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Electric-field-induced linear birefringence in $TmAl_3(BO_3)_4$

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The linear birefringence induced by the electric field was first detected in a $TmAl_3(BO_3)_4$ single crystal. The electric field dependence of the birefringence was investigated. The estimation of the electro-optical coefficient of the material gives $\approx 1.5 \times 10^{-10}$ cm/V for a wavelength 632.8 nm.

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1. INTRODUCTION

The noncentrosymmetric rare-earth aluminum borates $RAl_3(BO_3)_4$ belong to a trigonal system with the space group R32. These materials are potential candidates for a variety of practical applications based on the magnetoelectric effect, which is manifested in them [1–3]. For example, the magnetic field of 700 kOe induced the electric polarization $P = 300\ \mu C/m^2$ in $TmAl_3(BO_3)_4$, and a giant $P = 3.600\ \mu C/m^2$ in $HoAl_3(BO_3)_4$ [1,2]. Previously in the crystal $TmAl_3(BO_3)_4$ it was experimentally established that deformation induced by the magnetic field is linear with the electric polarization [2]. This allows one to make an assumption about the association between the magnetoelectric and piezoelectric properties of thulium aluminum borate. The single crystal of $TmAl_3(BO_3)_4$ is transparent for the visible light that makes possible to explore its electro-optical properties, including the Pockels effect. It is well known that the crystals with Pockels effect can be used in the construction of various optical emission control devices, such as light modulators, deflectors, switches, optical channels, etc.

The purpose of the present work is studying the electric-field-induced linear birefringence and estimation of the electro-optical coefficient of thulium aluminum borate.

2. EXPERIMENT

For investigation of the electro-optical effect in $TmAl_3(BO_3)_4$ the single crystal sample was cut in the form of a plane-parallel plate perpendicular to the trigonal *c*-axis. Typical single crystal plate dimensions are 4 mm × 4 mm and thickness $t = 230\ \mu m$. The experiments were performed at room temperature.

In the experiment, the linearly polarized light is directed along the trigonal axis of $TmAl_3(BO_3)_4$. The polarization plane of passed through the sample light is rotated by a certain angle due to the optical activity of this noncentrosymmetric crystal. The application of an electric field can decrease the optical class of crystal from uniaxial to a biaxial. In this case, the cross section of the optical indicatrix by the plane perpendicular to the trigonal axis c will be an ellipse. And right- and left-elliptically polarized modes will be propagated in the crystal. Between these modes there is a phase difference, $\Delta = \sqrt{\delta^2 + (2\rho)^2}$, where δ is a phase shift in the absence of spontaneous rotation ρ, 2ρ is a phase shift, which would be observed in the absence of linear birefringence. The linearly polarized light will generally be elliptically polarized after passing through the elliptically birefringent crystal. The magnitude of the ellipticity e is determined by the linear birefringence and is virtually independent of the spontaneous rotation. But it is valid only in the case when the polarization plane of light is directed at 45° to the main axis of the ellipse of the cross section of the optical indicatrix by the plane perpendicular to the trigonal axis and the value of Δ is small. As a result [4],

$$e \approx \frac{\delta}{2}. \tag{1}$$

The linear birefringence is related to the phase shift as follows,

$$\Delta n = \delta\lambda/2\pi t, \tag{2}$$

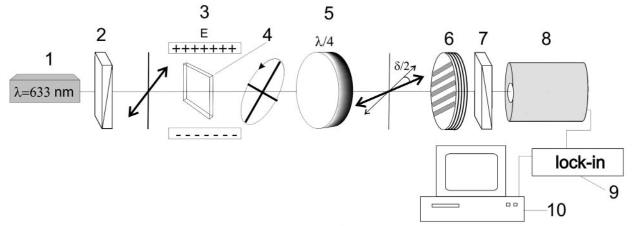

Fig. 1. Diagram of experimental setup: (1) laser with $\lambda = 632.8$ nm, (2) polarizer, (3) capacitor, (4) sample, (5) $\lambda/4$-plate, (6) modulator, (7) analyzer, (8) photoelectronic multiplier, (9) amplifier, (10) personal computer.

where λ is the light wavelength, t is thickness of the sample. In the experiments a quarter-wave plate was used as the compensator to measure the birefringence. The diagram of the experimental setup for δ-measurements based on the Senarmont method is shown in Fig. 1.

Measurements were carried out with the wavelength of a He–Ne laser $\lambda = 632.8$ nm (1). The light beam passed through the polarizer (2) and propagated along the c-axis ($\boldsymbol{k}\|c$). The electric field was created by the plates of the capacitor (3). The electric field value measurement error was less than 2.5% in the experiment. The sample (4) was placed inside of the capacitor. The direction of E coincides with the second-order crystal axis a ($\boldsymbol{E}\|a$). Elliptically polarized light, which came out of the crystal, is transformed by the $\lambda/4$ plate (5) in a linearly polarized one. The polarization plane was rotated by the angle $\delta/2$ relative to the polarization plane of light incident on the crystal. To measure the angle $\delta/2$, the modulation technique was applied with the modulation of the light polarization plane [modulator (6)] and the synchronous detection [amplifier (9)]. The output signal of the amplifier was applied to an input of a personal computer (10).

3. RESULTS AND DISCUSSION

The optical indicatrix of the $TmAl_3(BO_3)_4$ crystal with a point group 32 is an ellipsoid of rotation around the trigonal c-axis with the principal refractive indices n_a and n_c, measured along the a- and c-axis, respectively. As it was mentioned above, the electric field $\boldsymbol{E}$ can reduce the optical class of the crystal from the uniaxial to biaxial. In this case, the symmetric part of the dielectric impermeability a_{ij} will have additives Δa_{ij},

$$\Delta a_{ij} = r_{ijk} E_k + p_{ijlm} U_{lm}, \quad (3)$$

where E_k is the projection of the electric field vector on the coordinate axes. The tensor of electro-optic coefficients r_{ijk} is symmetric with respect to the ij indices and describes the primary electro-optic effect—linear birefringence caused by the redistribution of connected charges within the crystal. This birefringence is proportional to the first power of the electric field. The photoelastic coefficient tensor p_{ijlm} is symmetric with respect to the ij and lm index pairs and describes the secondary electro-optical effect caused by the electric-field-induced deformation of the piezoelectric crystal. U_{lm} are components of this deformation.

Consider the case when the electric field and measuring light beam are directed along the a-axis and c-axis of the crystal, respectively. The electric-field-induced linear birefringence Δn_{el} corresponding to the primary electro-optical effect can be determined by the following expression in the coordinate system $z\|c$ and $x\|a$:

$$\Delta n_{el} = n_x - n_y = 2 r n_a^3 E_x. \quad (4)$$

It was considered that the components of electro-optic coefficients tensor r_{xxx} and r_{yyx} are equal but have opposite signs $r_{xxx} = -r_{yyx} = r$ for the point crystal group 32.

Now consider the linear birefringence caused by the secondary electro-optical effect. The deformation U_{lm} occurs in the electric field in $TmAl_3(BO_3)_4$. The components of this deformation U_{lm} are related to the tensor of piezoelectric coefficients d_{lm} as follows:

$$U_{lm} = d_{lmk} E_k. \quad (5)$$

The tensor of piezoelectric coefficients is similar to the tensor of electro-optic coefficients. In the electric field $\boldsymbol{E}\|a$ the deformation with components $U_{xx} = d_{xxx} E_x$ and $U_{yy} = d_{yyx} E_x$ occurs in the crystal. If $d_{xxx} = -d_{yyx} = d$, then $U_{xx} = -U_{yy} = U$. Thus, the linear birefringence Δn_{def} caused by the deformation of crystal in an electric field can be determined as

$$\Delta n_{\mathrm{def}} = n_x - n_y = 2 n_a^3 (p_1 - p_2) U = 2 n_a^3 (p_1 - p_2) d E_x. \quad (6)$$

Using Eqs. (4) and (6), the birefringence induced by the electric field in the $TmAl_3(BO_3)_4$ crystal can be expressed as follows,

$$\Delta n = 2 n_a^3 (r + (p_1 - p_2) d) E_x = 2 n_a^3 r_g E_x, \quad (7)$$

where r_g is the electro-optical coefficient, depending both from primary and from secondary electro-optical effects.

The electric field dependence of the birefringence is shown in Fig. 2. This dependence demonstrates that the sign of the birefringence Δn changes with the sign of the electric field. The hysteresis was not found in experiments. In an electric field $E = 4 \times 10^3$ V/cm, the value of Δn reaches $8 \times 10^{-6} \pm 0.8 \times 10^{-6}$. As is known, the optical activity can influence the electro-optical effect [5]. The observed in experiment optical activity is quite small (≈0.3°). That is why it can be considered that the optical activity does not influence the electro-optical effect and

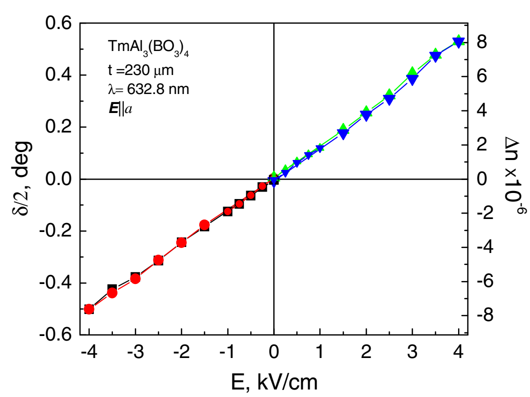

Fig. 2. Linear birefringence of light as a function of the applied electric field in $TmAl_3(BO_3)_4$ at room temperature for $\boldsymbol{E}\|a$. The light beam with $\lambda = 632.8$ nm propagates along the c-axis of the crystal. The thickness of the investigated sample is $t \approx 230$ μm.

the ellipticity e is determined by the linear birefringence only Eq. (1). In this case the error of the experiment is less than 10%. Presented dependence is well extrapolated by the linear law,

$$\Delta n = \alpha E_x, \tag{8}$$

where $\alpha = 2 \times 10^{-11}$ m/V.

Taking into account Eqs. (7) and (8) and using $n_a = 1.88$ for gadolinium aluminum borate [6], the electro-optical coefficient of $TmAl_3(BO_3)_4$ can be estimated: $r_g = \alpha/2n_a^3 \approx 1.5 \times 10^{-10}$ cm/V.

4. CONCLUSION

For the first time the linear birefringence induced by the electric field (Pockels effect) was detected experimentally in a $TmAl_3(BO_3)_4$ single crystal for geometry $\boldsymbol{E}\|a$ and $\boldsymbol{k}\|c$. The variation of linear birefringence under an applied electric field was investigated. The value of the birefringence was up to 8×10^{-6} in an electric field 4 kV/cm, for the light wavelength 632.8 nm at room temperature. The electro-optic coefficient, which included both primary and secondary Pockels effect, was evaluated by using the field dependence of the birefringence. The value of this coefficient was $\approx 1.5 \times 10^{-10}$ cm/V.

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