The studies of phase retardation plates by imaging polarimeter

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Abstract

Spatial inhomogeneity of the phase retardation in the birefringent plates of $LiNbO_3$ crystals are measured. The studies are performed with the imaging polarimeter which utilizes the computer registration and image processing. The apparatus have been used for the measurements of spatial distribution of the optical anisotropy parameters characterizing several single crystals.

Keywords: Polarimetry, image, birefringence, spatial distribution

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Introduction

Polarimetry is widely used for studying different crystal optical phenomena and determining the quality parameters of the optical components in polarization systems [1–3]. The most modern measuring techniques are now realized with the help of the apparatus employing video cameras as photodetectors. The possibility for processing images with computer methods increases essentially the amount of information derived out from the polarimeters. The latter are often called as imaging polarimeters [4–6].

High optical homogeneity of crystals is one of the principle parameters that determines the possibilities of their practical applications. Materials for polarization optics, nonlinear optics and quantum electronics should especially have a high optical quality. One of the main sources for optical inhomogeneity of the nonlinear crystals grown from the melt is the so-called residual strains. Besides, the twins may appear during the growing process, as well as macroscopic lowering of symmetry may occur. The most modern and relatively quick method for deriving the information concerning the spatial distribution of optical inhomogeneity is utilizing the so-called imaging polarimeters. High resolution of computer optical images enables one to reveal even slightest local changes, which are in most cases inaccessible for the ordinary single-ray schemes. In the present work the samples of $LiNbO_3$ are studied with the imaging polarimetric methods. These crystals belong to the symmetry group 3m, so should not possess the optical activity [7].

Experimental

In order to measure spatial optical inhomogeneities of crystals and phase retardation plates, we have built an experimental imaging polarimeter. It works out a common polarizer-sample-analyzer (PSA) scheme at the wavelength of $\lambda = 633$ nm (figure 1). The image of the sample under the study (with the dimensions 30×30 mm^2) is formed on the video sensor of a TV-camera and frame grabber system from every 384×288 pixel. A light intensity in every pixel is measured in a 0–255 gray scale. The measuring procedure is completely automated, for which the independent rotations of both polarizer and analyzer are foreseen, using the stepping motors.

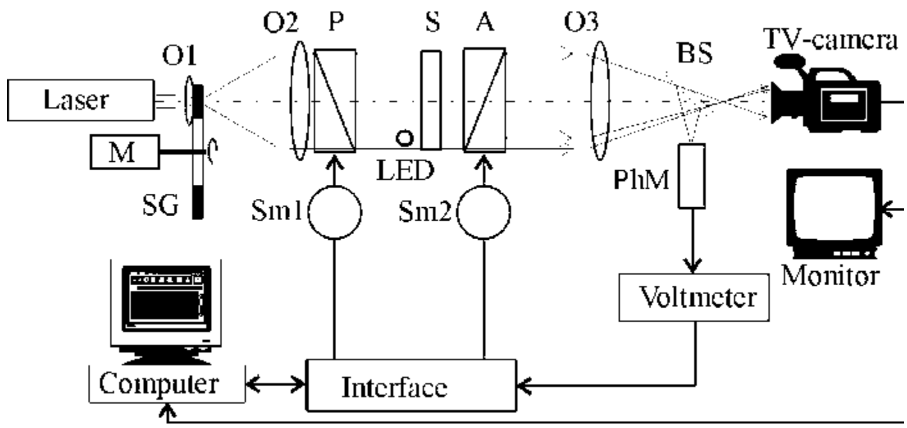

Fig.1. Optical scheme of the image polarimeter: M, motor; SG, scattering glass; O1, O2, optical system for producing a parallel beam of light; O3, objective which forms the image of sample; BS, beam splitter; SM1, SM2, stepping motor; PhM, photomultiplier

To provide necessary initial conditions for the functioning of the image polarimeter, preliminary measurements according to a single-ray scheme are needed. For this aim, a portion of light radiation is directed, with the help of a semitransparent mirror (beam splitter), at the photomultiplier connected with a digital voltmeter. The intensity of the light transmitted through analyzer is registered in the central part of the image. The polarization azimuth χ of the light emergent from the crystal is defined by the formula [8,9]

$$\chi(\theta) = \theta \cos\Delta + k \sin\Delta, \qquad (1)$$

where θ is the angle between the polarization vector of the incident linearly polarized light and the principal crystal axis, $\Delta = (2\pi/\lambda)\Delta nd$ is the phase retardation, k is the eigenwave ellipticity of crystal, Δn is the linear birefringence, d is the thickness of the sample. According to (1), the information on the phase retardation is to be derived from the slopes of the $\chi(\theta)$ dependence

$$\cos\Delta = d\chi/d\theta\,. \qquad (2)$$

Utilization of such measuring methods needs thoroughly the chosen of polarization components [10]. The test of their quality parameters is also possible when using the same apparatus. We used the Arens prism as a polarizer and the HR-type sheet linear analyzer.

A principal measuring procedure of polarimeter is seeking out the minimum intensity in the polarization system [10]. The dependence of the intensity I of light on the angular position α of the analyzer near the minimum may be well described by the expression

$$I(\alpha) = C_0 + C_1\alpha + C_2\alpha^2\ . \qquad (3)$$

Therefore $\alpha_{\min} = -C_1/(2C_2)$ is calculated easily on the base of the data of experimental measurements. Usually the intensity of light at the exit of polarization system in automated polarimeter for 30 discreet position of analyzer is measured in the vicinity of 1 deg. The determination of $\alpha_{\min}$ is carried out only when it is placed near the center of the scanning region. Within this a single-ray scheme, the cosΔ values are found only for a single point. However, even inside the cross section of the laser beams (the laser are often used as the light sources in polarimeters) this value can notably change. This is why we regard these measurements as preliminary and accessory for the image polarimeter.

Basing on the results of these preliminary measurements, the optimum values for the azimuths of polarizer and analyzer are found, for which the image of the investigated sample is grabbed by the computer. A typical number of images, which are associated with different mutual positions of polarizer and analyzer, is equal to 50. This corresponds to 5 positions of the polarizer separated by 0.4° steps, and 10 positions of the analyzer separated by 0.2° steps.

In order to eliminate the influence of automatic gain controlling by the TV camera on the measured intensity values, the image of a semiconductor light emitting diode (LED) is placed in some part of the whole field of the image. The intensity of the LED is invariable in the course of experiment (visually this intensity on figure 2a is lower, than on figure 2b), so that it can be used as a basic intensity signal.

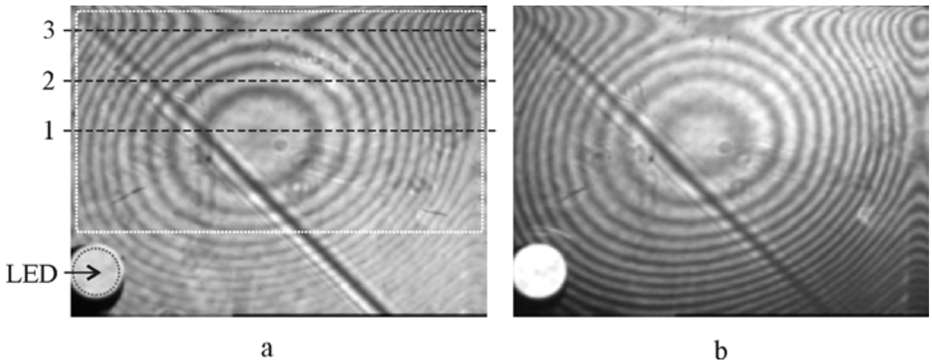

Fig.2. The two images of the $LiNbO_3$ crystal plate (thickness 1 mm) obtained in the polarimeter under the conditions of crossed polarizers and the azimuth $\theta \approx \pm 1°$ of incident polarized light. In the left lower part there is a field occupied by the reference light source LED (light emitting diode). The slope dark line is related to the features of the polarizer. For the rectangle selected on the left photo the spatial phases retardation changes are calculated, and for crossings 1,2,3 – dependence of the cosΔ and intensity versus coordinate *x*. Counting the beginning of coordinates (*x*,*y*) on figure 3 and 4 corresponds to the left lower corner of rectangle

The processing of all images is performed in the TIFF format and consists of the following stages:

- averaging of the images within the squares with the dimensions varying from 2×2 to 5×5 pixels
- distinguishing the part of the field filled with the LED radiation and, subsequently, normalizing the images after division of each intensity value by the average LED intensity
- distinguishing the part of the image filled with the sample under the test
- searching for the transmission minimums of the polarization system for every point of the averaged image and every fixed polarizer's position
- calculating the spatial distribution of the phase retardation and the optical birefringence changes
- plotting the graphs and creating the exported files (for the programs providing further representation of the results).

Results and discussions

Spatial distribution of the cosΔ value for the $LiNbO_3$ sample with a middle thickness of about 1.0 mm (fig.3) is characteristic for planeparallel crystal plate, when its thickness *d* is changing in a regular manner. As a rule, the thickness is maximal in the central part and gradually diminishes to the edges. It is typically for crystal plates, which are hand–made. The interference pattern on figure 2 represents the equal thickness bands. Multiple reflection of light and its interference leads to a periodicity in cosΔ.

The Jones matrix, which is offered in [11], can be used for taking into account the light reflection. Then the phase retardation measured within image polarimeter (Δ_{meas}) can be written as

$$\cos\Delta_{meas} = \frac{\cos\Delta - 2r^2}{1-2r^2\cos\Delta}, \quad (4)$$

where $r^2 = \left(\frac{1-\bar{n}}{1+\bar{n}}\right)^2 \cos\left(\frac{4\pi}{\lambda}\bar{n}d\right)$ and $\bar{n}$ is the principle refractive index. In the case of $LiNbO_3$ and $\lambda = 633$ nm the corresponding parameter $\left(\frac{1-\bar{n}}{1+\bar{n}}\right)^2$ is about 0.148. It means, that the light reflection in lithium niobate crystals strongly influences on measured phases difference and it is necessary to correct it using equation (4), especially in $\cos\Delta \approx 0$ region.

The pictures of spatial changes of measured values of cosΔ is better illustrated on figure 4. To compare the suitable light intensity changes of two images can also be seen from figure 2. The maximums of intensity on the left photo corresponds to minimums on the right. Insignificant intensity oscillations (especially in the central part) are not visible in calculated dependencies of cosΔ versus co-ordinate x. According to (4), the difference between minimum and maximum measured $\cos\Delta_{meas}$, ought to be equal 0.592 in $\cos\Delta \approx 0$ region. For the central part of the dependence on figure 4 ($y = 4$ mm) this difference is equal approximately 0.5. So, we can speak about satisfactory corelation between in theory predictable and measured phase difference.

It is obvious that such the thickness changes can be accounted when supposing the value birefringence to be constant and detect only small spatial variations of the latter. In the crystal under the test $\Delta n \approx 0.1$, so that one should determine cosΔ with the accuracy of 10^{-5}, that being of the order of the resolution characteristic for our apparatus.

A spatial modulation of the phase retardation, which takes place in the parallel light, may restrict the application of crystalline phase plates with a variable thickness. The period of the spatial modulation is less than 0.5 mm (see figure 4) may remain unnoticed using single-ray schemes.

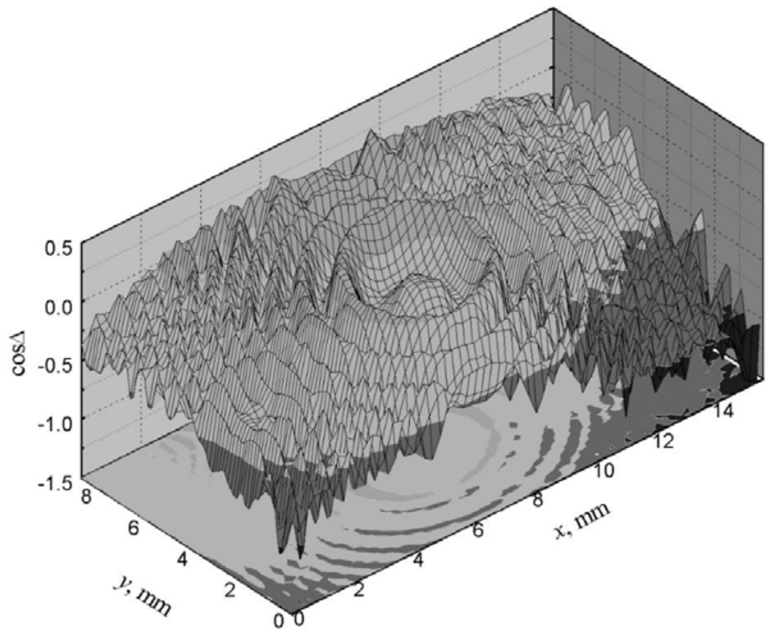

Fig. 3. Spatial distribution of cosΔ, calculated for $LiNbO_3$ x-plate, selected by dashed rectangle on figure 2a, with dimensions 15.8×8.75 mm^2

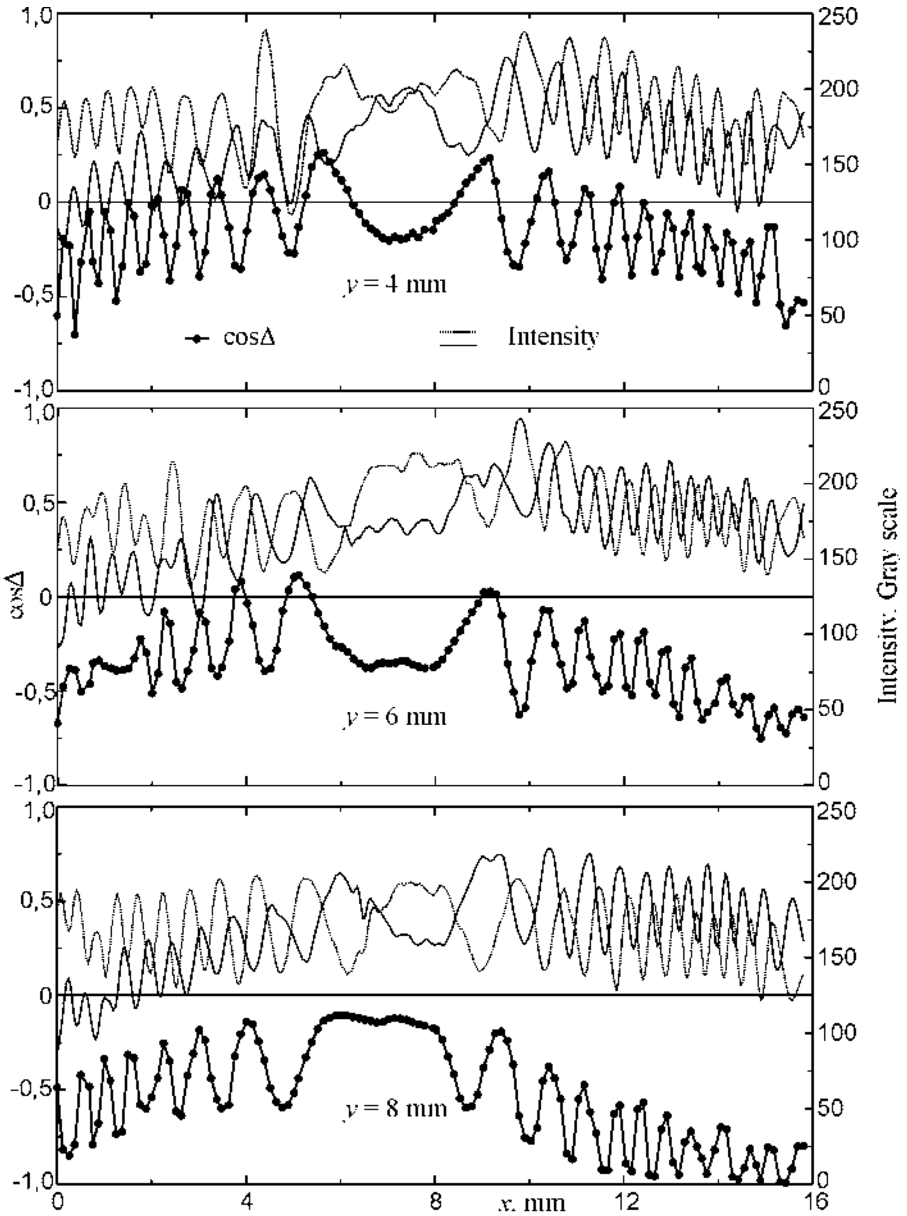

Fig. 4. Spatial changes of cosΔ (selected from figure 3) and light intensity (selected from figure 2) for *y* = 4 mm, 6 mm and 8 mm, picked out as 1,2,3 on figure 2a. Solid line – left photo, dashed line – right photo

Conclusion

The accuracy of measurements for the some optical anisotropy parameters in the single-ray polarimeters is much higher then in the imaging polarimeter. However, many applied problems exist there which put forward mainly the information of the spatial changes in those parameters. Utilizing the crystalline phase plates, which manifest a strong spatial distribution similar to that measured in this work, should turn out to be restricted, in particular in the system with the spatial light modulators. The apparatus described here enables to obtain rapidly the numerical values for the quantities under test. The latter feature in inaccessible in ordinary visual polariscopes.

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References

1. Azzam R.M.A. and Bashara N.M. Ellipsometry and polarized light. Ch.2. North-Holland Physics Publishing. Amsterdam (1988).
2. Melankholin N.M. Methods for studying the optical properties of crystals. Nauka. Moscow (1970). (in Russian)
3. Kobayashi J. and Uesu Y. J. Appl. Cryst. **16** (1983) 204–211.
4. Pezzaniti J.L., Chipman R.A. Opt. Eng. **34(6)** (1995) 1568–1573.
5. Bajor A., Galazka Z. Proceedings SPIE **3094** (1997) 147–158.
6. Krupych O.M., Vlokh R.O., Vlokh O.G. Ukr. J. Phys. Opt. **1** (2000) 35–39.
7. Nye J.F. Physical properties of crystals. Oxford University Press, Oxford (1985).
8. Vlokh O.G., Kushnir O.S. and Shopa Y.I. Acta Physica Polonica A **81** (1992) 571–578.
9. Shopa Y.I., Kravchuk M.O. Phys. stat. sol. (a), **158** (1996) 275–280.
10. Shopa Y.I., Kravchuk M.O. and Vlokh O.G. Proceedings SPIE **2648** (1995) 674–679.
11. Moxon J.R.L., Renshaw A.R. J. Rhys.: Condens. Matter, **2** (1990) 6807–6836.