle of the incident light. It is stressed that the incidence angle dependence measurement of the EO effect is important in a reflection configuration to take care of the refractive angle change in a proper way. Particularly, it is pointed out that the polarization angle dependence measurement of the EO effect is the most effective means to obtain the tensor ratio $r_{33}/r_{13}$, as well as the absolute value of $r_{13}$. Furthermore, the incidence angle dependence measurement allows a double check of the determination of the absolute value of $r_{13}$ in the reflection MZI. The polarization angle dependence measurement of the EO modulated signal in the transmission MZI uniquely determines the tensor ratio as well.

## 2. Analysis

The light intensity $I$ of the interference pattern from the MZI is of a sinusoidal form,

$$I = \frac{1}{2}\{E_{01}^2 + E_{02}^2 + 2|E_{01}||E_{02}|\cos(\phi_2 - \phi_1)\} \ , \tag{1}$$

where $E_{01}$ and $E_{02}$, and $\phi_1$ and $\phi_2$, are the field amplitudes and the phases of the light in each arm of the MZI. When the optical phase of the sample arm is modulated at a frequency $\Omega$ with the amplitude $A$, the light intensity from the MZI can be expanded in terms of $A$, resulting in

$$I = \frac{1}{2}\{E_{01}^2+E_{02}^2+2|E_{01}||E_{02}|\cos\phi\}-|E_{01}||E_{02}|A\sin\phi\cos\Omega t = I_0+I_\Omega \ . \tag{2}$$

We find that $I_0$ and $I_\Omega$ are related by the relative phase difference $\phi$ which is nothing but the optical bias in the reference arm. Noting that $I_0$ varies between $I_{\max}$ and $I_{\min}$ when the optical bias in the reference arm is changed, the modulated intensity $I_\Omega$ is expressed as

$$\begin{aligned} I_\Omega &= -|E_{01}||E_{02}|A\sin\phi\cos\Omega t \\ &= -\frac{1}{2}A\{I_{\max} - I_{\min}\}\sin\phi\cos\Omega t \\ &\equiv I_{sig}\sin\phi\cos\Omega t \ . \end{aligned} \tag{3}$$

The phase modulation amplitude $A$ is related to the EO coefficients $r_{13}$ and $r_{33}$ in different ways for the transmission and the reflection configurations. For a CP electrode sample, the light is normally incident on the film with a varying polarization angle. The relevant lengths are the film thickness and the separation between the electrodes. The incidence angle, on the other hand, can be varied for a PP electrode sample, as well as the polarization angle.

While the optical phase change is readily obtained for the transmission MZI, it's quite involved for the reflection MZI. We look at the reflection MZI more closely. Let the polarization angle of the linearly polarized light be $\varphi$ relative to the incidence plane, with $p$- and $s$- polarization corresponding to $\varphi = 0$ and $\varphi = \pi/2$, respectively. An additional optical phase $\psi$ is introduced in the beam in the sample arm after it reflects off the polymer film and this additional phase is given by

$$\psi = kns = kn\frac{2l}{\cos\alpha} , \tag{4}$$

where $l$ is the film thickness. Taking into account the optical phase change caused by both the refractive index change and the internal refractive angle, we find that the change in the optical phase $\psi$ is given by

$$\Delta\psi = k(s\Delta n + n\Delta s) . \tag{5}$$

Noting that the change in the geometrical path, $s = 2l/\cos\alpha$, is related to the change in the refractive angle, which in turn is related to the change in the refractive index through Snell's law, we obtain

$$\Delta s = \frac{2l}{\cos\alpha}\{(n-1)\tan^2\alpha\}\frac{\Delta n}{n} . \tag{6}$$

Hence, the change in the optical phase, $\Delta\psi$, is given as

$$\Delta\psi = \frac{2kl}{\cos\alpha}\{1 + (n-1)\tan^2\alpha\}\Delta n . \tag{7}$$

Taking these into consideration, we finally obtain the relationship between the phase modulation amplitude $A$ and the EO coefficients for both the transmission and reflection MZI.

$$A_{\text{Transmission}} = \frac{\pi n_\varphi^3 V_m l}{\lambda d}[r_{33}\cos^2\varphi + r_{13}\sin^2\varphi] , \tag{8}$$

$$\begin{aligned} A_{\text{Reflection}} &= \frac{\pi n^3 V_m}{\lambda}\frac{n}{(n^2-\sin^2\theta)^{1/2}}\{1+(n-1)\frac{\sin^2\theta}{n^2-\sin^2\theta}\} \\ &\times [r_{13}\{\frac{n^2-\sin^2\theta}{n^2}\cos^2\varphi + \sin^2\varphi\} + r_{33}\frac{\sin^2\theta}{n^2}\cos^2\varphi] , \end{aligned} \tag{9}$$

where $l$ the thickness of the film, $d$ the separation between two CP electrodes, $\theta$ the incidence angle, $\varphi$ the polarization angle, and $V_m$ is the ac modulation voltage.

In the experimental measurements, a lock-in technique is employed to measure the modulated intensity, $I_{sig} \sin \phi$ at a frequency $\Omega$, while the optical bias $\phi$ is scanned by rotating a glass plate at the reference arm. Hence, we find that the ratio of ac modulated intensity $I_{sig}$ to dc interference intensity is directly related to the modulated amplitude $A$ allowing the determination of $r_{13}$ and $r_{33}$. In the reflection MZI experiments, the intensity ratio is measured as a function of the incident angle $\theta$ for a fixed polarization angle $\varphi$, or as a function of the polarization angle $\varphi$ at a fixed incident angle $\theta$. In the transmission MZI, on the other hand, the incidence angle is fixed at the normal incidence, and only the polarization angle $\varphi$ is varied. In both cases the least-squares fitting of the measured intensity ratio provides an independent determination of the tensor ratio and the absolute value of $r_{13}$.

## 3. Experimental

A guest/host mixture of 4-(dicyanomethylene)-2-methyl-6-(p-dimethylamino-styryl-4H)-pyran /PIQ-2200 in a 6% weight concentration solution is prepared. A thin film of polymer, approximately 3$\mu$m, is spin-coated onto an ITO glass (reflection) or onto an optical substrate with a 10$\mu$m gap CP electrode (transmission) and cured at an elevated temperature.[8] The film is electrically poled at a field strength of 72V/$\mu$m at 220°C. A He-Ne laser was used as the light source and the photodiode was used for detection, and a linear polarizer and a half-wave plate combination controls the polarization angle of incident light. The lock-in technique is used to measure the ac modulated intensity. (See Figure 1.) A typical interference pattern contained 3 or 4 fringes, and a 500$\mu$m pinhole is placed in front of the detector to select a single fringe. Neutral density filters in the sample and the reference arms control the light intensity at each arm in order to achieve good contrast in the interference pattern.

In the transmission configuration, the polarization angle of the incident light, $\varphi$, is varied. This corresponds to the determination of EO coefficients in Eq.(8). We independently determine the EO coefficients of the poled polymer film by plotting the intensity ratio as a function of the modulation voltage for $p$- and $s$-polarized light for the reflection configuration. From the polarization angle dependence measurement of the modulated amplitudes (See Eq.(9)), the tensor ratio $r_{33}/r_{13}$ is determined to be 2.2, less than the value 3.0 predicted, by the thermodynamic model.[9-10] Also the absolute value of $r_{13}$ is determined from the least-squares fitting of the data points to the most general expression relating the EO coefficients with the modulated amplitudes, the incidence angle, and the polarization angle. As shown in Table 1, the results of the intensity ratio as a function of the polarization angle and the incidence angle provide the absolute values of $r_{13}$ in agreement within the experimental errors, confirming a proper consideration of the optical path change due to the refractive angle change.

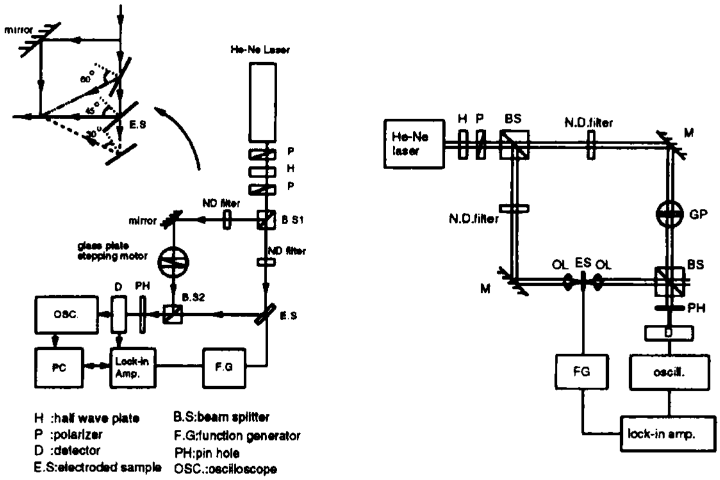


FIGURE 1. The experimental setup is shown. Left: reflection MZI, Right: transmission MZI

In summary a Mach-Zehnder interferometer is adopted to measure the EO coefficients in a poled EO polymer film. Both the CP and PP electrode structure employed in preparing and characterizing the polymer film enables the independent measurement of EO tensor components, which is highly relevant to the integrated optic waveguide structure.

| Incident Angle | Slope Ratio $p/s$ | $r_{13}$ $(m/V)$ | $r_{33}$ $(m/V)$ | $r_{33}/r_{13}$ |
|---|---|---|---|---|
| 30° | 1.1 | $1.0 \times 10^{-13}$ | $2.2 \times 10^{-13}$ | 2.1 |
| 45° | 1.3 | $8.4 \times 10^{-14}$ | $2.1 \times 10^{-13}$ | 2.5 |
| 60° | 1.4 | $7.1 \times 10^{-14}$ | $1.8 \times 10^{-13}$ | 2.6 |

TABLE 1. Results of reflection Mach-Zehnder interferometry measurement of EO coefficients

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