Obliquity of the acoustic energy flow in acoustooptic $\alpha - BaB_2O_4$ and $Li_2B_4O_7$ crystals

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Abstract

The obliquity effects for the acoustic energy flow are quantitatively analysed for both transverse and longitudinal acoustic waves that propagate in [011] plane of $\alpha - BaB_2O_4$ and $Li_2B_4O_7$ crystals. It is shown that for the slowest transverse acoustic wave the obliquity angle is equal to zero and thus the effect cannot have action on the efficiency of acoustooptic interaction.

Keywords: acoustooptic interaction, $\alpha - BaB_2O_4$, $Li_2B_4O_7$ crystals, acoustic waves, phase velocity, acoustic energy flow.

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Introduction

Crystals of $\alpha - BaB_2O_4$ (abbreviated hereafter as ABO) and $Li_2B_4O_7$ (LTB) are described respectively by the point symmetry groups $\bar{3}m$ and $4mm$ and belong to the family of borate crystals. These materials manifest a wide range of optical transparency (200–3000 nm for ABO and 200–6000 nm for LTB), high optical damage threshold, sufficient mechanical hardness and low hygroscopicity [1-4], which make them attractive for numerous applications in optoelectronics. Moreover, the LTB crystals are also known as an efficient material for the optical frequency multiplication, in particular for the deep UV region [5–6].

In our previous works [7–9] it has been shown that the ABO and LTB crystals can also be used as materials for acoustooptic applications. For example, the acoustooptic figure of merit (AOFM) of the ABO and LTB, for the case of acoustic wave propagating along the principal crystallographic directions, reaches respectively the values $M_2 = (54.5 \pm 7.4) \times 10^{-15}$ s^3/kg and $M_2 = 0.2 \times 10^{-15}$ s^3/kg (at $\lambda = 632.8$ nm and $T = 293$ K).

It is necessary to note that the AOFM values cited above are not the highest possible. Still higher AOFM for the ABO and LTB crystals could be reached for the slowest transverse acoustic wave propagating in the [011] plane. However, obliquity of the acoustic energy flow with respect to the wave normal can appear for this wave, which can lead to decrease in the efficiency of acoustooptic interaction. Let us remind in this respect that the acoustic obliquity effects for the energy flow are higher than their optical analogues. For example, the acoustic obliquity angle for TeO_2 crystals reaches $35°$ [10]. If the acoustic obliquity is too high, efficient acoustooptic interactions could become impossible. Therefore it is necessary to take into account the exact direction of the acoustic energy flow when designing acoustooptic devices. However, the corresponding data for the borate crystals have not yet been determined. Thus, the aim of the present paper is to study the obliquity effects for the acoustic energy in the ABO and LTB crystals.

Result and Discussions

Propagation of plane acoustic waves in crystals can be described with the well-known Christoffel equation [11],

$$C_{ijkl} m_j m_k p_l = \rho v^2 p_i , \tag{1}$$

where C_{ijkl} denote the components of elastic stiffness tensor, m the components of unit vector of the wave normal, p_i, p_l the components of unit vector of the displacement, ρ the density of material and v the phase velocity. The phase velocities are given by eigen values of Eq. (1). For each v value there is a solution, for which the p_l component could be determined as an eigen vector of Eq. (1). It follows from Eq. (1) that three acoustic waves can propagate along a given direction, with mutually orthogonal displacement vectors.

In a general case of acoustically dispersive and anisotropic media, the values of the phase and group velocities are different and, moreover, an obliquity of the acoustic energy flow direction with respect to the wave normal direction takes place. The components of the group-velocity vector W_j can be determined from the transformed Christoffel equation [11],

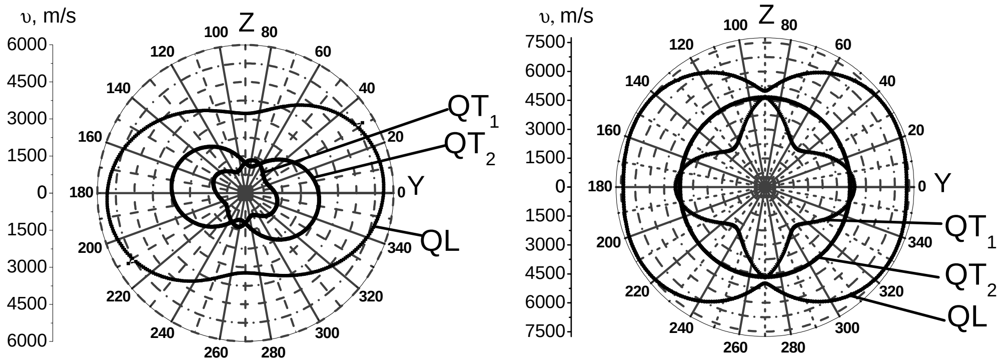
$$W_j = \frac{1}{\rho v} C_{ijkl} p_i p_l m_k . \tag{2}$$

One can calculate the angle between the directions of the energy flow and the wave normal (i.e., the obliquity angle) basing on the relation [10,11]

$$\tan(\varphi - \psi) = \frac{1}{v(\varphi)} \frac{\partial v}{\partial \varphi}, \tag{3}$$

where φ is the angle between the crystallographic axis and the wave normal direction, ψ the angle between the crystallographic axis and the acoustic energy flow direction and $v(\varphi)$ the acoustic wave velocity for the corresponding direction of the wave propagation. The relations describing changes in the acoustic wave velocity depending on the wave propagation direction ($v(\varphi)$) may be obtained from the same Christoffel equation.

Let us consider propagation of longitudinal and transverse acoustic waves in YZ plane for the cases of ABO and LTB. The acoustic wave velocities and the coefficients of the stiffness tensor for the ABO and LTB crystals have been determined in our previews works (see [9]). The surfaces of the acoustic wave velocities for ABO and LTB are shown in Fig. 1. As seen from Fig. 1a, the lowest acoustic wave velocity (QT_1) for ABO corresponds to the transverse acoustic wave propagating along the direction lying in [011] plane and making the angle $58°$ with Z axis. For the LTB crystals the slowest transverse acoustic wave (QT_1) propagates in [011] plane along the direction that makes the angle $39°$ with the Z axis.



(a) (b)

Fig. 1. Indicative surfaces of acoustic wave velocities for ABO (a) and LTB (b) crystals (*T* = 293 K): the notations QT_1 and QT_2 correspond to quasi-transverse acoustic waves and QL to quasi-longitudinal acoustic wave.

The obliquity angles between the acoustic energy flow direction and the wave normal for both the ABO and LTB crystals have been determined for different directions of the acoustic wave propagation. The dependences of the obliquity angle for the longitudinal and transverse acoustic waves upon the acoustic wave propagation direction are presented in Fig. 2.

When the transverse acoustic wave in ABO propagates in the [011] plane along the direction that makes the angle $58°$ with the Z axes (or the angle $32°$ with the Y axis), the obliquity tends to zero. As a consequence, the efficiency of the acoustooptic interaction would be maximal for these experimental conditions (see Fig. 2a). The largest acoustic obliquity ($-70.26°$) have been obtained for the transverse acoustic wave QT_2 polarised along the X axis that propagates in the [011] plane along the direction making the angle $26°$ with the Z axis. As seen from Fig. 1a, this direction corresponds to maximal angular changes in the acoustic wave velocity. The results obtained by us are in good agreement with the theoretical predictions, according to which the highest acoustic obliquity has to take place for the directions characterised with the highest angular changes in the acoustic velocity [11]. A zero acoustic obliquity should occur if the condition $\frac{\partial v}{\partial \phi} = 0$ is fulfilled. Then the directions of the vector corresponding to the acoustic energy flow and the wave normal vector coincide. For example, in the case of QT_1 wave propagating

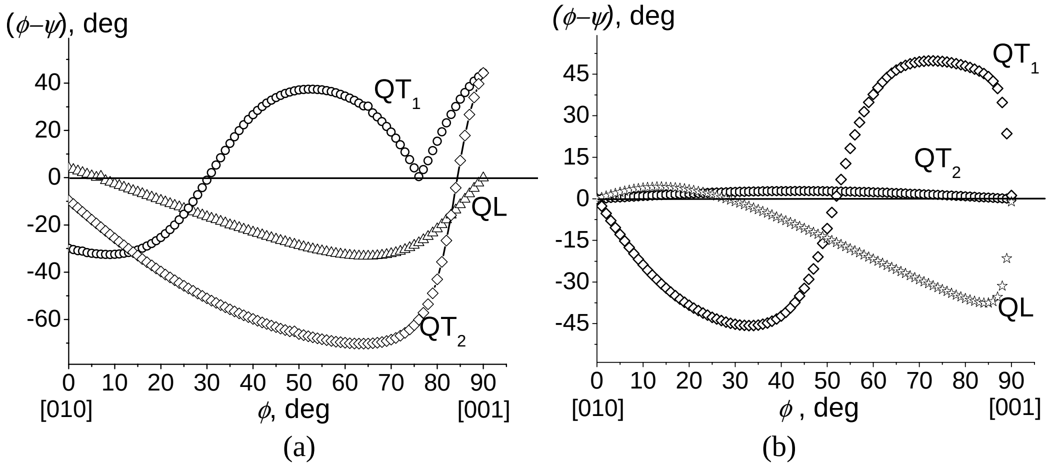


Fig. 2. Dependences of obliquity angle for the longitudinal and transverse acoustic waves upon direction of the acoustic wave propagation for the ABO (a) and LTB (b) crystals (T = 293 K).

in the ABO crystals the condition $\frac{\partial v}{\partial \phi} = 0$ holds true for the direction making the angle 32° with the Y axis.

As we have already mentioned, the slowest transverse acoustic wave (QT_1) in the LTB crystals propagates in the [011] plane along the direction inclined by 39° to the Z axis (see Fig. 1b). As seen from Fig. 2b, the acoustic obliquity is indeed equal to zero for this propagation direction of the QT_1 wave. It is seen from Fig. 1b that the acoustic wave velocity for the transverse acoustic wave QT_2 polarised along the X axis does not depend significantly on the wave propagation direction and so the condition $\frac{\partial v}{\partial \phi} = 0$ is approximately fulfilled in the all range of ϕ. As a result, the acoustic obliquity angle is small. Similar to the case of ABO, the highest acoustic obliquity here also corresponds to the direction of maximal angular changes in the acoustic wave velocity.

On the basis of the results described above one can conclude that the obliquity angle for the acoustic energy flow is equal to zero for the transverse acoustic waves propagating in the [011] plane along the direction that makes the angle 58° with the Z axis (for the ABO crystals) and for the slowest transverse acoustic wave propagating in the [011] plane along the direction that makes the angle 39° with the Z axis (for the LTB crystals).

Conclusions

The obliquity effects for the acoustic energy flow have been analysed for the both cases of longitudinal and transverse acoustic waves propagating in the ABO and LTB crystals. It has been shown that the deviation of direction of the acoustic energy flow from that of the wave vector should be equal to zero under the experimental conditions that correspond to the highest acoustooptic figure of merit for the case of interaction with the slowest acoustic waves, thus permitting efficient acoustooptic interaction.

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