Development of microscopic measurement system for electro-optic effect

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This paper reports a microscopic electro-optic (EO) effect measurement system that is based on the Senarmont method and enables measurement of the EO coefficients (Kerr coefficients) of submillimeter-sized crystalline materials. In this study, an estimation of the electric field applied to the crystalline sample was performed with a finite-element method because the parallel plate electrodes were required to be on the same side of the sample surface. Reproducible values of the EO coefficients of submillimeter-sized (Pb,La)(Zr,Ti)O₃ transparent ceramics were obtained only if this estimation was taken into account. This system will effectively increase the speed of searches for new EO materials.

Keywords: Electro-optic effect, Optical microscopy, Kerr effect

1. Introduction

The electro-optic (EO) effect is a phenomenon in which a refractive index changes when an electric field is applied to a crystal. It is defined theoretically as the transformation of the optical indicatrix by an electric field. This phenomenon is described by Eq. (1):²

\[ \Delta n \left( \frac{1}{n_i^2} \right) = r_{ijk} E_k + r_{jkl} E_l E_i + \cdots \]  

where \( n_i \) is the refractive index, \( E_k \) and \( E_i \) are electric fields, \( r_{ijk} \) is the Pockels coefficient, and \( r_{jkl} \) is the Kerr coefficient. The Pockels effect involves a refractive index change in proportion to an applied electric field, and the proportionality factor is the Pockels constant. On the other hand, the Kerr effect represents a refractive index change in proportion to the square of the applied electric field, and the proportionality factor is the Kerr constant.

Materials that exhibit the EO effect are applied in light switches, variable-focus lenses, measurement probes of super-high-speed integrated circuit, and electric field sensors. Optical modulators for optical communication are among the main products that use the EO effect. There are several types of the modulators, and the Mach-Zehnder-type optical modulator using LiNbO₃ single crystals is mainly used at the present day. Recent progress requires another material with a higher EO effect than that of LiNbO₃. Such a material would lead to higher-performance, more integrated, and smaller modulators. The currently existent materials include Pb₁₋ₓLaₓZr₁₋ₓTiₓO₃ (PLZT) transparent ceramics and KTa₀·₆₅Nb₀·₃₅O₃ (KTN) single crystals. However, PLZT contains lead, which is a toxic element, and KTN crystals require extremely precise temperature control because of their highly temperature-dependent permittivities. Thus, searches for additional materials are demanded even now.

When new materials are developed, measurement of their EO effects is, of course, indispensable. The conventional measurement equipment requires crystalline samples to be transparent, chemically homogenous crystalline, and larger than 1 mm, and it is generally very difficult to grow such samples. However, crystals with micrometer-order sizes are comparatively easy to prepare. The aim of this study was to construct an EO effect measurement system for such micrometer-sized crystals. For this purpose, the Senarmont method, which will be explained in the next chapter, was selected. This report describes the process of miniaturizing the measurement system.

2. Experimental procedure

2.1 Setup of microscopic measurement system for EO effect

Before presenting our measurement system, we introduce the conventional measurement system and measurement principles. Figure 1 is a schematic of a conventional EO coefficient measurement system. This system determines the EO coefficient by utilizing birefringence measurement in a method called the Senarmont method, which is widely used because of its easy implementation. The Senarmont arrangement used in this study consisted of a laser light source, linear polarizer, sample, linear analyzer, and photodetector. In this type of system, the circular

![Schematic drawing of conventional EO measurement system based on Senarmont method.](image-url)
polarization of the laser light is converted to linear polarization via the polarizer. When a sample possesses birefringence, the linear polarization is changed to elliptical polarization after the light penetrates the sample. Then, the converted light filters through the analyzer, and its intensity is measured by the photodetector. In practical measurement of EO coefficients, the light intensity obtained in the same polarization direction as the analyzer and polarizer is defined as the maximum light intensity, \( I_0 \). The measured intensity \( I \) is divided by maximum light intensity, and the relative intensity \( I/I_0 \) is calculated. This calculation is represented by the following equation:

\[
\frac{I}{I_0} = \sin^2 \frac{\Gamma}{2},
\]

where \( I \) is the measured light intensity, \( I_0 \) is the maximum light intensity, and the relative intensity \( I/I_0 \) is related to the phase difference \( \Gamma \) between ordinary light and extraordinary light. Moreover, \( \Gamma \) is expressed by the equation

\[
\Gamma = \frac{2\pi d \Delta n}{\lambda},
\]

where \( d \) is the thickness of the sample, \( \Delta n \) is the birefringence, and \( \lambda \) is the laser wavelength. The EO effect appears as a non-zero value of \( \Delta n \) being observed after applying an electric field to the sample. In an isotropic material, because the Kerr constant \( R \) is dominant, \( \Delta n \) is represented as

\[
\Delta n = -\frac{n^3 R E^2}{2},
\]

where \( n \) and \( E \) are the refractive index and electric field, respectively, and \( R \) characterizes the EO effect. As shown in Fig. 1, the electric field must be perpendicular to the optical path of the incident laser. Because of the size of the laser spot and the requirement of handling the sample, the conventional system requires millimeter-sized crystals.

**Figure 2** shows the microscopic measurement system for the EO effect that was developed in this study. The system was constructed by remodeling an epi-illumination, transmission-type polarizing microscope (Olympus BX51) and consists of a He–Ne laser with \( \lambda = 632.8 \) nm, probes, a CCD camera, and a photodetector. The visual field of the irradiation is narrowed by a condenser lens, and the sample is irradiated with the laser light. Because the laser light spreads as it passes the sample and analyzer, the objective lens and eye lens condense the light again. The CCD camera and photodetector are alternately used to set the sample and measure the light intensity, respectively. The probes attached to the right and left sides of the sample stage apply the electric field.

### 2.2 Sample preparation

\( \text{Pb}_{0.81}\text{La}_{0.09}\text{Zr}_{0.65}\text{Ti}_{0.35}\text{O}_3 \) (PLZT) transparent ceramics, which are commercially available, were used in this study. The transmittance of PLZT ceramics with 0.2 mm thickness is 67% at \( \lambda = 632.8 \) nm, and the refractive index \( n \) is 2.465 at \( \lambda = 1500 \) nm. The reference value of \( R \) is \( 3.8 \times 10^{-16} \text{m}^2/\text{V}^2 \). In this investigation, the PLZT ceramics were crushed down to a size of several hundred microns and were then buried in resin. The samples were produced by polishing both sides of the ceramics to reduce their sizes to 70 \( \mu \)m. Subsequently, Au electrodes were formed on the surface on one side of each ceramic by a photolithography method, as shown in **Fig. 3(a)**. The gap between the electrodes was 20 \( \mu \)m, as shown in Figs. 3(b) and 3(c). The probes shown in Fig. 2 were contacted to these electrodes when the electric field was applied. The measurements were performed as the electric field was applied.

### 3. Results and discussion

The laser spot passing through the condenser lens was approximately 300 \( \mu \)m in diameter and yielded a high \( I_0 \) value. Even though the electric field was applied, the \( I \) value did not change and was equal to \( I_0 \). That is, \( I/I_0 \) was unity during the measurement. In addition, due to the condenser lens, the laser light intensity decreased radially outward from the center of the laser spot. These phenomena remained when the high-magnification condenser lens was used. Therefore, a shading mask with a rectangular hole measuring \( 900 \times 1700 \mu \text{m}^2 \) was fabricated and was inserted in front of the CCD camera or photodetector. **Figures 3(c) and 3(d)** are views of the sample without and with the shading mask, respectively. The mask permitted the light to pass through the sample only between the electrodes. As a result, \( I/I_0 \) was properly detected. After the \( I/I_0 \) values were obtained, the apparent \( \Gamma \) was calculated using Eq. (2). However, in this study, the measurement system required careful consideration of Eqs. (3) and (4). In Eq. (3), \( d \) is known on the condition that the electric field is applied between the electrodes formed on both sides of the sample. Under this condition, \( E \) is uniform across the entire sample and, hence, must be known. In this study, the parallel plate

![Fig. 2. Schematic drawing of microscopic EO measurement system developed in this study.](image)
electrodes were formed on one side of the sample, as shown in Fig. 3. Therefore, we analyzed $E$ applied in the sample using a finite element method. In Eq. (4), $E$ was represented as a function of voltage $V$ along the $x$, $y$, and $z$ axes of the orthogonal coordinate system. The $x$ and $y$ axes correspond to the directions perpendicular to the distance between electrodes and along it, respectively, while the $z$ axis is parallel to the thickness of the sample. In the method, we performed the analysis in two dimensions, specifically, in the $yz$ plane. We fabricated a 40,000 mesh by dividing the area of $y \times z = 10 \times 10 \mu m^2$ into rectangles in the sample between electrodes and fabricated a 120,000 mesh by dividing the area of $y \times z = 100 \times 70 \mu m^2$ into quadrangles. The applied electric field was set to be uniform within each mesh. The magnitude of the calculated voltage is shown in Fig. 4. The features of the magnitude are very similar to those reported in Ref. 19, confirming the correctness of our analysis. When laser light passes through a certain mesh, Eqs. (3) and (4) may be combined to derive the following equation:

$$\Delta V = -\frac{\pi n^2 R}{\alpha} E(V, x, y, z)^2 \Delta d,$$

where $\Delta V$ is the phase difference between the ordinary and extraordinary rays in a certain mesh, and $\Delta d$ is the height of the mesh along the $z$ axis, that is, the laser path. In actuality, laser light is gradually modulated whenever it passes through a mesh. As a result, the phase difference along the $z$ axis $\Delta \Gamma_z$ may be obtained as the integral value of $\Delta V$ within the sample thickness from the following equation:

$$\Gamma_z = \int_0^d -\frac{\pi n^2 R}{\alpha} E(V, x, y, z)^2 \Delta d,$$

where $d$ is the sample thickness. Then, substituting $\Gamma_z$ from Eq. (6) for $\Gamma_z$ in Eq. (2), the relative intensity $I/I_0$ along the $z$ axis may be represented by the following equation:

$$\frac{I}{I_0} = 1 - \sin^2\left[\frac{1}{2} \sum_{d} -\frac{\pi n^2 R}{\alpha} E(V, x, y, z)^2 \Delta d\right].$$

In this study, because the laser light was distributed in intensity along the lateral direction, $I/I_0$ must be the average value of all of the $I/I_0$ values. Hence, $I/I_0$ may be expressed by

$$\frac{I}{I_0} = \frac{1}{S} \sum_{S} \frac{i}{I_0} \Delta S,$$

where $S$ is the gross area of the laser light, and $\Delta S$ is the area of a certain mesh showing a particular $i/I_0$ value. By substituting Eq. (7) into Eq. (8), the actual $I/I_0$ value may be obtained from the following equation:

$$\frac{I}{I_0} = \frac{1}{S} \sum_{S} \sin^2\left[\frac{1}{2} \sum_{d} -\frac{\pi n^2 R}{\alpha} E(V, x, y, z)^2 \Delta d\right] \Delta S.$$  

(9)

Equation (9) connects the measured relative intensity with the result of the finite element method. Therefore, $R$ can be calculated by fitting the measured value to the calculated values.

We characterized the PLZT transparent ceramics as typical isotropic EO materials with high $R$ values to demonstrate the microscopic measurement system. Figure 5 shows the relative intensity change with applied voltage in the PLZT ceramics. The intensity measurements were performed from 1 to 41 in 2 V intervals. Each measurement was taken for approximately 3 s to ensure the stabilization of the intensity. The light intensity seems to be proportional to the square of the applied voltage as the voltage increases. The light intensity as the voltage decreases shows hysteresis. The measured values were fitted according to Eq. (9). The resulting $R$ of the sample was $3.4 \times 10^{-16} m^2/V^2$, which agrees well with the reference value of $3.8 \times 10^{-16} m^2/V^2$. This result illustrates that it is possible to measure the Kerr effects of submillimeter-sized EO materials using the microscopic measurement system developed in this study.

4. Conclusion and outlook

In this study, a microscopic measurement system based on the Senarmont method was developed for characterization of the EO effect of submillimeter-sized crystalline samples. The Kerr coefficient $R$ of the PLZT transparent ceramics crushed to a size of several hundred microns was measured and was found to be in accordance with the reference value. This system only requires the estimation of the electric field in the sample using the finite element method, and this estimation involves significantly less effort than the difficult growth of large single crystals. We are confident that this system will accelerate the search for new EO materials.

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