Gradient thermooptical effect in $LiNbO_3$ crystals

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Abstract.

This paper is devoted to the studying of the influence of temperature gradient on the refractive indexes of $LiNbO_3$ crystals. In our experiments, the temperature gradient was created in $LiNbO_3$ crystals along the crystallophysical axes *X* and *Y*. The optical beam was propagated along the *Z*-axis. The temperature gradient with maximum value $\partial T/\partial x_k$=2.25×10^4 K/m was induced. The distribution of induced birefringence was studied by imaging polarimetry. The components of the third rank tensor that describes the gradient thermooptical effect were calculated using experimental results.

Key words: gradient thermooptical effect, temperature gradient, lithium niobate, imaging polarimetry

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Introduction

As it was already reported [1], the gradient crystallooptical effects appearing at the nonhomogeneous fields consist in a change of refractive indices or gyration tensor on applied field gradient. One of such effects is gradient thermooptical effect. It is described by third rank polar tensor:

$$\Delta B_{ij} = r_{ijk}\,\partial T/\partial x_k\,, \qquad (1)$$

where ΔB_{ij} is the change of polarization constants, x_k is the Cartesian coordinate and r_{ijk} is the third rank polar tensor. Other gradient phenomena such as gradient electrooptical and gradient piezooptical effects are described by the fourth and fifth rank tensors respectively and therefore should be smaller than the gradient thermooptical effect. There is only one report about the experimental study of this effect [2]. The authors [2] have observed the appearance of a birefringence in $LiNbO_3$ crystals with light being propagated and a thermal gradient applied along the Z-axis. However, as it follows from the point group of symmetry for $LiNbO_3$ crystal, such a thermal gradient cannot induce the birefringence along the optical axis. Therefore, the origin of the thermal gradient effect is not clearly understood yet. It is obvious that thermal flows should exist in different directions in the case of a temperature gradient. It means that this experiment possesses time dynamics as well as the appearance of non-homogeneous mechanical strains. Thus, we have used a CCD camera to study the gradient thermooptical effect. In this paper we study the gradient thermooptical effect in $LiNbO_3$ crystals by the imaging polarimetry technique.

Experimental set-up and measurement procedure

The imaging polarimeter was described in [3]. The instrument is schematically shown in Fig.1. In the case of a gradient thermooptical effect study, it is important to provide a minimal

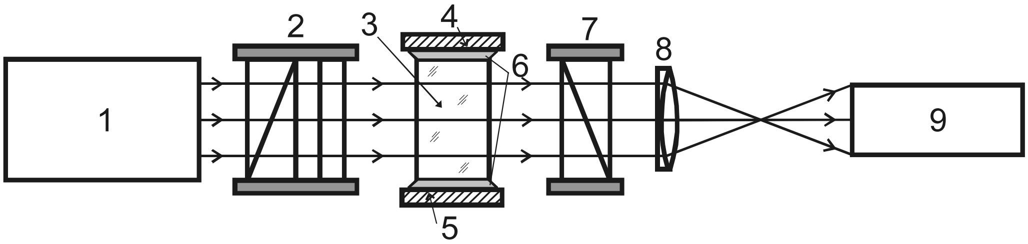


Fig. 1. Optical scheme of the imaging polarimeter. 1 - light source; 2 - polarization generator (polarizer and compensator λ/4); 3 - sample; 4 - heater, 5 - cooler, 6 – thermo conductive paste, 7 - analyzer; 8 - objective lens; 9 - CCD camera.

measuring time. Therefore, the measuring procedure was simplified comparing with the procedure described in [3]. Compensator in polarization generator is in 45°- position with respect to the polarizer. As a result, the light exited from polarization generator is circularly polarized. To measure polarization state of light transmitted through the sample, the analyzer is rotated from 0° to 180°. The sample's image is recorded each 6 degrees. After the analyzer reaches 90°, the light beam is shut and background image is recorded. The time of measuring procedure is less than 24 seconds. Then the image files are analysed. The azimuth dependencies of intensity ***I*** (with background extracted) are fitted by the sine function for each pixel of the image:

$$\boldsymbol{I} = C_1+C_2\sin(2(\boldsymbol{a}-C_3)), \qquad (2)$$

where ***a*** is analyzer's azimuth. Azimuths C_3 of minima positions corresponding to the optical indicatrix axis orientation are calculated. Fitting parameters C_1 and C_2 give the ellipticity of light that is related with the retardance of the sample:

$$\cos(2\varepsilon)=C_2/C_1 \qquad (3)$$

$$\cos(\Gamma) = \sin(2\varepsilon), \qquad (4)$$

where ε is ellipticity angle and Γ is phase retardation.

Temperature gradient was created by the Peltier semiconductor cooler and electrical heater. To provide uniform temperature on the sample faces thermo conductive paste was used. Using this paste also allows to avoid the sample gripping as well as an appearance of additional stresses caused by thermal expansion. The maximum value of temperature gradient was 2.25×10^4 K/m and maximum value of temperature difference was 68.5 K.

Experimental results and discussions

Two samples were studied in this work. In both cases light was propagated along the *Z*-axis. Temperature gradient was created in the *X*- and the *Y*-direction respectively. The image for the first sample is presented in Fig. 2a. The sample sizes were following x= 4.10 mm, y= 3.85 mm

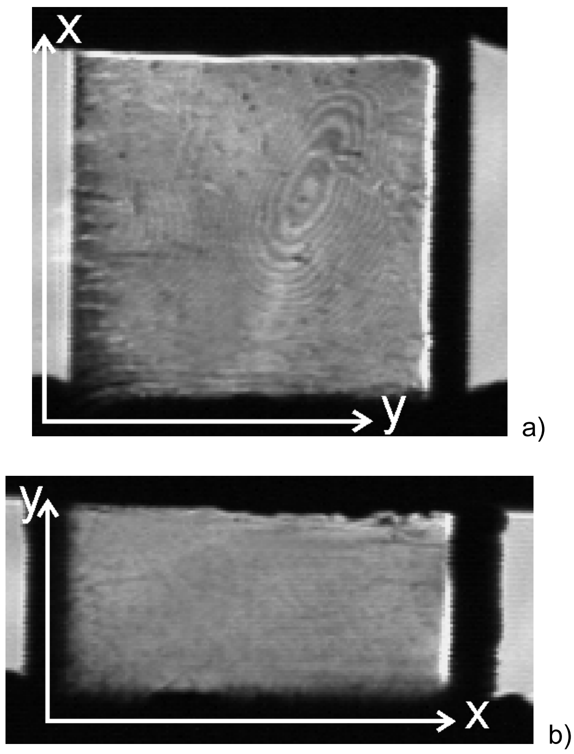
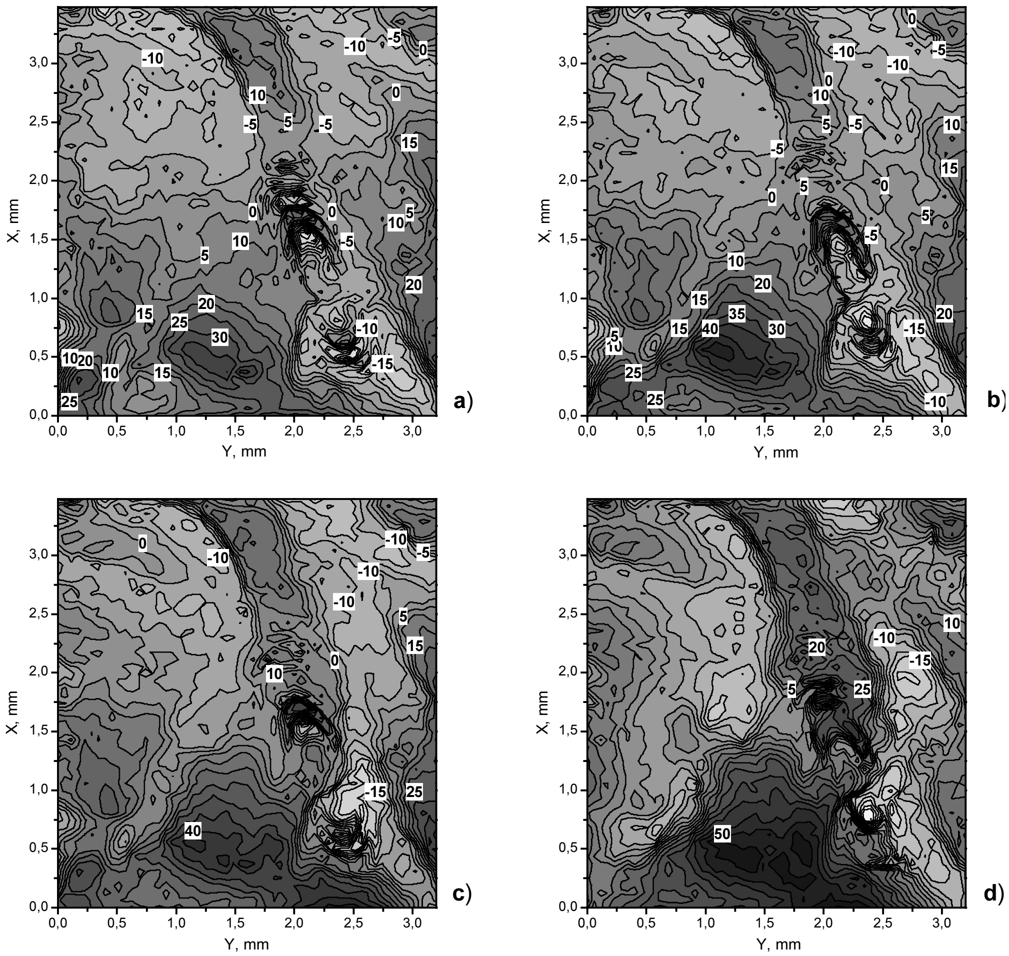


Fig. 2. Images of the samples of Z-cut of $LiNbO_3$ in the polarimeter. Temperature gradient is created in vertical direction: a) along X axis; b) along Y axis.



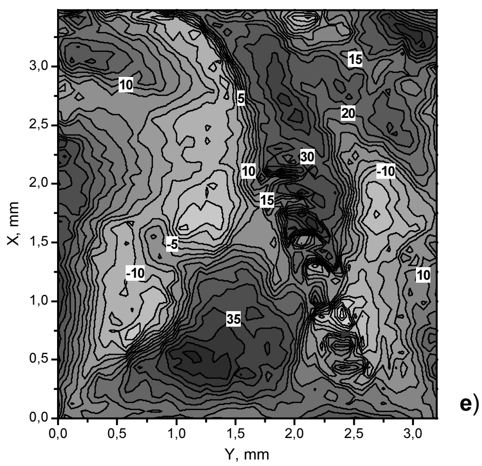


Fig. 3. Maps of the birefringence (10^{-7}) across the sample aperture for the $\partial T/\partial x$ values: a) $5.1\cdot10^3$ K/m; b) $7.3\cdot10^3$ K/m, c) $10.2\cdot10^3$ K/m, d) $12.9\cdot10^3$ K/m, e) $16.6\cdot10^3$ K/m

and z= 5.46 mm. The image for the second sample is presented in Fig. 2b. The sample sizes were x=4.91 mm, y=2.31 mm and z=5.00 mm.

In Fig. 3 and Fig. 4 the topographical maps of induced birefringence at the thermal gradients $\partial T/\partial x$ and $\partial T/\partial y$ are presented respectively. As it is seen, there are changes of phase difference at different thermal gradients. Because of quarter-wave plate used in polarization generator inevitably is imperfect and not uniform across the beam, each point of the sample is illuminated by light with polarization weakly differing from circular. To plot the dependencies of induced birefringence on temperature gradient, we choose the pixels on the images of the samples, which correspond to exactly circular incident

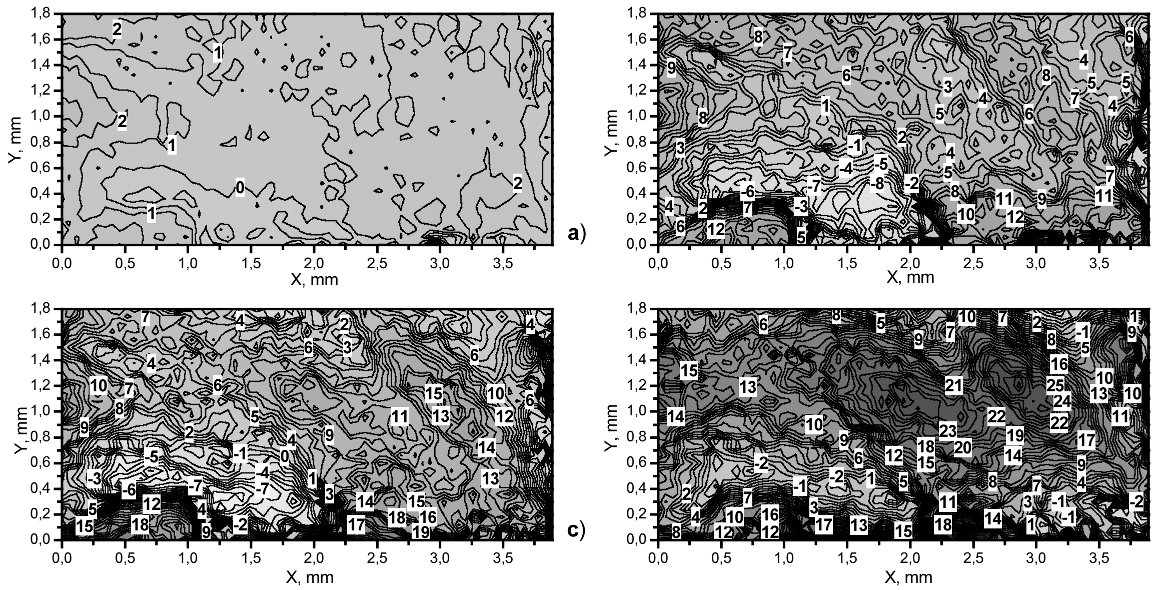


Fig. 4. Maps of the birefringence (10^{-7}) across the sample aperture for the $\partial T/\partial y$ values: a) $5.6\cdot10^3$ K/m; b) $9.5\cdot10^3$ K/m, c) $17.3\cdot10^3$ K/m, d) $22.5\cdot10^3$ K/m,

light. In Fig.5 and Fig.6 plots for these points are presented. These dependencies are linear.

Equations of optical indicatrix for the crystals, which belong to the point group of symmetry 3m are written as

$$B_{11}(x^2+y^2)+B_{33}z^2+2r_{51}\frac{\partial T}{\partial x}xz-2r_{22}\frac{\partial T}{\partial x}xy=1; \quad (5)$$

$$\begin{aligned}(B_{11}-r_{22}\frac{\partial T}{\partial y})x^2+(B_{11}+r_{22}\frac{\partial T}{\partial y})y^2+\\ +B_{33}z^2+2r_{51}\frac{\partial T}{\partial y}yz=1\end{aligned}. \quad (6)$$

Induced birefringence in *Z*-direction in the case of gradient $\partial T/\partial x$ should be twice greater than in the $\partial T/\partial y$ case:

$$\Delta n = 2n_o^3 r_{22}\frac{\partial T}{\partial x}; \quad (7)$$

$$\Delta n = n_o^3 r_{22}\frac{\partial T}{\partial y}. \quad (8)$$

The coefficient calculated for the $\partial T/\partial x$ case is $r_{22}=(4.61\pm0.49)\times10^{-12} m/K$ and for the $\partial T/\partial y$ case $r_{22}=(4.85\pm0.43)\times10^{-12} m/K$. These values are close.

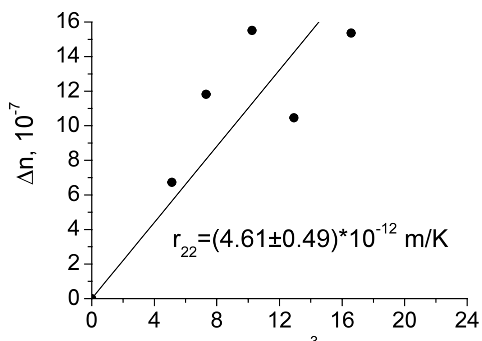


Fig. 5. Dependence of induced birefringence on thermal gradient $\partial T/\partial x$ for chosen point of first sample.

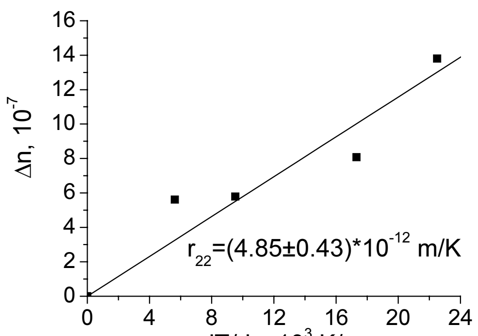


Fig. 6. Dependence of induced birefringence on thermal gradient $\partial T/\partial y$ for chosen point of second sample.

Conclusions

1. The phenomenological description of gradient thermooptical effect is proposed. The gradient thermooptical effect in $LiNbO_3$ crystal is studied experimentally.

2. The topographical maps of induced phase differences at the different temperature gradients are obtained using the imaging polarimetry technique. The change of phase difference at the different thermal gradient is observed.

3. The dependencies of induced birefringence Δn_z on thermal gradients $\partial T/\partial x$ and $\partial T/\partial y$ were obtained. The coefficient of gradient thermooptical effect calculated for $\partial T/\partial x$ case is $r_{22}=(4.61\pm0.49)\times 10^{12}$ m/K and for $\partial T/\partial y$ case is $r_{22}=(4.85\pm0.43)\times10^{-12} m/K$. These values are close.

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