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Polarization Properties of Signals in $Bi_{12}SiO_{20}$ Electrooptic Devices

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The accurate polarization state of the light inside BSO crystal was calculated with consideration of optical activity. By solving Maxwell's equations, the general form of the polarization matrix for any direction of the electric field was obtained. Examples of output polarization states in BSO crystals were also calculated, and their properties were discussed.

I. INTRODUCTION

Single crystal bismuth silicon oxide ($Bi_{12}SiO_{20}$: BSO) has received much attention for real time optical signal processing and optical computing applications due to its unique combination of a high photoconductivity with a large electrooptic effect[1-6]. In BSO electrooptic devices, the large natural optical activity in BSO crystal makes the polarization property of signals complicated. If the optical activity is not considered, the polarization states for light propagation in basic BSO electrooptic devices can be simply calculated[7,8]. When we consider optical activity, the calculation of the polarization properties in BSO crystals is not quite as simple, because the birefringence change is a function of the intrinsic optical activity of the crystal as well as the extrinsic electrooptic effect.

The polarization properties of the light in BSO or other optically active crystals for the principal crystallographic orientations were calculated using coupled wave equations[9]. But, in transverse BSO electrooptic devices in which the direction of the electric field inside the crystal is not fixed in one direction, we need a more complex polarization transformation matrix to describe the polarization state for any direction of the electric field.

In this paper, general polarization properties for simple transverse electrooptic BSO devices with the electric field applied in an arbitrary direction are described on the basis of the solution of Maxwell's equations. From this calculation, the polarization properties of these devices with and without consideration of optical activity are compared.

2. Electrooptic Effect in BSO with Optical Activity

In electrooptic crystals, the polarization properties of light can be changed by an electric field induced refractive index change. In general, a BSO crystal is considered to be a linear electrooptic material, in which the refractive index change is linearly proportional to the applied electric field.

Let's consider the crystal geometry of BSO as shown in Fig. 1. Since the crystl structure of BSO is zincblende, it is possible to obtain the theoretical maximum phase retardation in this crystal geometry if optical activity is not considered[8]. Here, we define the x-direction as the $[\bar{1}10]$ crystal axis direction, the y-direction as the [001] direction, and the z-direction as the [110] direction. In the discussion that follows, we assume that the light propagation direction is exactly oriented along the z-axis in order to derive the basic polarization properties of this configuration.

With the crystal orientation for a transverse BSO electrooptic device, there are two possible electric field components inside the crystal. One component is E_x, which is perpendicular to the [001] crystallographic direction. Another one is Ey, which is parallel to the [001] direction.

Since the refractive index changes and the corresponding eigenstates of polarization are a function of optical activity as well as of the electrooptic effect, it is difficult to find a general form of polarization transformation matrix. Here, we solve Maxwell's equations directly to find the polarization state of the light[10,11].

In this calculation, it is better to use the dielectric constant to express the refractive index, because it is customary to express Maxwell's equations in terms of the dielectric constant rather than the refractive index. The dielectric constant at optical frequencies can be expressed as,

$$\varepsilon=\varepsilon_0 n^2, \tag{1}$$

in which ε_0 is the permittivity of free space and n is the refractive index.

The the dielectric tensor of an optically active crystal can be expressed as a 2 × 2 matrix corresponding to the x and y directions when the light propagates along the z direction. In the matrix, the optical activity is expressed by an off-diagonal imaginary term:

$$\varepsilon=\begin{pmatrix} \varepsilon & i\gamma \\ -i\gamma & \varepsilon \end{pmatrix}, \tag{2}$$

in which γ is a constant proportional to the optical rotatory power ρ. The constant γ can be expressed as,

$$\gamma=2\left(\frac{\varepsilon}{\omega^2\mu}\right)^{1/2}\rho, \tag{3}$$

in which ω is the angular frequency of light and μ is the permeability of air.

When an electric field is applied to the crystal, this dielectric tensor is modified according to the electrooptic properties of the crystal. With the crystal geometry as shown in Fig. 1, the dielectric constant matrix is modified as shown in Eq. (4) below, which contains the electric field components E_x and E_y:

$$\bar{\varepsilon}=\begin{pmatrix} \varepsilon+a & \gamma i+b \\ -i\gamma+b & \varepsilon \end{pmatrix}, \tag{4}$$

with $a = \varepsilon n^2 r_{41} E_y$, and $b = \varepsilon n^2 r_{41} E_x$, in which r_{41} is the linear electrooptic coefficient of BSO.

Here, we assume that a plane wave propagates inside the crystal along the z direction. From Maxwell's equations, we can obtain the eigenvalues of the propagation constant as:

$$k_\pm=\frac{1}{2}\omega^2\mu[2\varepsilon+a\pm(a^2+4b^2+4\gamma^2)^{1/2}]. \tag{5}$$

We can also obtain two polarization eigenstates inside the crystal, which are expressed as:

$$\begin{pmatrix} P_{x1} \\ P_{y1} \end{pmatrix}=\begin{pmatrix} 1 \\ -i\alpha \end{pmatrix}\exp[i(\omega t-k_+ z)], \tag{6}$$

and

$$\begin{pmatrix} P_{x2} \\ P_{y2} \end{pmatrix}=\begin{pmatrix} 1 \\ i\beta \end{pmatrix}\exp[i(\omega t-k_- z)]. \tag{7}$$

The constants α and β, which determine the ellipticity of the eigenmode polarization state, are:

$$\alpha=\frac{a-(a^2+4b^2+4\gamma^2)^{1/2}}{2(-\gamma+bi)}, \tag{8}$$

and

$$\beta=\frac{a+(a^2+4b^2+4\gamma^2)^{1/2}}{2(\gamma-bi)}. \tag{9}$$

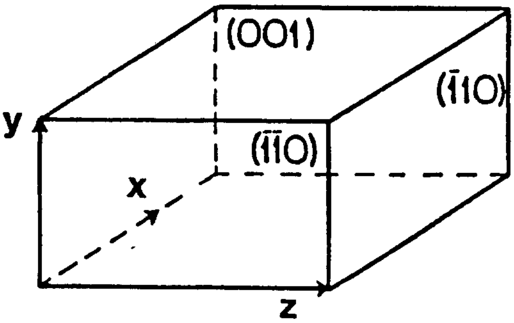

Fig. 1. Crystal orientation for maximum phase retardation in BSO.

From these results, we can obtain the output electric field of the light wave $\begin{pmatrix} P_{xL} \\ P_{yL} \end{pmatrix}$ from the input electric field of the light wave $\begin{pmatrix} P_{xo} \\ P_{yo} \end{pmatrix}$ when the light propagates for a distance L inside the crystal:

$$\begin{pmatrix} P_{xL} \\ P_{yL} \end{pmatrix} = \frac{1}{\alpha+\beta} \begin{pmatrix} e^{-i\sigma L}\beta+\alpha & (e^{-i\sigma L}-1)i \\ -\alpha\beta(e^{-i\sigma L}-1)i & e^{-i\sigma L}+\beta \end{pmatrix} \begin{pmatrix} P_{x0} \\ P_{y0} \end{pmatrix}, \tag{10}$$

in which δ, the propagation constant difference between the two eigenmodes, is given by:

$$\delta = k_+ - k_-. \tag{11}$$

The polarization properties of the emergent signal in a general transverse BSO electrooptic device with any electric field direction can be calculated from the above general form of the polarization matrix.

3. Polarization Properties of Signals in $Bi_{12}SiO_{20}$ Electrooptic Devices

First, we compare the polarization states of the output light with and without optical activity to observe the effects of optical activity. When the electric field is applied in the x direction inside the crystal as shown in Fig. 1 with an input polarization of light of $\begin{pmatrix} 1 \\ 0 \end{pmatrix}$, without consideration of optical activity, the output light is elliptically polarized as shown in Fig. 2 (a). Here, we chose the physical parameters of BSO as, n = 2.53, and $r_{41} = 4.4 \times 10^{-12}$ m/V. We also chose L = 2 mm and $E_x = 1 \times 10^6$ V/m, which are the typical values in BSO electrooptic devices. The major and minor axes of the ellipse are the x and y axes, and the output polarization state can be expressed as $\begin{pmatrix} 0.759 \\ -0.661i \end{pmatrix}$. When optical activity is considered with an optical rotatory power of 21.4 °/mm, the output polarization state can be expressed as $\begin{pmatrix} 0.947 \\ -0.321i \end{pmatrix}$ with the major axis rotated by 63.1 ° as shown in Fig. 2 (b). This major axis rotation is larger than the rotation by 20.3 ° due only to optical activity without applying the electric field (42.8 °).

Fig. 3 shows the output polarization properties when the electric field is applied in the y-direction. If optical activity is not considered, there is no plarization change in the output state for an input polarization direction of $\begin{pmatrix} 1 \\ 0 \end{pmatrix}$ But, when optical activity is considered, the output polarization becomes elliptical with a polarization state of $\begin{pmatrix} 0.9767 \\ -0.2147i \end{pmatrix}$ and the major polarization axis is rotated by 41.3 °. In this case, the rotation of polarization axis decreases by 1.5 ° compared to the polarization axis rotation due only to optical activity.

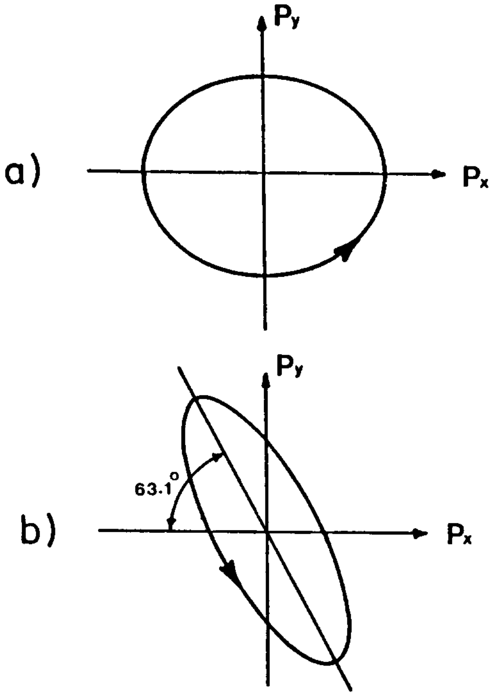

Fig. 2. Output polarization state changes in BSO with x-direction electric field application a) without and b) with consideration of optical activity.

In device applications, it is important to know the light intensity passed through a crossed polarizer, the axis of which is oriented to block the light entirely when no electric field is applied. This transmitted fraction is quite different from that determined by the minor axis component of the output polarization ellipse, because the principal axis also rotates as a function of both the electric field strength and the optical activity as mentioned above.

Fig. 4 (a) shows the transmittance as a function of input polarization angle, with and without consideration of optical activity, when an electric field in

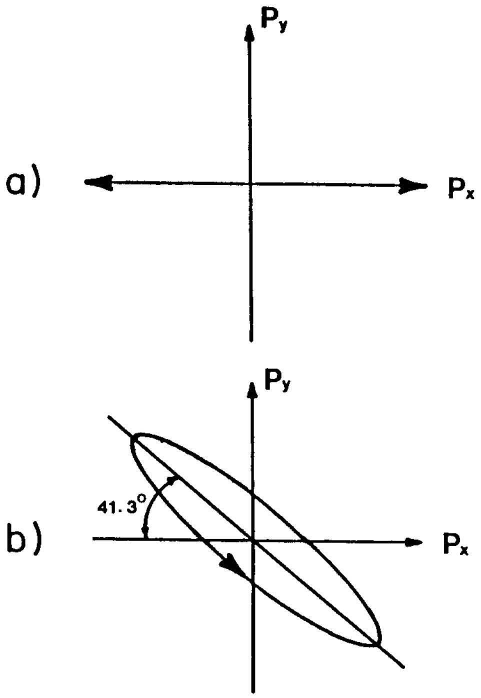

Fig. 3. Output polarization state changes in BSO with y-direction electric field application a) without and b) with consideration of optical activity.

the x-direction, $E_x = 10^6$ V/m, is applied to a 2 mm long BSO crystal. When optical activity is not considered in the calculation, the transmittance is an exact sinusoidal function with maximum transmittance obtained for the $\binom{1}{0}$ or the $\binom{0}{1}$ input polarization states. But, when optical activity is considered, the maximum transmittance is obtained with an input polarization angle of 21.4°, and the maximum transmittance decreases from 42% to 36%. This input angle shift, which corresponds to $\rho L/2$, is due mainly to the optical activity of BSO.

Fig. 4 (b) shows the transmittance for the case of y-direction electric field application. In this case, the maximum transmittance can be achieved with $\binom{1}{1}$ polarization, with the transmittance of 12% when no optical activity is included. This is 3.5 times smaller in value than that of x-direction electric field application, because the phase difference induced by a y-direction electric field is half of that induced by an x-direction electric field. Since the output intensity is proportional to the square of a sinusoidal function of the phase difference, we obtained the transmittance of 42% for the x-direction electric field case, while it is 12% for the y-direction electric field case.

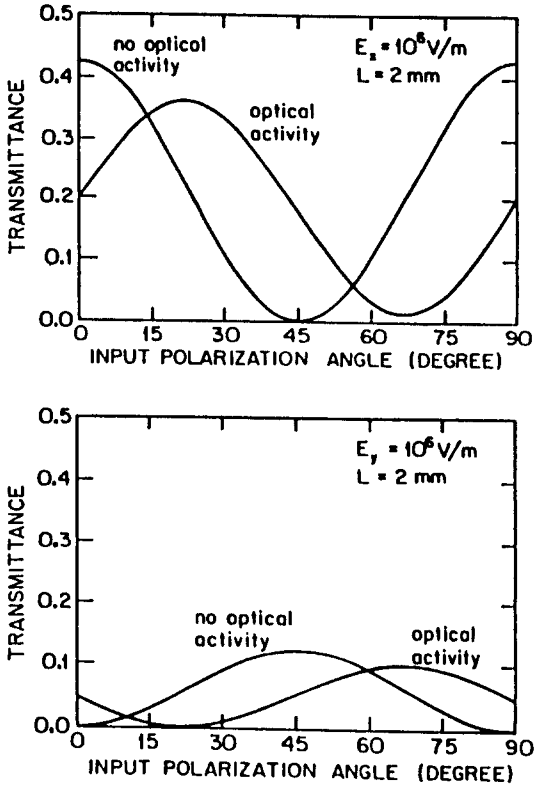

Fig. 4. Transmittance changes with different input polarization directions a) when x-direction electric field is applied b) when y-direction electric field is applied.

When optical activity is included in the calculation, the maximum output intensity also decreases to 10% with 21.4° rotation of an input polarization angle, which is the same as in the x-direction electric field application case. From these results, we can see that x-direction electric field application will result in a better modulation efficiency than y-direction electric field application, even when the optical activity is included.

If the crystal has no optical activity, the transmittance is independent of the crystal length as long as we maintain a constant electric field-optical path

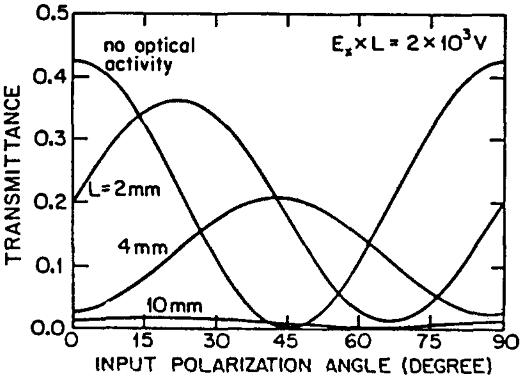

Fig. 5. Transmittance comparison with different crystal lengths. If the crystal has not optical activity, the transmittance is independent on the crystal length as long as we maintain a constant electric field-crystal length product.

length product. But, this is not true for a crystal which has optical activity. Fig. 5 shows the transmittance as a function of input polarization for different crystal lengths when the product of the electric field strength and the crystal length is constant. The transmittance for optimum input polarization decreases as the device length increases. Thus the effect of optical activity sets an upper bound on the interaction length for obtaining the maximum transmittance.

4. Conclusion

To understand the polarization properties of the signal in the electrooptic devices with an optically active crystal such as BSO, we calculated the accurate polarization state of the light inside BSO crystal for any direction of the electric field with consideration of optical activity. By solving Maxwell's equations, the general form of the polarization matrix was obtained. Using this matrix, examples of output polarization states in the BSO crystals were calculated and their properties were discussed. From these calculations, we can observe the effect of optical activity on the signal performance in BSO electrooptic devices. In particular, the signal decrease due to optical activity is critical for device performance. This occurs because the interaction length of the light with the electric fields is limited by the effects of optical activity. Perhaps other electrooptic materials could be employed that does not exhibit optical activity, and hence could show significant performance advantages over BSO.

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비스무스실리콘 산화물 단결정을 이용한 전기광학 장치에서의 편광 특성

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비스무스실리콘 산화물 단결정에서의 빛의 편광특성을 광활성도를 고려하여 계산하였다. 멕스웰 방정식을 이용하여 임의의 방향의 전기장에 대해 적용되는 일반적인 편광 변환행렬을 구하였으며 이것을 이용하여 몇 가지 경우의 편광 특성을 검토하여 보았다.