Polarisation singularities of optical beam propagating in imperfect quartz crystals

Vasylkiv Yu., Savaryn V., Smaga I., Skab I. and Vlokh R.

Institute of Physical Optics, 23 Dragomanov St., 79005 Lviv, Ukraine,
e-mail: vlokh@ifo.lviv.ua

Received: 02.10.2012

Abstract. We have revealed experimentally polarisation singularities in the optical beam propagating through quartz crystals along the direction of optic axis and discussed their origin. It has been supposed that the singularities are caused by a screw dislocation of crystalline structure.

Keywords: crystalline structure, dislocations, polarisation singularities, optical vortices

PACS: 42.50.Tx, 78.20.Fm, 42.50.-p, 78.20.hb, 61.50.-f, 61.72.Ff
UDC: 535.5, 548.4

Recently we have developed an accurate method for measuring piezooptic coefficients, which is based on creation of 2D spatially inhomogeneous mechanically stressed state in crystals via torsion [1–4]. Using $LiNbO_3$ and α-BaB_2O_4 crystals as examples, we have determined the coefficients π_{14} with very low relative errors not exceeding a few percent [2]. We have also demonstrated that the piezooptic coefficient π_{14} can be quite simply determined for the point symmetry groups 3m and $\bar{3}$m of a trigonal crystallographic system. These are just the groups that characterise $LiNbO_3$ and α-BaB_2O_4 crystals, respectively.

Notice that quartz crystals belonging to the point symmetry group 32 have a piezooptic tensor of the same form as that for the groups 3m and $\bar{3}$m. As a consequence, the initial goal of the present study has been determining the piezooptic coefficient π_{14} for the quartz crystals. However, we have found out that, up to the torsion moment of $M_Z = 0.15$ Nm applied around the principal *Z* axis, no optical birefringence changes are detected for the light propagating along the *Z* direction which coincides with the optic axis. Of course, this could have been caused by the fact that the piezooptic coefficient π_{14} for the quartz crystals is comparatively small (according to the data [5], it is equal to -0.11×10^{-12} m^2/N only). Nonetheless, we have revealed a following interesting phenomenon. When a wide parallel beam propagates along the optic axis of a SiO_2 crystal, which has not been subjected to torsion stresses, two polarisation singularities exist in different parts of a sample (see Fig. 1). A corresponding experimental set up and a method for measuring the optical phase difference $\Delta\Gamma$ and the angle of optical inicatrix rotation ζ_Z have been described in detail in our recent work [6]. The aim of the present work to describe and attempt to interpret the singularities mentioned above.

The singularities found by us are characterised by a zero value of a so-called residual linear optical birefringence ($\Delta n_{XY} = \Delta\Gamma\lambda / 2\pi d_Z$, with $\lambda = 632.8$ nm being the light wavelength and d_Z = 15.85 mm the sample thickness along the *Z* direction) and by the optical indicatrix rotation of

180 deg occurring when the tracing angle changes by 360 deg. Hence, these singularities reveal the topological defect strength equal to $\pm 1/2$. Notice also that the two singularities differ by their signs of optical indicatrix rotation. Namely, the indicatrix of the upper part of the sample rotates anticlockwise (the topological defect strength is equal to –1/2), whereas the clockwise rotation is peculiar for the lower part (the topological defect strength of 1/2).

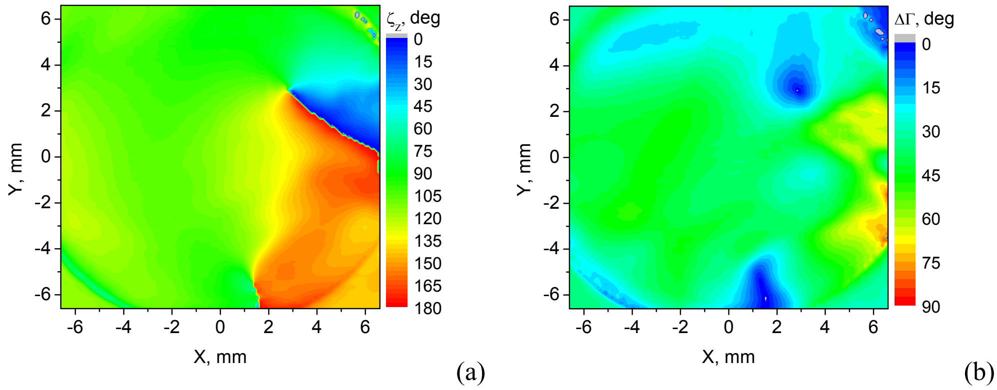

Fig. 1. Spatial maps of optical indicatrix rotation angle (a) and optical phase difference (b) measured for the SiO_2 crystals.

Now let us analyse possible origins of the appearance of polarisation singularities mentioned above. A first reason can be a residual optical birefringence induced by residual mechanical stresses. Then the crystal should become optical biaxial and the nuclei of the singularities should correspond to the outlets of optic axes. However, in our case the singularity nuclei are not characterised by a zero phase difference, otherwise the optic axes must have been inclined by some small angle with respect to the direction of beam propagation. Moreover, the directions of optical indicatrix rotations should have been the same in the case of optical biaxiality (cf., e.g., with the appearance of optical vortex at conical refraction [7]). A second possible reason can be induction of a stress field of special configuration by some ordered structural imperfections. Linear defects of crystalline structure (e.g., dislocations) can be such imperfections [8]. For example, a line of screw dislocations with the Burgers vector b parallel to [001] direction can produce the stress tensor components

$$\sigma_4 = -\frac{G_1 b}{2\pi}\frac{X}{X^2+Y^2},\ \ \sigma_5 = -\frac{G_1 b}{2\pi}\frac{Y}{X^2+Y^2},\ \ \sigma_1=\sigma_2=\sigma_3=\sigma_6=0, \qquad (1)$$

where $|b| = c/2$, c denotes the lattice parameter, $G_1 = 1/S_{44}$ the shear module, S_{44} the elastic compliance tensor component, and X and Y the coordinates.

Notice that the screw dislocations with the mentioned Burgers vector are indeed peculiar for the crystalline quartz [9]. Hence, if the screw dislocation appears in SiO_2 crystals, with the b vector parallel to the [001] direction, the relations for the increments of optical impermeability tensor components ΔB_i in XY plane may be written as

$$\Delta B_1 = \pi_{14}\sigma_4,\ \ \Delta B_2 = -\pi_{14}\sigma_4,\ \ \Delta B_6 = \pi_{14}\sigma_5\,. \qquad (2)$$

Then the equations for the optical birefringence and the angle of optical indicatrix rotation acquire the forms

$$\Delta n_{XY} = n_o^3\pi_{14}\sqrt{\sigma_4^2+\sigma_5^2} = \frac{n_o^3\pi_{14}G_1 b}{2\pi\sqrt{(X^2+Y^2)}} = \frac{n_o^3\pi_{14}G_1 b}{2\pi\rho}\ , \qquad (3)$$

$$\tan 2\zeta_Z = \frac{2B_6}{B_1 - B_2} = \frac{\sigma_5}{\sigma_4} = \frac{Y}{X} = \tan\varphi \, , \; \zeta_Z = \varphi / 2 \, , \qquad (4)$$

where n_o is the ordinary refractive index, $X = \rho\cos\varphi$ and $Y = \rho\sin\varphi$.

A comparison of experimental data with the theoretical relations testifies that the rotation of optical indicatrix around the polarisation singularity cores is well described by Eq. (4). Then the screw dislocations observed by us should be characterised with the Burgers vectors of the opposite signs. However, the experimental spatial distribution of the phase difference not too well conforms to Eq. (3). Of course, the maximum residual birefringence is not so high, being approximately equal to 7×10^{-6}. Nevertheless, this birefringence value is reached at the distance of few millimetres from a dislocation core. At the same time, the corresponding distance dealt with in the study [9] has been equal to tens of micrometers only. The latter peculiarity may be related to the fact that Eqs. (1) describing the coordinate dependence of the stress tensor component represent only a rough approximation [10]. More strictly, they have been derived exclusively on the basis of linear elasticity and so do not account for possible influences of a finite size and a nature of the dislocation core

References

1. Skab I, Smaga I, Savaryn V, Vasylkiv Yu and Vlokh R, 2011. Torsion method for measuring piezooptic coefficients. Cryst.Res.Technol. **46**: 23–36.
2. Vasylkiv Y, Savaryn V, Smaga I, Skab I and Vlokh R. 2011. On determination of sign of the piezooptic coefficients using torsion method. Appl. Opt. **50**: 2512–2518.
3. Vasylkiv Yu, Savaryn V, Smaga I, Skab I and Vokh R, 2010. Determination of piezooptic coefficient π_{14} of $LiNbO_3$ crystals under torsion loading. Ukr. J. Phys. Opt. **11**: 156–164.
4. Skab I, Vasylkiv Yu, Savaryn V and Vlokh R, 2010. Relations for optical indicatrix parameters in the conditions of crystal torsion. Ukr. J. Phys. Opt. **11** 193–240.
5. Shaskolskaya M P, Acoustic crystals. Moscow: Nauka (1982).
6. Skab I, Vasylkiv Yu, Savaryn V and Vlokh R, 2011. Optical anisotropy induced by torsion stresses in $LiNbO_3$ crystals: appearance of an optical vortex. J. Opt. Soc. Amer. A. **28**: 633–640.
7. Berry M V, Jeffrey M R and Mansuripur M, 2005. Orbital and spin angular momentum in conical diffraction. J. Opt. A: Pure & Appl. Opt. **7:** 685–690.
8. Friedel J, Dislocations. Oxford: Pergamon Press (1964).
9. Chuan zhen Ge, 1991. Birefringence images of screw dislocations viewed end-on in cubic crystals. J. Appl. Phys. **69**: 7556–7564.
10. Chuvyrov A N, Mazitov R M, Kalimgulov A R and Lebedev Yu A, 2009. The structure and properties of quartz crystals grown from fluoride solutions: Part II. The Burgers vector of the growth screw superdislocations. Crystallogr. Rep. **54**: 692–696.

Vasylkiv Yu., Savaryn V., Smaga I., Skab I. and Vlokh R., 2012. Polarisation singularities of optical beam propagating in imperfect quartz crystals. Ukr.J.Phys.Opt. **13**: 204 – 206.

Анотація. *Експериментально виявлено поляризаційні сингулярності в промені, що поширюється вздовж оптичної осі в кристалах кварцу, та обговорено природу цих сингулярностей. Припускається, що вони спричинені гвинтовими дислокаціями кристалічної структури.*