
Piezo-optic Properties of α -BaB₂O₄ and LiB₄O₇ Crystals

Martunyk-Lototska I., Mys O., Dyachok Ya., Dudok T., Adamiv V, Burak Ya. and Vlokh R.

Institute of Physical Optics, 23 Dragomanov Str., 79005 Lviv, Ukraine

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Abstract

Photoelastic coefficients of α -BaB₂O₄ and LiB₄O₇ crystals are calculated on the basis of piezo-optic measurements performed with interferometric technique and the elastic compliance and stiffness data. Using the experimental results, the acousto-optic (AO) figure of merit (FM) has been estimated for the possible geometries of AO interaction. It is shown that the AO FM for the ABO and LTB crystals reach respectively the values $M_2=243.4 \times 10^{-15} \text{ s}^3/\text{kg}$ and $M_2=2.57 \times 10^{-15} \text{ s}^3/\text{kg}$, if the interaction with the slowest ultrasonic waves ($v=933.5 \text{ m/s}$ and $v=3173 \text{ m/s}$) is concerned. The directions of propagation and polarization of those acoustic waves are obtained on the basis of construction of indicative surfaces of the acoustic wave velocities.

Key words: piezo-optic effect, borate crystals, photoelastic effect

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Introduction

α -BaB₂O₄ and LiB₄O₇ crystals belong to borate crystal family and are described respectively with the point symmetry groups 3m and 4mm. Acentric borate crystals are widely used as nonlinear optical materials due to high values of their nonlinear susceptibilities [1,2] and a high level of optical damage threshold [3]. In our previous papers [4,5] we have reported that, for example, β -BaB₂O₄ is characterized with quite low transverse acoustic wave velocities and could be therefore used as a promising acousto-optic (AO) material. The value of AO figure of merit (abbreviated hereafter as AOFM) for β -BaB₂O₄ crystals [5] calculated on the basis of photoelastic coefficients, refractive indices and the ultrasonic wave velocities is comparable with those typical for the well-known AO materials such as lithium niobate or Pb₂MoO₅ [6]. However, the growing process for β -BaB₂O₄ crystals is time-consuming, when compare to

α -BaB₂O₄ and LiB₄O₇. On the other side, the photoelastic parameters that affect the AOFM of α -BaB₂O₄ and LiB₄O₇ crystals are still unknown (to our knowledge, only p_{66} coefficient has been determined for LiB₄O₇ crystals [7]). This is why we report below the results of studies of piezo-optic effect in these crystals, together with the estimation of AOFM.

Experimental results

α -BaB₂O₄ and LiB₄O₇ crystals were grown with the Czochralski method. Single crystals of a good optical quality with $3 \times 3 \times 3 \text{ cm}^3$ dimensions were obtained after a one-week growing process. Their piezo-optic coefficients were measured at room temperature with interferometric technique using the Mach-Zender interferometer ($\lambda=632.8 \text{ nm}$). For avoiding ambiguity in the presentation of results, the elastic contribution was derived with the aid of the relationship $\delta(\Delta n d)_{ij} = \pi_{ijkl} \sigma_{kl} - (n_c - 1) S_{ijkl} \sigma_{kl}$. The ultrasonic

wave velocities were measured at room temperature with the pulse-echo overlap method [8]. The accuracy for the absolute velocity values was about 0.5%. The acoustic waves in samples were excited with LiNbO₃ transducers characterized with the resonance frequency of $f = 10$ MHz, the bandwidth of $\Delta f = 0.1$ MHz and the acoustic power from $P_a = 1$

to 2W. The photoelastic coefficients were calculated on the basis of elastic stiffness data obtained earlier [9], using the known formula $p_{\lambda\mu} = \pi_{\lambda\nu} C_{\nu\mu}$.

The results for the piezooptic coefficients of LiB₄O₇ crystals are presented below in the form of matrix:

$$\pi_{\lambda\nu} = \begin{pmatrix} \pi_{11} & \pi_{12} & \pi_{13} & 0 & 0 & 0 \\ \pi_{12} & \pi_{11} & \pi_{13} & 0 & 0 & 0 \\ \pi_{31} & \pi_{31} & \pi_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & \pi_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & \pi_{44} & 0 \\ 0 & 0 & 0 & 0 & 0 & \pi_{66} \end{pmatrix} = \begin{pmatrix} -2.75 & -0.45 & 1.08 & 0 & 0 & 0 \\ -0.45 & -3.52 & 1.08 & 0 & 0 & 0 \\ -2.53 & -2.53 & 2.9 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1.1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1.1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1.05 \end{pmatrix} \times 10^{-12} m^2 / N$$

while for α -BaB₂O₄ we have

$$\pi_{\lambda\nu} = \begin{pmatrix} \pi_{11} & \pi_{12} & \pi_{13} & \pi_{14} & 0 & 0 \\ \pi_{12} & \pi_{11} & \pi_{13} & -\pi_{14} & 0 & 0 \\ \pi_{31} & \pi_{31} & \pi_{33} & 0 & 0 & 0 \\ \pi_{41} & \pi_{41} & 0 & \pi_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & \pi_{44} & 2\pi_{41} \\ 0 & 0 & 0 & 0 & \pi_{14} & \pi_{66} \end{pmatrix} = \begin{pmatrix} 1.58 & 2.08 & -4.32 & -14.22 & 0 & 0 \\ 2.08 & 1.58 & -4.32 & 14.22 & 0 & 0 \\ 1.52 & 1.52 & -7.24 & 0 & 0 & 0 \\ 2.85 & 2.85 & 0 & -24.58 & 0 & 0 \\ 0 & 0 & 0 & 0 & -24.58 & 5.7 \\ 0 & 0 & 0 & 0 & -14.22 & 0.5 \end{pmatrix} \times 10^{-12} m^2 / N$$

The calculated values of photoelastic coefficients for LiB₄O₇ crystals are as follows:

$$p_{\lambda\mu} = \begin{pmatrix} p_{11} & p_{12} & p_{13} & 0 & 0 & 0 \\ p_{12} & p_{11} & p_{13} & 0 & 0 & 0 \\ p_{31} & p_{31} & p_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & p_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & p_{44} & 0 \\ 0 & 0 & 0 & 0 & 0 & p_{66} \end{pmatrix} = \begin{pmatrix} -0.32 & -0.04 & -0.06 & 0 & 0 & 0 \\ -0.04 & -0.32 & -0.06 & 0 & 0 & 0 \\ -0.24 & -0.24 & -0.02 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.05 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.05 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.06 \end{pmatrix}$$

The same values for α -BaB₂O₄ crystals may be written as

$$p_{\lambda\mu} = \begin{pmatrix} p_{11} & p_{12} & p_{13} & p_{14} & 0 & 0 \\ p_{12} & p_{11} & p_{13} & -p_{14} & 0 & 0 \\ p_{31} & p_{31} & p_{33} & 0 & 0 & 0 \\ p_{41} & -p_{41} & 0 & p_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & p_{44} & p_{41} \\ 0 & 0 & 0 & 0 & p_{14} & p_{66} \end{pmatrix} = \begin{pmatrix} 0.03 & 0.16 & 0.14 & 0.06 & 0 & 0 \\ 0.16 & 0.03 & 0.14 & -0.06 & 0 & 0 \\ -0.15 & -0.15 & -0.16 & 0 & 0 & 0 \\ -0.05 & 0.05 & 0 & -0.1 & 0 & 0 \\ 0 & 0 & 0 & 0 & -0.1 & -0.05 \\ 0 & 0 & 0 & 0 & 0.06 & -0.07 \end{pmatrix}$$

Discussion

Basing upon the photoelastic coefficients determined above, together with the ultrasonic velocities, crystal density and the refractive indices, one can estimate the AOFM for different geometries of AO interaction, under the circumstances that the incident light and the

acoustic wave propagate along the principal axes of optical indicatrix (see Table 1a,b).

It is interesting to note that the Bragg conditions can be satisfied only in a few cases of anisotropic AO interaction. The maximum value of AOFM ($M_2 = 32.971 \times 10^{-15} s^3/kg$) refers to the ABO crystals and corresponds to the case of

Table 1a. AO parameters of the LTB crystals ($\rho=2420\text{kg/m}^3$, $n_o=1.6084$ and $n_e=1.5516$).

Acoustic wave		p	$ p_{\text{eff}} $	n	Light		$M_2, 10^{-15},$ s^3/kg or possibility for matching the Bragg conditions
V, m/s	Propagation direction, Polarization				Direction	Polarization	
7358	[100], [100]	p_{11}	0.32	n_e	[010]	[100]	not
		p_{31}	0.24	n_o		[001]	not
		p_{11}	0.32	n_o	[001]	[100]	not
		p_{12}	0.04	n_o		[010]	not
7460	[010], [010]	p_{11}	0.32	n_e	[100]	[010]	not
		p_{31}	0.24	n_o		[001]	not
		p_{12}	0.04	n_o	[001]	[100]	not
		p_{11}	0.32	n_o		[010]	not
5036	[001], [001]	p_{13}	0.06	n_e	[100]	[010]	not
		p_{33}	0.02	n_o		[001]	not
		p_{13}	0.06	n_e	[010]	[100]	not
		p_{33}	0.02	n_o		[001]	not
4448	[100], [010]	p_{66}	0.06	n_o	[001]	[100], [010]	not
4769	[100], [001]	p_{44}	0.05	n_e	[010]	[100], [001]	0.134
4610	[010], [001]	p_{44}	0.05	n_e	[100]	[010], [001]	0.149

interaction with the slowest acoustic wave having the direction of propagation [100] and that of polarization [001] (see Figure 1).

On the other hand, it follows from the calculated indicative surfaces of ultrasonic velocities that the minimum value of

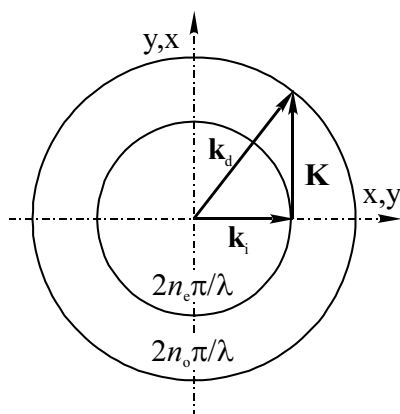


Fig. 1. Diagram of AO interaction in the ABO crystals for the case of propagation of acoustic wave and the incident optical wave along one of the principal axis of optical indicatrix (in this particular case the value $M_2=32.971 \times 10^{-15} \text{s}^3/\text{kg}$ can be achieved).

$v=933.5\text{m/s}$ for the ABO crystals corresponds to the acoustic wave with the k -vector lying in (011) plane and making the angle 18° with respect to z axis and the projections of the unit displacement vector $X_z=0.457$, $X_y=-0.899$ and $X_x=0$ (see Figure 2a). The LTB crystals exhibit the two such directions of propagation for the slowest waves, with the same velocities ($v=3173\text{m/s}$), i.e. we have the cases:

- 1) k -vector lies in (011) plane at the angle of 39° with respect to z axis; the projections of the unit displacement vector are $X_z=0.794$, $X_y=-0.606$ and $X_x=0$ (Figure 2b);
- 2) k -vector lies in (101) plane at the angle of 54° with respect to z axis; the projections of the unit displacement vector are $X_z=0.79$, $X_y=0$ and $X_x=-0.61$ (Figure 2b).

Let us evaluate the AOFM for the both cases mentioned above. For this aim one should derive the expression for the effective photoelastic coefficient p_{eff} . Let us, for instance, consider the ABO crystals and the incident

Table 1b. AO parameters of the ABO crystals ($\rho=3747\text{kg/m}^3$, $n_o=1.667$ and $n_e=1.528$).

Acoustic wave		p	p _{eff}	n	Light		M ₂ , 10 ⁻¹⁵ s ³ /kg or possibility for matching the Bragg conditions
V, m/s	Propagation direction, Polarization				Direction	Polarization	
5649	[100], [100]	p ₁₁	0.03	n _e	[010]	[100]	not
		p ₃₁	0.15	n _o		[001]	not
		p ₂₁	0.16	n _o	[001]	[010]	not
		p ₁₁	0.03	n _o		[100]	not
5437	[010], [010]	p ₁₁	0.03	n _e	[100]	[010]	not
		p ₄₂ =-p ₄₁	0.05	n _o		[001], [010]	0.075
		p ₃₁	0.15	n _o		[001]	not
		p ₄₂ =-p ₄₁	0.05	n _e		[010], [001]	0.045
		p ₁₂	0.16	n _o	[001]	[100]	not
		p ₂₂ =p ₁₁	0.03	n _o		[010]	not
3221	[001], [001]	p ₂₃ =p ₁₃	0.14	n _e	[100]	[010]	not
		p ₃₃	0.16	n _o		[001]	not
		p ₁₃	0.14	n _e	[010]	[100]	not
		p ₃₃	0.16	n _o		[001]	not
2959	[100], [010]	p ₅₆ =p ₄₁	0.05	n _o	[010]	[001], [100]	0.468
		p ₄₁ =p ₅₆	0.05	n _e		[100], [001]	0.277
		p ₆₆	0.07	n _o	[001]	[010], [100]	not
		p ₆₆	0.07	n _o		[100], [010]	not
1186	[100], [001]	p ₅₅ =p ₄₄	0.1	n _o	[010]	[001], [100]	32.971
		p ₅₅ =p ₄₄	0.1	n _e		[100], [001]	19.555
		p ₆₅ =p ₁₄	0.06	n _o	[001]	[010], [100]	not
		p ₆₅ =p ₁₄	0.06	n _o		[100], [010]	not
1230	[010], [001]	p ₂₄ =-p ₁₄	0.06	n _e	[100]	[010]	not
		p ₄₄	0.1	n _o		[001], [010]	29.557
		p ₄₄	0.1	n _e		[010], [001]	17.530
		p ₁₄	0.06	n _o	[001]	[100]	not
		p ₂₄ =-p ₁₄	0.06	n _o		[010]	not
2942	[010], [100]	p ₆₆	0.07	n _o	[001]	[010], [100]	not
		p ₆₆	0.07	n _o		[100], [010]	not

optical wave propagated along the [010] direction with E_3 polarization. The acoustic wave (according to the Bragg condition, the acoustic frequency should be equal to $f_a=3 \times 10^9 \text{Hz}$) is propagated in the (011) plane at the angle of 18° with respect to z axis and the projections of the unit displacement vector are as follows: $X_z=0.457$, $X_y=-0.899$ and $X_x=0$. Then the optical indicatrix equation may be written as

$$\begin{aligned}
 & (B_1 + p_{12}e_2 + p_{13}e_3 + p_{14}e_4)x^2 + \\
 & + (B_1 + p_{11}e_2 + p_{13}e_3 - p_{14}e_4)y^2 + \\
 & (B_3 + p_{31}e_2 + p_{33}e_3)z^2 + \\
 & + 2(p_{44}e_4 - p_{41}e_2)yz = 1
 \end{aligned} \quad (1)$$

where B_i are the optical impermeability constants and e_j the strains induced by the acoustic wave. After rewriting Eq. (1) in the proper coordinate system of crystal, we obtain

$$\begin{aligned}
& (B_1 + p_{12}e_2 + p_{13}e_3 + p_{14}e_4)X^2 + \\
& (B_1 + p_{11}e_2 + p_{13}e_3 - p_{14}e_4 + \frac{(p_{44}e_4 - p_{41}e_2)^2}{(B_1 - B_3 + (p_{11} - p_{31})e_2 + (p_{13} - p_{33})e_3 - p_{14}e_4)})Y^2 + \\
& (B_3 + p_{31}e_2 + p_{13}e_3 - \frac{(p_{44}e_4 - p_{41}e_2)^2}{(B_1 - B_3 + (p_{11} - p_{31})e_2 + (p_{13} - p_{33})e_3 - p_{14}e_4)})Z^2 = 1
\end{aligned} \quad (2)$$

The change in the refractive index n_3 is given by

$$\Delta n_3 = \frac{1}{2} n_3^3 \left\{ p_{31}e_2 + p_{13}e_3 - \frac{(p_{44}e_4 - p_{41}e_2)^2}{\left(\frac{1}{n_1^2} - \frac{1}{n_3^2} + (p_{11} - p_{31})e_2 + (p_{13} - p_{33})e_3 - p_{14}e_4\right)} \right\}, \quad (3)$$

as well as by the relations $\frac{1}{n_1^2} - \frac{1}{n_3^2} \gg (p_{11} - p_{31})e_2 + (p_{13} - p_{33})e_3 - p_{14}e_4$ and

$$p_{31}e_2 + p_{13}e_3 \gg \frac{(p_{44}e_4 - p_{41}e_2)^2}{2 \left[\frac{1}{n_1^2} - \frac{1}{n_3^2} + (p_{11} - p_{31})e_2 + (p_{13} - p_{33})e_3 - p_{14}e_4 \right]}.$$

Eq. (3) may be simplified to the form

$$\Delta n_3 \approx 0.5 \times n_3^3 \{ p_{31}e_2 + p_{13}e_3 \}. \quad (4)$$

After considering the orientation of the displacement vector of acoustic wave, Eq.(4) becomes

$$\Delta n_3 \approx 0.5 \times n_3^3 \{ -0.899p_{31} + 0.457p_{13} \} e. \quad (5)$$

Taking the values $p_{31}=-0.15$, $p_{13}=0.14$ and the relation $p_{ef} = \{ -0.899p_{31} + 0.457p_{13} \}$ into account, one can arrive at $p_{eff}=0.19$ and $M_2=150.32 \times 10^{-15} \text{ s}^3/\text{kg}$. It can be seen that in case of the ultrasonic velocity achieving its lowest value (933.5m/s; to be compared with the value 1186m/s), the AOFM would increase drastically up to $150.32 \times 10^{-15} \text{ s}^3/\text{kg}$ (cf. with the previous value $32.971 \times 10^{-15} \text{ s}^3/\text{kg}$). If we change the direction of the incident optical beam from the angle $\alpha=18^\circ$ to $\alpha=180^\circ$ with respect to the z axis (see Figure 3a) and change additionally the frequency of the acoustic wave from $f_a=135 \times 10^6 \text{ Hz}$ (the collinear diffraction) to $f_a=29 \times 10^9 \text{ Hz}$, the AOFM would also change

from $M_2=240.7 \times 10^{-15} \text{ s}^3/\text{kg}$ through the value $M_2=150.32 \times 10^{-15} \text{ s}^3/\text{kg}$ (for k_i parallel to the y axis) up to $M_2=243.4 \times 10^{-15} \text{ s}^3/\text{kg}$. This effect is only owing to anisotropy of the refractive index n_e .

Let us now analyze the case of LTB crystals. When the incident optical wave is propagated along the [010] direction with E_3 polarization, while the acoustic wave (according to the Bragg condition, the acoustic frequency should be equal to $f_a=2.8 \times 10^9 \text{ Hz}$) is propagated in the (011) plane at the angle of 39° with respect to the z axis (the relevant projections of the unit displacement vectors being $X_z=0.794$, $X_y=-0.606$ and $X_x=0$), the optical indicatrix equation may be written as

$$\begin{aligned}
& (B_1 + p_{12}e_2 + p_{13}e_3)x^2 + \\
& + (B_1 + p_{11}e_2 + p_{13}e_3)y^2 + \\
& (B_3 + p_{31}e_2 + p_{33}e_3)z^2 + 2p_{44}e_4yz = 1
\end{aligned} \quad (6)$$

Rewriting Eq. (6) in the proper coordinate system of the crystal, we get

$$\begin{aligned}
& [B_1 + p_{12}e_2 + p_{13}e_3]X^2 + \left[B_1 + p_{11}e_2 + p_{13}e_3 + \frac{(p_{44}e_4)^2}{(B_1 - B_3 + (p_{11} - p_{31})e_2 + (p_{13} - p_{33})e_3)} \right]Y^2 + \\
& \left[B_3 + p_{31}e_2 + p_{13}e_3 - \frac{(p_{44}e_4)^2}{(B_1 - B_3 + (p_{11} - p_{31})e_2 + (p_{13} - p_{33})e_3)} \right]Z^2 = 1
\end{aligned} \quad (7)$$

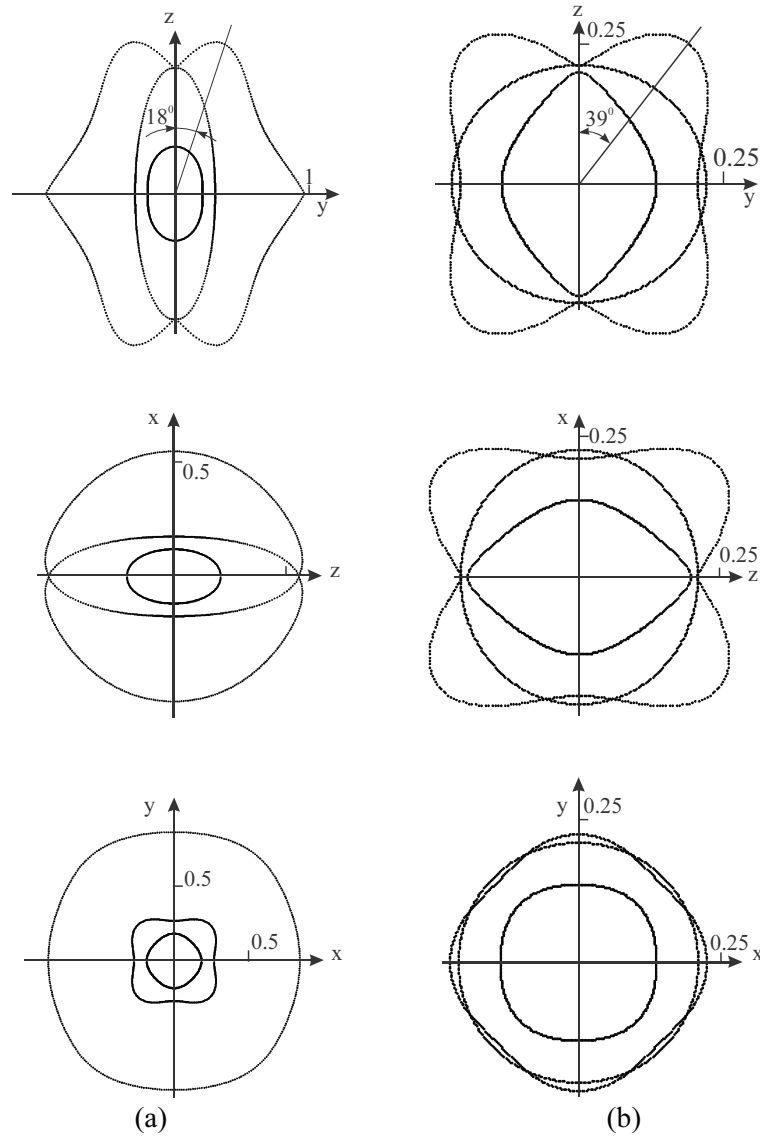


Fig. 2. Indicative surfaces of acoustic wave velocities in the ABO (a) and LTB (b) crystals.

Then the change in the refractive index n_3 reduces to

$$\Delta n_3 \approx \frac{1}{2} n_3^3 \{ p_{31} e_2 + p_{13} e_3 \}. \quad (8)$$

With accounting for the orientation of the displacement vector of acoustic wave, Eq. (8) yields in

$$\Delta n_3 \approx \frac{1}{2} n_3^3 \{ -0.606 p_{31} + 0.794 p_{13} \} e. \quad (9)$$

Since $p_{ef} = \{ -0.606 p_{31} + 0.794 p_{13} \}$ and $p_{31} = -0.24$, $p_{13} = -0.06$, we obtain $p_{ef} = 0.1$ and $M_2 = 2.07 \times 10^{-15} \text{ s}^3/\text{kg}$. If the ultrasonic velocity achieve its lowest value (3173m/s, not

4610m/s), the AOFM would increase by more than order of magnitude ($2.07 \times 10^{-15} \text{ s}^3/\text{kg}$; to be compared with the previous value $0.149 \times 10^{-15} \text{ s}^3/\text{kg}$). Again, in case of changing direction of the incident optical beam from the angle $\alpha = 39^\circ$ to $\alpha = 180^\circ$ with respect to the z axis (see Figure 3b), as well as simultaneously changing the frequency of the acoustic wave from $f_a = 732 \times 10^6 \text{ Hz}$ (the collinear diffraction) to $f_a = 77.7 \times 10^9 \text{ Hz}$, the AOFM would evolve from $M_2 = 2.35 \times 10^{-15} \text{ s}^3/\text{kg}$ through $M_2 = 2.07 \times 10^{-15} \text{ s}^3/\text{kg}$ (for k_i parallel to the y axis) up to $M_2 = 2.57 \times 10^{-15} \text{ s}^3/\text{kg}$. Quite similar to the ABO crystals, this is owing to anisotropy of n_e .

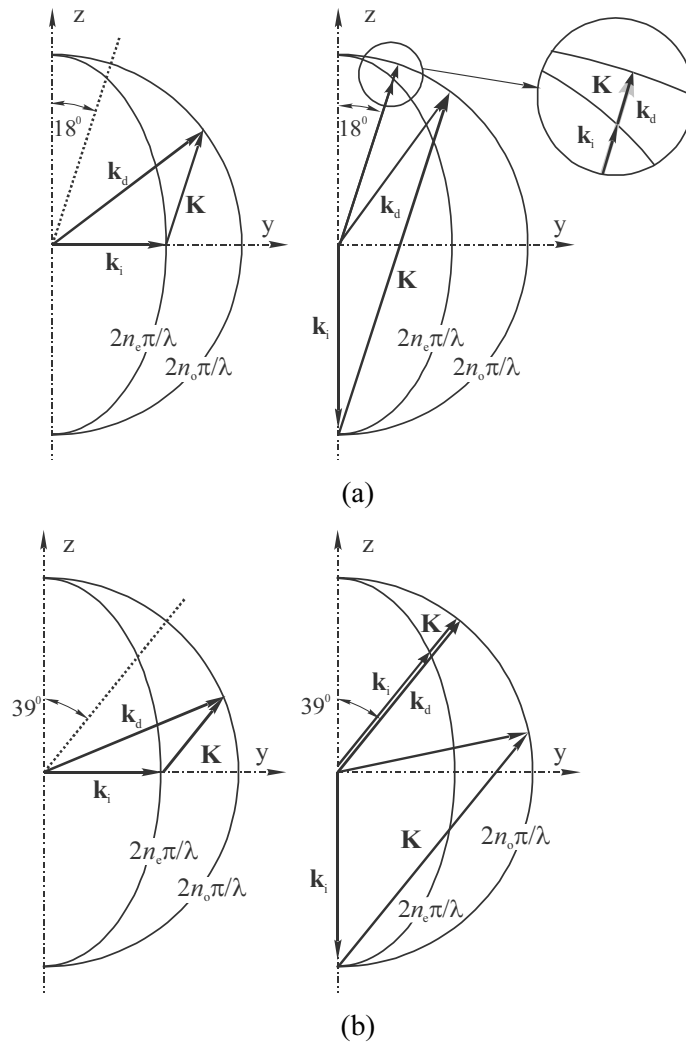


Fig. 3. Diagram of AO interaction with the slowest acoustic waves in the ABO (a) and LTB (b) crystals.

The same value of the AOFM may be obtained when considering the second case of AO interaction in the LTB crystals. However, it is quite possible that the orientation of the acoustic wave vector intermediate between (011) and (101) planes could provide a less value of the ultrasonic wave velocity, when compare with the mentioned planes.

Conclusion

In conclusion, one can notice that the ABO and LTB borate crystals manifest a high AOFM. The value $M_2=243.4 \times 10^{-15} \text{ s}^3/\text{kg}$ for the ABO crystals is comparable, in the order of magnitude, with those typical for good AO materials such as TeO₂, for example. It is evident from the presented results that the most important

criterion for the choice of crystals with a high value of AO parameter M_2 is the velocity of the acoustic wave. Moreover, we have shown that the propagation direction of the slowest acoustic wave does not necessarily coincide with the principal axes of the optical indicatrix ellipsoid. While changing the propagation direction of the acoustic wave (e.g., in the xy -plane), we have to take changing orientation of the displacement vector into consideration, the latter leading to the corresponding changes in the p_{eff} parameter.

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References

1. Cheng W.-D., Huang J.-S., Lu J.-X. *Phys. Rev. B.* **57** (1998) 1527.
2. Whatmore R.W., Shorrocks N.H., O'Hara C., Alinger F.W. *Electron. Lett.* **17** (1981) 11.
3. Vlokh R., Dyachok Ya., Krupych O., Burak Ya., Martynyuk-Lototska., Andrushchak A., Adamiv V. *Ukr. J. Phys. Opt.* **4** (2003) 101.
4. Andrushchak A.S., Adamiv V.T., Krupych O.M., Martynyuk-Lototska I.Yu., Burak Ya.V., Vlokh R.O. *Ferroel.* **238** (2000) 299.
5. Adamiv V., Burak Ya., Martynyuk-Lototska I., Vlokh R., Vlokh O., Dudok T. Patent of Ukraine, 08.05.2002, N53370A.
6. Shaskolskaya M.P. *Acoustic crystals* (Moscow, Nauka) 1982 632p (in Russian).
7. Martynyuk-Lototska I., Mys O., Adamiv V., Burak Ya., Vlokh R. *Ukr. J. Phys. Opt.* **3** (2002) 267.
8. Papadakis E.P. *J. Acoust. Soc. Amer.* **42** (1967) 1045.
9. Martynyuk-Lototska I., Mys O., Krupych O., Adamiv V., Burak Ya., Vlokh R., Schranz W. *Ferroelectrics*. (at press).