Piezooptic and acoustic properties of $KLiB_4O_7$ crystals

Mys O., Adamiv V., Martynyuk-Lototska I., Burak Ya. and Vlokh R.

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

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Abstract

This work is devoted to studies of piezooptic (PO), acoustic and acoustooptic (AO) properties of $KLiB_4O_7$ crystals. The complete matrices of PO coefficients, elastic stiffness and compliance coefficients are determined. The estimated magnitude of AO figure of merit for these crystals is found to be $M_2 = (46 \pm 16) \times 10^{-15}$ s^3/kg for the case when the slowest ultrasonic wave is dealt with.

Keywords: $KLiB_4O_7$ crystals, piezooptic and photoelastic effects, elastic properties, acoustooptic figure of merit

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Introduction

In our recent work [1] the optical properties and temperature behaviour of some components of the acoustic wave velocities for $KLiB_4O_7$ (KLTB) crystals have been studied and interpreted. It has been shown that the KLTB is optically negative, optically biaxial and optically active crystal, which exhibits transparency in a wide spectral range [2, 3]. When combining these properties with a high optical resistance [4], which is typical for the most of borates, the crystals mentioned above may in principle represent attractive material for acoustooptic (AO) operation of high-power laser beams. However, since the complete matrices of piezooptic (PO) and photoelastic tensors have not yet been determined for these crystals, their AO figure of merit could not be estimated even approximately. On the other side, while studying the optical properties of KLTB crystals, we have observed a number of imperfections inside samples, such as air bubbles and cracks. It has been shown later that numerous structural defects of the KLTB crystals are caused by high viscosity of the growth melt of KLTB that hinders mixing the melt and so leads to accumulation of impurities such as air bubbles on the crystallization front [5]. Notice also that the defects can lead to some uncertainty in the data obtained for the PO coefficients in view of non-elasticity and strain relaxation (see, e.g., [6]). Thus, the aim of the present paper is to reinvestigate PO parameters for the KLTB crystals, to measure the acoustic wave velocities, calculate the matrices of elastic stiffnesses and photoelastic coefficients and to estimate the AO figure of merit.

Experimental

KLTB crystals have been obtained with multi-graded technique of the solid-phase synthesis, which is often used for growing borate compounds. At the room temperature KLTB belongs to the acentric point symmetry group 222, with the lattice parameters $a = 8.4915$ A, $b = 11.1415$ A and $c = 12.6558$ A [7]. The directions of crystallographic axes for the KLTB crystals have been determined using the X-ray diffraction technique.

For the studies of PO properties of the KLTB crystals, a rectangular sample with facets perpendicular to crystallographic directions [110], [011] and [101] has been prepared. The PO coefficients have been determined experimentally with the aid of both interferometric Mach-Zehnder method and polarimetric Senarmont technique. After the interferometric measurements, the PO coefficients have been calculated with the relation

$$\pi_{im} = \frac{2\delta\Delta}{\sigma_m d_k n_i^3} . \quad (1)$$

The polarimetric measurements have resulted in the difference of PO coefficients calculated as

$$n_i^3 \pi_{im} - n_j^3 \pi_{jm} = \frac{2\delta(\Delta n)}{\sigma_m} . \quad (2)$$

Here $\delta(\Delta n)_{ij} = \Delta\varphi\lambda / \pi d_k$ is the change in the PO birefringence, $\Delta\varphi$ the rotation angle of light polarization plane passed through the quarter-wave plate used in the polarimetric setup, $\delta\Delta = k\lambda/2$ the change in the optical path acquired at the wavelength λ between the interferometer arms due to application of k-multiple half-wave stress σ_m, d_k the sample thickness in the direction of light propagation and n_i, n_j the refractive indices.

The acoustic wave velocities have been studied with a pulse-echo overlap method, using piezoelectric $LiNbO_3$ transducers (the resonant frequency $10\,\mathrm{MHz}$, the bandwidth $\Delta f = 0.1\,\mathrm{MHz}$ and the acoustic power $1-2\,\mathrm{W}$). The corresponding accuracy has been equal to 0.5%. The elastic stiffness tensor components have been calculated on the basis of Christoffel formula:

$$C_{ijkl} = C_{\nu\mu} = \frac{\rho v^2}{p_i m_j m_k p_l} = \frac{\rho v^2}{L_\nu L_\mu} , \quad (3)$$

$$(i, j \leftrightarrow \nu = 1,...6; k, l \leftrightarrow \mu = 1,...6),\ L_\nu = \begin{cases} p_i m_j \ (i, j \leftrightarrow \nu = 1,2,3) \\ p_i m_j + m_i p_j \ (i, j \leftrightarrow \nu = 4,5,6) \end{cases} .$$

The elastic compliance ($S_{\mu\nu}$) and photoelastic ($p_{\lambda\mu}$) tensor components are defined respectively by the relations

$$p_{\lambda\mu} = \pi_{\lambda\nu} C_{\nu\mu} , \quad (4)$$

and

$$C_{\nu\mu} S_{\mu\nu} = \delta_{\lambda\nu} , \qquad (5)$$

where C_{ijkl} denote the elastic stiffness tensor components, ρ the crystal density, p_i, p_l the Cartesian components of polarization of the acoustic wave, m_j, m_k the components of the unit wave vector of the acoustic wave and $\delta_{\lambda\nu}$ the Kronecker delta.

Results and discussion

The values of the PO coefficients $\pi_{\lambda\nu}$ obtained by the interferometric method may be presented in the form of matrix:

$$\pi_{\lambda\nu} = \begin{bmatrix} 2.7 \pm 0.8 & -(11.0 \pm 3.0) & 2.3 \pm 0.7 & 0 & 0 & 0 \\ -(3.6 \pm 1.2) & -(16.0 \pm 5.0) & -(4.13 \pm 1.6) & 0 & 0 & 0 \\ 5.0 \pm 2.0 & -(9.8 \pm 3.3) & 6.4 \pm 2.8 & 0 & 0 & 0 \\ 0 & 0 & 0 & -(20.7 \pm 6.2) & 0 & 0 \\ 0 & 0 & 0 & 0 & 3.9 \pm 1.2 & 0 \\ 0 & 0 & 0 & 0 & 0 & 7.1 \pm 2.1 \end{bmatrix} \mathrm{pm^2/N}$$

These values are in satisfactory accordance with the data presented in [1] and agree quite well with the differences of PO coefficients obtained by us with the Senarmont method:

$$\left| n_3^3 \pi_{33} - n_1^3 \pi_{13} \right| = (18.0 \pm 4.0) pm^2 / N , \left| n_1^3 \pi_{12} - n_2^3 \pi_{22} \right| = (20.0 \pm 4.0) pm^2 / N ,$$

$$\left| n_3^3 \pi_{31} - n_1^3 \pi_{11} \right| = (10.6 \pm 2.2) pm^2 / N , \left| n_1^3 \pi_{11} - n_2^3 \pi_{21} \right| = (26.0 \pm 5.2) pm^2 / N ,$$

$$\left| n_2^3 \pi_{23} - n_3^3 \pi_{33} \right| = (35.2 \pm 7.0) pm^2 / N , \left| n_2^3 \pi_{22} - n_3^3 \pi_{32} \right| = (16.6 \pm 3.3) pm^2 / N .$$

The ultrasonic velocities are collected in Table 1. It is seen that the values of those velocities are too high to expect efficient AO applications of the KLTB crystals. For

Table 1. Ultrasonic wave velocities for KLTB crystals at $T = 293\mathrm{K}$.

V_{ij}	Direction of wave propagation	Direction of wave displacement vector	Velocity, m/s
V_1	[100]	[100]	6460 ± 70
V_2	[010]	[010]	4320 ± 40
V_3	[001]	[001]	5415 ± 150
V_4	[010]	[001]	2820 ± 30
V_5	[100]	[001]	3060 ± 40
V_6	[100]	[010]	3050 ± 30
V_7	[011]	[011]	5170 ± 50
V_8	[101]	[101]	5590 ± 60
V_9	[110]	[110]	5320 ± 50

example, the lowest velocity is found to be $v_4 = 2820 \pm 30\,\text{m/s}$, i.e. approximately three times higher than that for TeO_2 crystals.

Using the ultrasonic wave velocities, the PO tensor coefficients and Eqs. (3)–(5), one can calculate the elastic stiffnesses and compliances, as well as the photoelastic tensor:

$$C_{\nu\mu} = \begin{bmatrix} 91.4 & 7.3 & 15.6 & 0 & 0 & 0 \\ 7.3 & 40.9 & 28.2 & 0 & 0 & 0 \\ 15.6 & 28.2 & 64.2 & 0 & 0 & 0 \\ 0 & 0 & 0 & 17.4 & 0 & 0 \\ 0 & 0 & 0 & 0 & 20.5 & 0 \\ 0 & 0 & 0 & 0 & 0 & 20.4 \end{bmatrix} \times 10^9\,\text{N/m}^2,$$

$$S_{\mu\nu} = \begin{bmatrix} 1.1 & -0.02 & -0.27 & 0 & 0 & 0 \\ -0.02 & 3.5 & -1.5 & 0 & 0 & 0 \\ -0.27 & -1.5 & 2.3 & 0 & 0 & 0 \\ 0 & 0 & 0 & 5.7 & 0 & 0 \\ 0 & 0 & 0 & 0 & 4.9 & 0 \\ 0 & 0 & 0 & 0 & 0 & 4.9 \end{bmatrix} \times 10^{-11}\,\text{m}^2\text{/N}.$$

The cumulative errors of determination of the elastic stiffness coefficients are as follows: C_{11} (1%), C_{22} (1%), C_{33} (3%), C_{44} (1%), C_{55} (1.5%), C_{66} (1%), C_{12} (8%), C_{13} (13%) and C_{23} (13%). However, the error associated with determination of the most of photoelastic coefficients exceeds 100%. The exceptions are the coefficients p_{44}, p_{55} and p_{66}, which can be derived with the relative error of 33%. The values of these coefficients are $p_{44} = -0.4$ and $p_{55} \approx p_{66} = 0.1$.

Basing on the results obtained above and the known theoretical relation, one can estimate the AO figure of merit:

$$M_2 = \frac{p_{ef}^2 n^6}{\rho\, v^3} = (46 \pm 16) \times 10^{-15}\ \text{s}^3/\text{kg}, \qquad (6)$$

where we have taken the parameters $v_4 = 2850 \pm 30\,\text{m/s}$, $p_{44} = -0.4$ and $\rho = 2.19 \times 10^3\,\text{kg/m}^3$. This figure is nearly of the same order of magnitude as that obtained for BBO crystals, though it is 10 times larger than that typical for LTB crystals [8,9].

Conclusion

As a result of present studies, we have experimentally obtained the matrix of PO coefficients and acoustic wave velocities for the KLTB crystals. The matrices of elastic stiffness and compliance, as well as some photoelastic coefficients have been determined on the basis of these data. The AO figure of merit has been calculated for the slowest acoustic wave.

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