Conference Paper

Laser Conoscopy Study of Optical Anomalies in Uniaxial Crystals

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Abstract

New experimental possibilities of detecting fine optical anomalies in uniaxial crystals are demonstrated on a level with numerical estimation of refractive index and mechanical stress variations that cause distortions of the optical indicatrix. New possibilities are due to the use of an exact equation for isochromes derived for uniaxial crystals without mathematical simplifications commonly used by other authors. It allows one to calculate and graphically reproduce the theoretical form of isochromes of any orders in the conoscopic picture of an ideal crystal with known principal refractive indices, the thickness and orientation of the crystal surfaces, and also the wavelength of the radiation and the parameters of the optical circuit. A computer comparison of the theoretical image with an experimental conoscopic picture of a real crystal, fixed by a color digital camera on a semitransparent screen, is performed. The data on the variations of refractive indices and mechanical stresses in the crystal are retrieved from the mathematical processing of differences in the conoscopic images. The applications of the proposed method for the analysis of optical homogeneity of paratellurite and lithium niobate single crystals are presented.

Keywords: method of conoscopy, isochromes, piezo-optic effect

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Received: 28 January 2018
Accepted: 15 March 2018
Published: 25 April 2018

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Selection and Peer-review under the responsibility of the PhIO Conference Committee.

1. INTRODUCTION

Recently [1] an exact solution of isochrome equation was derived for uniaxial crystals without simplifications employed in other studies:

$$\left(N_0^2 - N_e^2\right)\left[\frac{Y\sin\psi}{\frac{m\lambda\sqrt{X^2+Y^2+f^2}}{h} + \sqrt{N_0^2\left(X^2+Y^2+f^2\right) - X^2 - Y^2}} + \cos\psi\right]^2 =$$

$$= N_0^2\left[\frac{X^2+Y^2-N_e^2\left(X^2+Y^2+f^2\right)}{\left(\frac{m\lambda\sqrt{X^2+Y^2+f^2}}{h} + \sqrt{N_0^2\left(X^2+Y^2+f^2\right) - X^2 - Y^2}\right)^2} + 1\right], \quad (1)$$

where N_0 is the main value of ordinary refraction index, N_e is the main value of the extraordinary refraction index, ψ is the angle between the normal to the crystal surface and optical axis, *m* is the isochrome order, λ is the light wavelength in vacuum, *h* is the crystal thickness, *f* is the focus length of projection system, and *X* and *Y* are the point coordinates in the conoscopic pattern.

Successive squaring of equation (1) results in an equivalent eight-degree polynomial of two variables with fifteen coefficients of extremely cumbersome form. Therefore, it is more convenient to carry out computer analysis of the form with isochrome with the equation written in the form (1).

Furthermore relatively recently lasers of the visible range have been used in conoscopy studies as sources of conical beams of linearly polarized radiation [1-3]. In broad laser beams, the conoscopic patterns became more informative than those obtained with the aid of polarization microscopes and polariscopes, since the angles of the solutions of cones of rays decreased, which made it possible to observe isochromes in the study of large single crystals. However, the method, improved in this way, has been used to date to obtain only qualitative data. For example, in [2, 3], the presence of an anomalous biaxiality in lithium niobate crystals was established, and conclusions were drawn about the optical quality of crystals on the basis of a subjective evaluation of the correctness of the shape of isochrome. In many respects this situation was explained by the state of the theory of the method of the conoscopy, which excluded any numerical estimates of the deviations of the isochrome form of real crystals from the theoretical one.

Obtaining the exact isochrome equation [1] opens the way for numerical analysis of optical homogeneity of crystals with the help of laser conoscopy. Analysis of the exact equation (1) showed that the relations used earlier not only do not give the correct arrangement of isochromes, but also distort their true form at a qualitative level. For example, it was believed that the isochromes of uniaxial crystals are always curves of the second order [4, 5]. In the case of the coincidence of the optical axis with the normal to the mutually parallel faces of the element from the crystal, these are circles. At the angles between them from zero to 54° there are ellipses, and with a further increase in the angle to 90°, when the optical axis and the normal are orthogonal, these are hyperbolas. In fact, only when the axis coincides with the normal isochromes – this is really a curve of the second order – a circle. With mutual orthogonality, the axes and the normals are fourth-order curves resembling hyperbolas. In arbitrary cases, the isochromes of uniaxial crystals are 8th-order curves having a rather complex shape. The isochrome pattern always has a plane of symmetry, the intersection of which with the image plane is the line projection of the optical axis of the crystal. Thus, equation (1) allowed us to analyze conoscopic figures not only in special cases, but also for arbitrary orientation of the crystal elements.

The goals of this work were to identify optical anomalies in uniaxial single crystals by laser conoscopy, as well as a numerical estimation of the factors causing the anomalies.

2. MATERIALS AND METHODS

The objects of investigation in the present study were large crystals of paratellurite and lithium niobate, grown from a melt by the Czochralski method. Optical elements were cut from the crystals having faces coinciding with the crystallographic planes (001) and (110).

The optical scheme for observation of conoscopic figures is shown in Fig. 1.

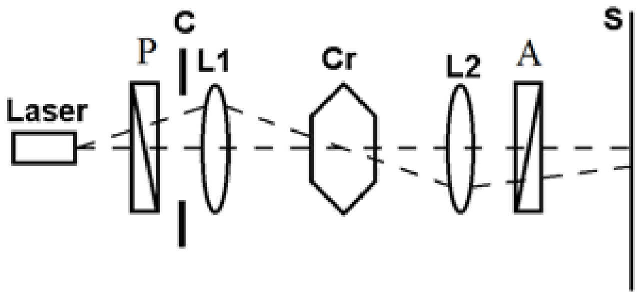

Figure 1: Optical system for laser-assisted observation of conoscopy figures.

The laser beam of linearly polarized light, expanded by a collimator C, is converted into a conical laser beam with the help of the lens L1, passes through the crystal Cr and is focused by the lens L2 with an analyzer A behind it thus forming a conoscopic picture on the semitransparent screen S fixed by a color digital camera.

An image of an isochrome of a real crystal is introduced into a computer program that compares it with an image of isochrom calculated theoretically for an ideal crystal. The program for calculating isochromic patterns is based on equation (1) from [1]. For obtaining conoscopic figures, we used continuous lasers with emission wavelengths of 488, 533 and 633 nm and radiation powers of 60, 200 and 30 mW, respectively.

3. RESULTS

Figure 2 shows the conoscopic picture of a lithium niobate single crystal obtained in the [001] direction.

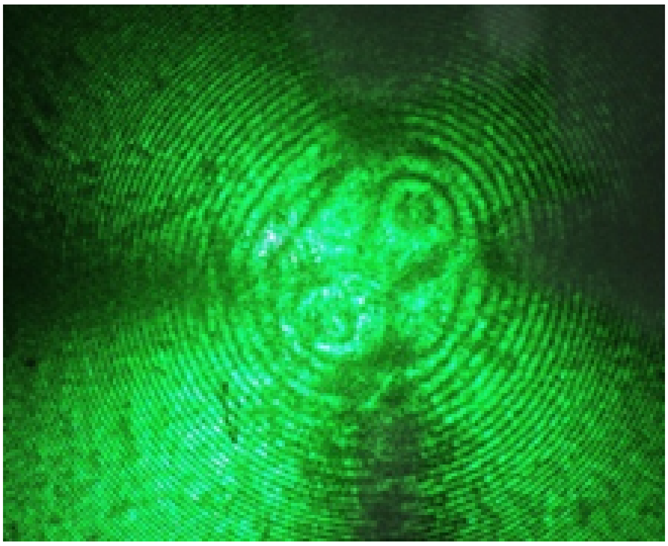

Figure 2: Conoscopic picture of a lithium niobate single crystal. Angle of anomalous biaxiality 2V = 50′.

It shows clearly the anomalous biaxiality of the crystal caused by residual mechanical stresses. From the experimentally measured angle of the anomalous biaxiality, it is easy to calculate the true angle 2V between the induced axes according to formula

$$2V = 2\arcsin\left\{\frac{\sin\left[\operatorname{arctg}\left(l/2d\right)\right]}{N_o}\right\}, \quad (2)$$

where l is the distance between the exit points of the axes on the screen, d is the distance between the output surface of the crystal and the screen. In the investigated crystal this value was 50′.

Figure 3 shows the conoscopic figure of a single crystal of paratellurite. In contrast to the theoretical prediction of regular isochrome circles clearly visible isochrome kinks are observed. The system of kinks on isochromes is elongated along the direction of the optical anomaly – the swirl. Such inhomogeneities may be occasionally observed visually on the screen in the form of a series of long. However, qualitative characterization of the crystal anomalies by this method is not possible.

The dependence of the change in the position of the second-order isochrome (m = 2) on the variations in the refractive indices in the paratellurite single crystal is shown in Fig. 4. Figure 5 shows the combination of the experimental and theoretical patterns obtained by the laser conoscopy method. A computer program based on equation (1) calculates the path differences between the points of neighboring isochromes and finds variations in the refractive indices in a real crystal. The mechanical stress σ in the

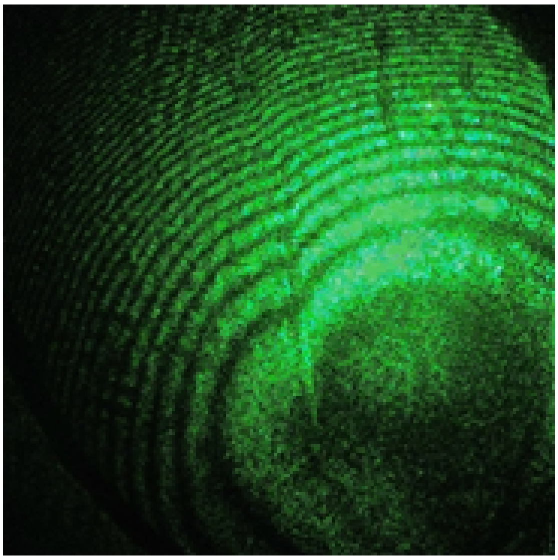

Figure 3: A series of kinks on neighboring isochromes along the optical swirl as observed on a translucent screen in the direction of the optical axis (ψ = 0).

crystal is then calculated in the region with the anomaly using the equation describing the piezo-optical effect [5]:

$$tg\ V_a = \frac{\sqrt[4]{\left[\left(\pi_{1\mu} - \pi_{2\mu}\right)\sigma_\mu\right]^2 + \left(2\pi_{6\mu}\sigma_\mu\right)^2}}{\sqrt{N_0^{-2} - N_e^{-2}}}, \quad (3)$$

where $\pi_{i\mu}$ are the piezo-optical coefficients and V_α is the half-angle value between the axes.

For the picture in Figure 3, the maximum variations in the refractive indices are 10^{-4}, and the mechanical compressive stresses in the direction orthogonal to the styli are 10 MPa.

4. DISCUSSION

Thus, optical anomalies in crystals of paratellurite and lithium niobate grown from a melt by the Czochralski method were detected and investigated using the laser conoscopy method. Among the optical inhomogeneities, local variations in the refractive indices of ordinary and extraordinary rays, swirls, anomalous biaxiality were revealed. The accuracy in determining the variations in the refractive indices is not inferior to the accuracy given by other interference methods, and is 10^{-5}. The residual mechanical stresses in crystals, caused by defects formed during growth, reach the maximum values of 10 MPa in the regions with swirls. A computer program that uses

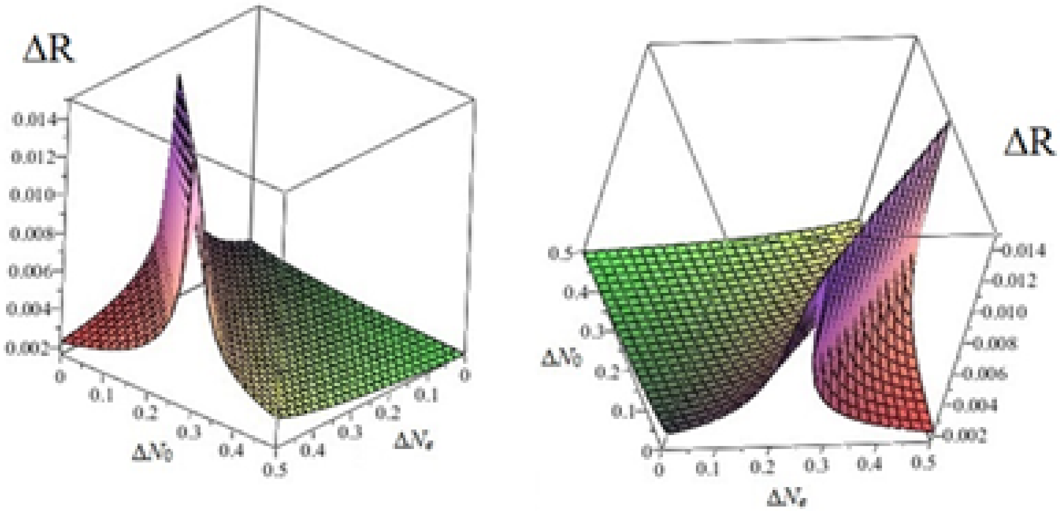

Figure 4: Dependence of the variations of ΔR position of second order isochrome of paratellurite for [001] direction on the variations in the refractive indices of the ordinary ΔN_o and extraordinary rays ΔN_e. Light wavelength λ = 533 nm.

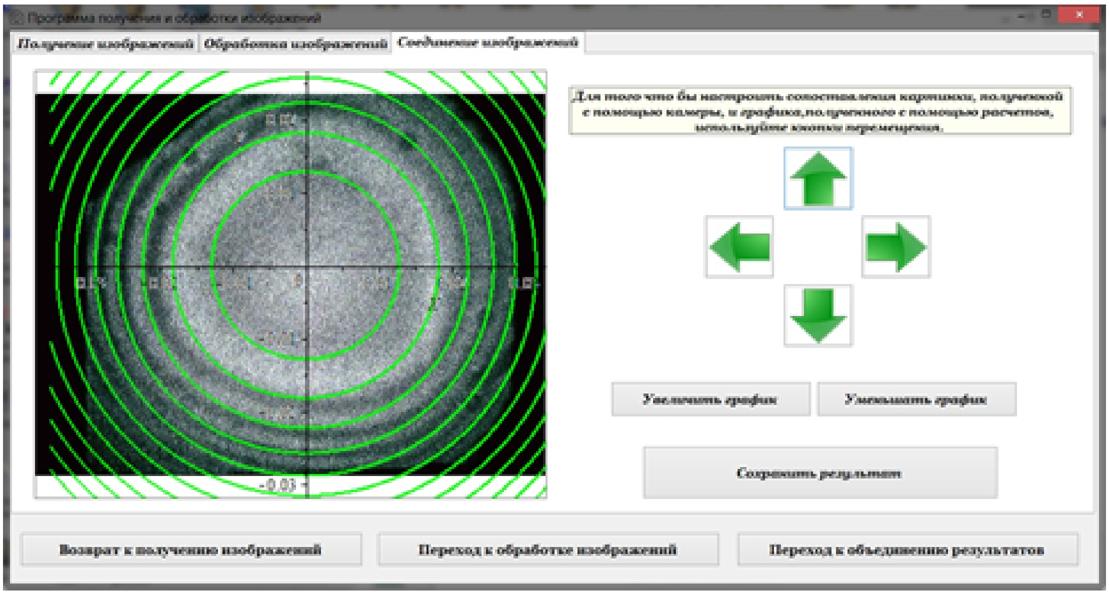

Figure 5: Computer superposition of ideal and real conoscopic patterns of a paratellurite single crystal with the aim of calculating variations in refractive indices and mechanical stresses in regions with optical anomalies.

the exact isochrome equation (1) allows one to quickly analyze conoscopic patterns and find the numerical characteristics of optical anomalies in large volumes of crystals.

5. CONCLUSION

The proposed and tested method for studying optical anomalies is promising in metrology of homogeneity and optical quality of crystals. It makes it possible to detect and classify optical anomalies in uniaxial crystals, as well as to calculate refractive index variations and mechanical stresses, leading to distortions in their optical indicatrix. The method can be used to establish and calculate the wedge-shaped optical elements from crystals, as well as to observe in real time the changes in the refractive indices when the crystals are heated due to the passage of powerful laser beams or ultrasound in powerful acousto-optical devices.

Information about the anomalies and their location in optical crystals is also important for the development of advanced crystal growth technologies.

The work was performed using the facilities of the Shared resource center of Tver State University within the Government task on scientific activity (3.5786.2017/8.9).

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