Anisotropy of acousto-optic figure of merit for LiNbO₃ crystals: anisotropic diffraction

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We have developed a method for the analysis of anisotropy of an acousto-optic figure of merit (AOFM), which is valid for the case of anisotropic diffraction in the trigonal crystals of the point symmetries 3m, 32, and 3m. The method is verified via the example of LiNbO₃ crystals. The relations for the effective elasto-optic coefficients and the AOFM are obtained for the three types of acousto-optic (AO) interactions peculiar for the anisotropic AO diffraction: the interaction of a so-called type VII with a quasi-longitudinal acoustic wave and the interactions of types VIII and IX with two quasi-transverse acoustic waves. The AO diffraction geometries providing maximal AOFM values have been determined for each of the mentioned interaction types. We have found that the maximum AOFM proper for LiNbO₃ is equal to 15.9 × 10⁻¹⁵ s³/kg. This value is achieved at the type IX of AO interactions in the interaction plane rotated by 60.0 deg around the principal X axis with respect to the principal X–Z plane. The type VIII of AO interactions is characterized by a comparable AOFM (15.1 × 10⁻¹⁵ s³/kg), which is realized in the Y–Z interaction plane. A close comparison of our results with the available experimental data demonstrates their fairly good agreement.

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1. INTRODUCTION

Acousto-optic (AO) diffraction is widely used for operating optical radiation (see, e.g., [1]). The AO diffraction is utilized in many optoelectronic devices such as AO deflectors and modulators, including integrated optical ones [2,3], radio-frequency spectrum analyzers [4], polarization converters [5,6], tunable AO filters [6–8], etc. Polarization switches and the tunable AO filters often operate using a so-called anisotropic AO diffraction, which is accompanied by changes in the polarization state of the diffracted optical beam with respect to the incident beam. One of the main parameters characterizing the AO diffraction is its efficiency described by the relation [9]:

\[ \eta = \sin^2 \left( \frac{\pi}{\lambda_0 \cos \Theta_B} \sqrt{\frac{P_{ac}L}{2H} M_2} \right) \]  

or, under the condition \( \eta \ll 1 \),

\[ \eta = \frac{\pi^2 L}{2\lambda_0^2 H \cos \Theta_B} M_2 P_{ac} \]  

Here, \( \lambda_0 \) is the wavelength of optical radiation in vacuum, \( \Theta_B \) the Bragg angle, \( P_{ac} \) the power of the acoustic wave (AW), \( L \) the length of AO interaction, \( H \) the width of piezoelectric transducer, and \( M_2 \) the AO figure of merit (AOFM). In fact, the diffraction efficiency is proportional to the AW power and the proportionality coefficient is just the AOFM. The latter is defined by a set of constitutive coefficients:

\[ M_2 = \frac{n_i^3 n_d^3 p^2_{ef}}{\rho v^3}, \]  

where \( n_i \) and \( n_d \) denote the refractive indices of respectively the incident and diffracted optical waves, \( p_{ef} \) implies the effective elasto-optic coefficient (EEC), \( v \) the AW velocity, and \( \rho \) the material density. The other parameters entering the relations in Eqs. (1) and (2) are geometric or they are determined by the acoustic and optical wavelengths, together with the phase-matching conditions. Thus, the efficiency of the AO diffraction depends heavily on the material properties. From the viewpoint of decreasing energy consumption, it would be important to find out the geometries of AO interactions that provide the maximum AOFM values, following from the facts of actual acoustic, refractive, and elasto-optic anisotropies.

In our recent works [10–13], we have developed the approach for the analysis of AOFM anisotropy, which is valid for the isotropic materials, including the cubic crystals [10], as well as some of the tetragonal crystals (the symmetry groups...
422, 4mm, 42m, and 4/mmm) [11,12]. In the case of tetragonal crystals, the analysis has been performed on the example of a well-known AO material, TeO2 crystals, and has included isotropic and anisotropic AO diffractions. As a result, a number of new, previously unknown, geometries of efficient AO interactions have been revealed for the paratellurite crystals.

Note that decreasing symmetry of crystalline materials implies significant complication of the matrices of elastic stiffnesses and the EECs, with increasing number of their independent components. Then, the AW velocities acquire additional anisotropy and the relations for the effective EECs become more complicated. Hence, generalization of our method for the case of lower-symmetry groups represents a separate problem. In particular, in our last work [13], we have analyzed the AOFM anisotropy for the symmetry groups belonging to the trigonal system (3m, 32, and 3̅m) on the example of LiNbO3 crystals for isotropic AO diffraction. Note that all of the groups mentioned above have the same structure of the elasto-optic and elastic stiffness tensors.

In spite of the fact that the AOFM for LiNbO3 is not high enough, the material demonstrates many other properties that make it an advanced material for various AO applications. Lithium niobate has a low AW attenuation in the high-frequency range [14,15], thus enabling their utilization in the AO devices associated with integrated optical waveguides [3]. For instance, the acoustic attenuation equals to about 1 dB/cm at the AW frequency equal to 1 GHz [15]. Moreover, the crystal mentioned can be used for the wideband AO interactions that implement a number of modern techniques (e.g., multiple surface AW transducers, multiple tilted surface AW transducers, phased surface AWs and stepped surface AWs [15–17]). As a result of our earlier analyses, we have found that, under the conditions of isotropic AO diffraction, the maximum AOFM for LiNbO3 is equal to 11.62 × 10^{-15} \text{s}^3/\text{kg}. It is peculiar for the geometry of AO interactions of the shear AW propagating in the Y-Z plane (the velocity 3994 m/s) with the optical wave polarized in the same plane.

The anisotropic diffraction in LiNbO3 is also of a great importance. In particular, it is well known that the polarization converters and the tunable AO filters mentioned before are often based upon lithium niobate [6,7]. Note also that the methods needed for analyzing the anisotropy of AOFM in the case of anisotropic diffraction differ from those used for the isotropic diffraction. This is because the coupled modes are orthogonally polarized under the conditions of anisotropic interactions. Attempts at the analysis of AOFM anisotropy in the LiNbO3 crystals under the conditions of anisotropic AO diffraction have been made in a number of works. However, all of these works have considered only particular cases of the diffraction. For example, the authors of the study [18] have analyzed the anisotropic AO diffraction in lithium niobate under the condition of AO interactions with the longitudinal AW, while in [8] only the collinear type of AO interactions has been analyzed for the LiNbO3 crystals.

On the other hand, the analysis of AOFM anisotropy in lithium niobate under the conditions of anisotropic AO diffraction presented in [19] has been limited to the AO interactions in the principal planes Z-X and Z-Y of the Fresnel ellipsoid. Nonetheless, it has been found that the maximal AOFM is reached for the case of a fast shear AW propagating in the Y-Z plane [19]. At the same time, the authors of [20] have found that the maximal AOFM at the anisotropic AO diffraction in LiNbO3 is equal to 22 × 10^{-15} \text{s}^3/\text{kg} and corresponds to the interaction with a slow shear AW that propagates in the Y-Z plane. Similar results (the AOFM as large as 15.9 × 10^{-15} \text{s}^3/\text{kg} at \lambda = 632.8 \text{nm}) for the AO interaction plane Y-Z have been reported in the study [21]. However, the directions of AW propagation reported in [20] and [21] differ essentially. In addition, the relations for the EECs have not been presented in all of the mentioned works, thus hindering attempts to calculate in practice the AOFM parameter.

The present work continues the analyses presented in our earlier study [13]. It develops the method for the analysis of AOFM anisotropy under the conditions of anisotropic AO diffraction for the trigonal crystals that belong to the groups of symmetry 3m, 32, and 3̅m, with LiNbO3 as a specific example.

### 2. METHOD OF ANALYSIS

The lithium–niobate crystals belong to the point symmetry group 3m. Their crystallographic setting is such that one of the symmetry mirror planes is perpendicular to the crystallographic axis a [22] and the axis c is parallel to the threefold symmetry axis. Further on, we will accept the crystallographic axes a, b, and c to correspond, respectively, to the X, Y, and Z axes of the Fresnel ellipsoid. The ordinary and extraordinary refractive indices are equal respectively to \(n_o = 2.286\) and \(n_e = 2.203\), so that LiNbO3 is optically negative (\(n_o > n_e\)) [22]. The elasto-optic coefficients determined in our earlier work [23] at \(\lambda = 632.8 \text{nm}\) are equal to \(p_{11} = -0.023 \pm 0.017\), \(p_{12} = 0.076 \pm 0.014\), \(p_{13} = 0.147 \pm 0.019\), \(p_{31} = 0.157 \pm 0.007\), \(p_{33} = 0.141 \pm 0.013\), \(p_{41} = 0.057 \pm 0.004\), \(p_{44} = -0.051 \pm 0.011\), and \(p_{46} = 0.126 \pm 0.004\). The elastic stiffness coefficients at the constant electric field are as follows:

\[
\begin{align*}
C_{11} &= 2.03, \quad C_{12} = 0.573, \quad C_{13} = 0.752, \quad C_{33} = 2.42, \\
C_{44} &= 0.595, \quad C_{66} = 0.728, \quad \text{and} \quad C_{14} = 0.085 \quad \text{(in the units of } 10^{11} \text{ N/m}^2) \quad [24].
\end{align*}
\]

Finally, the density is equal to \(\rho = 4640 \text{ kg/m}^3\) [24].

The method employed by us for the analysis of AOFM anisotropy is similar to that described in the study [12] for the case of crystals belonging to the tetragonal system. Three different types of the anisotropic interactions can be realized here (see [12] for more details): (1) the type VII of AO interactions of the incident optical wave with the longitudinal AW termed as QL; (2) the type VIII of AO interactions of the incident optical wave with the longitudinal AW, QT1; and (3) the type IX of AO interactions of the incident wave with the transverse AW, QT2. In all of the cases, the incident optical waves are considered to be linearly polarized. Note also that the rest of possible interaction types, I to VI, correspond to the isotropic AO diffractions [12].

Now let us consider the AO interactions in the Z-X plane (see Fig. 1). The incident optical wave propagates at the angle \(\theta\) with respect to the X axis and the optical diffracted wave at the angle \(\gamma\) with respect to the wave vector of the incident wave. Here, the incident light is assumed to be polarized as the extraordinary wave, i.e., its polarization vector belongs to
the Z–X plane and remains perpendicular to the wave vector of the incident wave. Then, the diffracted wave is polarized as the ordinary one, being parallel to the Y axis. For each \( \theta \) angle considered, which is changed from 0 to 180 deg with the steps 10–20 deg, the angle \( \gamma \) changes by 360 deg (with the step 1 deg) in such a way that the wave vector of the diffracted wave rotates anticlockwise.

As seen in Fig. 1, the direction of the AW vector changes whenever the angle \( \theta \) does. For instance, we deal with a nonlinear AO diffraction whenever \( \theta \) is equal to 0 or 180 deg. Then, the three wave vectors, those of the two optical waves and the AW, remain collinear. This kind of interaction cannot be accomplished when \( \theta \) is 90 or 270 deg because the optical birefringence is equal to zero along these directions. The orientation of the AW vector can be determined by the angle \( \chi \) between the AW vector and the X axis (see [12]). We have

\[
\chi = \arctan\left(\frac{n_x n_y \sin(\theta + \gamma) - n_z \sin \theta}{n_x n_y \cos(\theta + \gamma) + n_z \cos \theta}\right),
\]

for optically positive crystals and

\[
\chi = \arctan\left(\frac{n_x \sin(\theta + \gamma) - n_y n_z \sin \theta}{n_x \cos(\theta + \gamma) - n_y n_z \cos \theta}\right),
\]

for optically negative ones, including the case of LiNbO\(_3\). In Eq. (5), \( n^s \) depends on the angles of rotation of the interaction plane \( \phi_X \) and \( \phi_Y \) around the X and Y axes, respectively:

\[
n^s = \frac{n_{n_x n_y}}{\sqrt{n_x^2 \cos^2(\phi_X) + n_y^2 \sin^2(\phi_X) + n_z^2 \cos^2(\phi_Y) + n_Y^2 \sin^2(\phi_Y)}}.
\]

The components of the strain tensor caused by the AW would depend on the AW vector direction. Therefore, we have a single nonzero strain component \( e_1 \) for the longitudinal AW that propagates along the X axis with the velocity \( v_{11} = v_{QL} \). We deal with the only components \( e_5 \) or \( e_6 \) for the transverse A\( W \)s that propagate along the X axis and are polarized parallel to the Z (\( v_{13} = v_{QT_1} \)) or Y (\( v_{12} = v_{QT_2} \)) axes. When the AW vector rotates by the angle \( \chi \), the strain components for the longitudinal wave QL can be written as

\[
e'_1 = e_1 \cos^2 \chi, \quad e'_5 = e_1 \sin^2 \chi, \quad e'_5 = e_1 \sin \chi \cos \chi.
\]

Similar relations hold true for the transverse wave QT\(_1\),

\[
e'_1 = e_5 \sin 2\chi, \quad e'_5 = -e_5 \sin 2\chi, \quad e'_5 = e_5 \cos 2\chi,
\]

and for the transverse wave QT\(_2\),

\[
e'_6 = 2e_6 \cos \chi, \quad e'_4 = -2e_6 \sin \chi.
\]

After rotating the incident and diffracted optical wave vectors in the Z–X plane, we have to change the interaction plane by rotating it around the Z, X, and Y (initially the Y–Z plane) axes by the angles \( \phi_X, \phi_Y \), and \( \phi_Y \), respectively. Under these rotations, the AO interaction occurs in the new planes \( X'Z' \), \( XZ' \), and \( YZ' \). The latter rotations modify the strain tensor components. We write out these components separately for different A\( W \)s:

(i) QL

\[
e_1(\phi_X) = e_1', e_2(\phi_X) = e_1' \cos^2 \phi_X, \quad e_3(\phi_X) = e_3', \quad e_4(\phi_X) = -e_5' \sin \phi_X, \quad e_5(\phi_X) = e_5' \cos \phi_X, \quad e_6(\phi_X) = -e_5' \sin \phi_X \cos \phi_X,
\]

(ii) QT\(_1\)

\[
e_1(\phi_Y) = e_1' \cos^2 \phi_Y, \quad e_2(\phi_Y) = e_1' \sin^2 \phi_Y, \quad e_3(\phi_Y) = e_5' \cos \phi_Y, \quad e_4(\phi_Y) = -e_5' \sin \phi_Y, \quad e_5(\phi_Y) = e_5' \sin \phi_Y, \quad e_6(\phi_Y) = 2e_6' \cos \phi_Y,
\]

where \( e_1' \) (or \( e_2' \) in the case of rotation of the Y–Z plane around the Y axis), \( e_3' \) and \( e_5' \) are taken from Eq. (7); and \( e_4' \) (or \( e_6' \) in the case of rotation of the Y–Z plane around the Y axis) are taken from Eq. (8);
where the induction vector components are as follows:

\[
D_1 = -D_0 \sqrt{1 - \frac{\sin \theta \sin \phi_X}{\sqrt{1 - \sin^2 \theta \cos^2 \phi_X}}} \sin \theta \cos \phi_X,
\]

\[
D_2 = -D_0 \frac{\sin \theta \sin \phi_Y}{\sqrt{1 - \sin^2 \theta \cos^2 \phi_Y}} \sin \theta \cos \phi_Y,
\]

\[
D_3 = D_0 \sqrt{1 - \sin^2 \theta \cos^2 \phi_Y},
\]

Finally, the appropriate relations for the \( YZ' \) plane can be presented as

\[
E_1 = -\Delta B_{11} D_0 \sqrt{1 - \frac{\sin \theta \sin \phi_Y}{\sqrt{1 - \sin^2 \theta \cos^2 \phi_Y}}} \sin \theta \cos \phi_Y
\]

\[+ \Delta B_{12} D_0 \frac{0.5 \sin^2 \theta \sin 2\phi_Y}{\sqrt{1 - \sin^2 \theta \cos^2 \phi_Y}} + \Delta B_{13} D_0 \sqrt{1 - \sin^2 \theta \cos^2 \phi_Y},
\]

\[
E_2 = -\Delta B_{21} D_0 \sqrt{1 - \frac{\sin \theta \sin \phi_X}{\sqrt{1 - \sin^2 \theta \cos^2 \phi_X}}} \sin \theta \cos \phi_X
\]

\[+ \Delta B_{22} D_0 \frac{0.5 \sin^2 \theta \sin 2\phi_X}{\sqrt{1 - \sin^2 \theta \cos^2 \phi_X}} + \Delta B_{23} D_0 \sqrt{1 - \sin^2 \theta \cos^2 \phi_X},
\]

where

\[
D_1 = D_0 \sin \theta \sin \phi_Z, \quad D_2 = D_0 \sin \theta \cos \phi_Z \quad \text{and} \quad D_3 = D_0 \cos \theta.
\]

The electric field of the diffracted wave in the \( XZ' \) interaction plane is given by

\[
E_1 = -\Delta B_{11} D_0 \sqrt{1 - \frac{\sin \theta \sin \phi_X}{\sqrt{1 - \sin^2 \theta \cos^2 \phi_X}}} \sin \theta \cos \phi_X
\]

\[+ \Delta B_{12} D_0 \frac{0.5 \sin^2 \theta \sin 2\phi_Y}{\sqrt{1 - \sin^2 \theta \cos^2 \phi_Y}} + \Delta B_{13} D_0 \sqrt{1 - \sin^2 \theta \cos^2 \phi_Y},
\]

\[
E_2 = -\Delta B_{21} D_0 \sqrt{1 - \frac{\sin \theta \sin \phi_X}{\sqrt{1 - \sin^2 \theta \cos^2 \phi_X}}} \sin \theta \cos \phi_X
\]

\[+ \Delta B_{22} D_0 \frac{0.5 \sin^2 \theta \sin 2\phi_X}{\sqrt{1 - \sin^2 \theta \cos^2 \phi_X}} + \Delta B_{23} D_0 \sqrt{1 - \sin^2 \theta \cos^2 \phi_X},
\]

(i) the rotation of the interaction plane around the \( Z \) axis:

\[
P_{\text{eff}}^{(\text{VII})} = \left\{ \begin{array}{l}
\left[ p_{11} \cos^2 \chi \cos^2 \phi_Z + p_{12} \cos^2 \chi \sin^2 \phi_Z + p_{13} \sin^2 \chi + p_{14} \sin \phi_Z \sin 2\chi \sin \theta \right] \sin \theta

\[+ \left[ p_{16} \cos^2 \chi \sin 2\phi_Z + p_{15} \sin 2\phi_Z \cos \phi_Z \right] \sin \theta

\[+ \left[ p_{44} \sin 2\phi_Z \cos \phi_Z \right] \sin \theta

\[+ \left[ p_{17} \cos^2 \chi \sin^2 \phi_Z + p_{18} \sin^2 \phi_Z \cos \phi_Z \right] \sin \theta

\[+ \left[ p_{45} \sin 2\phi_Z \sin \phi_Z + p_{41} \sin^2 \phi_Z \cos 2\phi_Z \cos \theta \right] \sin \theta
\end{array} \right\}^2,
\]
(ii) the rotation of the interaction plane around the X axis:

\[ P_{cf}^{(VII)} = \left\{ \begin{array}{l}
-\left[ p_{11} \cos^2 \chi + p_{12} \sin^2 \chi \sin^2 \varphi_X + p_{13} \sin^2 \chi \cos^2 \varphi_X + p_{14} \sin 2 \varphi_X \sin^2 \chi \right] \sqrt{1 - \frac{\sin \theta \sin \varphi_X}{\sqrt{1 - \sin^2 \theta \cos^2 \varphi_X}} \sin \theta \cos \varphi_X} \\
-\left[ p_{66} \sin 2 \chi \sin \varphi_X + p_{14} \sin 2 \chi \cos \varphi_X \right] \frac{\sin \theta \sin \varphi_X}{\sqrt{1 - \sin^2 \theta \cos^2 \varphi_X}} \sin \theta \cos \varphi_X \\
+ \left[ p_{44} \sin 2 \chi \cos \varphi_X + p_{41} \sin 2 \chi \sin \varphi_X \right] \sqrt{1 - \sin^2 \theta \cos^2 \varphi_X} \\
-\left[ p_{66} \sin 2 \chi \sin \varphi_X + p_{14} \sin 2 \chi \cos \varphi_X \right] \frac{\sin \theta \sin \varphi_X}{\sqrt{1 - \sin^2 \theta \cos^2 \varphi_X}} \sin \theta \cos \varphi_X \\
\left[ p_{12} \cos^2 \chi + p_{11} \sin^2 \chi \sin^2 \varphi_X + p_{13} \sin^2 \chi \cos^2 \varphi_X - p_{14} \sin 2 \varphi_X \sin^2 \chi \right] \frac{\sin \theta \sin \varphi_X}{\sqrt{1 - \sin^2 \theta \cos^2 \varphi_X}} \sin \theta \cos \varphi_X \\
+ \left[ p_{44} \sin^2 \chi \sin 2 \varphi_X + p_{41} \left( \cos^2 \chi - \sin^2 \chi \sin^2 \varphi_X \right) \right] \sqrt{1 - \sin^2 \theta \cos^2 \varphi_X} \\
\end{array} \right\}^{2}, \quad (26) \]

(iii) the rotation of the interaction plane around the Y axis:

\[ P_{cf}^{(VII)} = \left\{ \begin{array}{l}
-\left[ p_{11} \sin^2 \chi \sin^2 \varphi_Y + p_{12} \cos^2 \chi + p_{13} \sin^2 \chi \cos^2 \varphi_Y + p_{14} \cos \varphi_Y \sin 2 \varphi_Y \right] \sqrt{1 - \frac{\sin \theta \sin \varphi_Y}{\sqrt{1 - \sin^2 \theta \cos^2 \varphi_Y}} \sin \theta \cos \varphi_Y} \\
-\left[ p_{66} \sin 2 \chi \sin \varphi_Y + p_{14} \sin 2 \chi \cos \varphi_Y \right] \frac{\sin \theta \sin \varphi_Y}{\sqrt{1 - \sin^2 \theta \cos^2 \varphi_Y}} \sin \theta \cos \varphi_Y \\
+ \left[ p_{44} \sin^2 \chi \sin 2 \varphi_Y + p_{41} \sin 2 \chi \sin \varphi_Y \right] \sqrt{1 - \sin^2 \theta \cos^2 \varphi_Y} \left[ D^t \right] \\
-\left[ p_{66} \sin 2 \chi \sin \varphi_Y + p_{14} \sin 2 \chi \cos \varphi_Y \right] \frac{\sin \theta \sin \varphi_Y}{\sqrt{1 - \sin^2 \theta \cos^2 \varphi_Y}} \sin \theta \cos \varphi_Y \\
\left[ p_{12} \sin^2 \chi \sin^2 \varphi_Y + p_{11} \cos^2 \chi + p_{13} \sin^2 \chi \cos^2 \varphi_Y - p_{14} \cos \varphi_Y \sin 2 \varphi_Y \right] \frac{\sin \theta \sin \varphi_Y}{\sqrt{1 - \sin^2 \theta \cos^2 \varphi_Y}} \sin \theta \cos \varphi_Y \\
+ \left[ p_{44} \sin^2 \chi \sin 2 \varphi_Y + p_{41} \left( \sin^2 \chi \sin^2 \varphi_Y - \cos^2 \chi \right) \right] \sqrt{1 - \sin^2 \theta \cos^2 \varphi_Y} \\
\end{array} \right\}^{2}, \quad (27) \]

(2) the type VIII of AO interactions

(i) the rotation of the interaction plane around the Z axis:

\[ P_{cf}^{(VIII)} = \left\{ \begin{array}{l}
\left[ \left( p_{11} \cos^2 \varphi_Z + p_{12} \sin^2 \varphi_Z - p_{13} \right) \sin 2 \chi - 2 p_{14} \cos 2 \chi \sin \varphi_Z \right] \sin 0.5 \sin \theta \\
\left[ -0.5 p_{66} \sin 2 \chi \sin 2 \varphi_Z + p_{14} \cos 2 \chi \cos 2 \varphi_Z \right] \sin \theta + \left[ p_{44} \cos 2 \chi \cos \varphi_Z - 0.5 p_{41} \sin 2 \chi \sin 2 \varphi_Z \right] \cos \theta \\
\left[ -0.5 p_{66} \sin 2 \chi \sin 2 \varphi_Z + p_{14} \cos 2 \chi \cos 2 \varphi_Z \right] \sin \theta \\
\left[ + p_{12} \cos^2 \varphi_Z + p_{11} \sin^2 \varphi_Z - p_{13} \right] \sin 2 \chi + 2 p_{14} \cos 2 \chi \sin \varphi_Z \sin 0.5 \sin \theta \\
\left[ - p_{44} \cos 2 \chi \sin \varphi_Z + 0.5 p_{41} \sin 2 \chi \cos 2 \varphi_Z \right] \cos \theta \\
\end{array} \right\}^{2}, \quad (28) \]

(ii) the rotation of the interaction plane around the X axis:

\[ P_{cf}^{(VIII)} = \left\{ \begin{array}{l}
-0.5 \left[ p_{11} - p_{12} \sin^2 \varphi_X + p_{13} \cos^2 \varphi_X - p_{14} \sin 2 \varphi_X \right] \sin 2 \chi \sqrt{1 - \frac{\sin \theta \sin \varphi_X}{\sqrt{1 - \sin^2 \theta \cos^2 \varphi_X}} \sin \theta \cos \varphi_X} \\
-\left[ p_{66} \sin \varphi_X + p_{14} \cos \varphi_X \right] \cos 2 \chi \frac{\sin \theta \sin \varphi_X}{\sqrt{1 - \sin^2 \theta \cos^2 \varphi_X}} \sin \theta \cos \varphi_X \\
+ \left[ p_{44} \cos \varphi_X + p_{41} \sin \varphi_X \right] \cos 2 \chi \sqrt{1 - \sin^2 \theta \cos^2 \varphi_X} \\
-\left[ p_{66} \sin \varphi_X + p_{14} \cos \varphi_X \right] \cos 2 \chi \frac{\sin \theta \sin \varphi_X}{\sqrt{1 - \sin^2 \theta \cos^2 \varphi_X}} \sin \theta \cos \varphi_X \\
+ \left[ -0.5 p_{12} \sin^2 \varphi_X + p_{13} \cos^2 \varphi_X + p_{14} \sin 2 \varphi_X \right] \sin 2 \chi \sqrt{1 - \frac{\sin \theta \sin \varphi_X}{\sqrt{1 - \sin^2 \theta \cos^2 \varphi_X}} \sin \theta \cos \varphi_X} \\
0.5 \left[ - p_{44} \sin 2 \varphi_X + p_{41} \right] \sin 2 \chi \sqrt{1 - \sin^2 \theta \cos^2 \varphi_X} \\
\end{array} \right\}^{2}, \quad (29) \]
(iii) the rotation of the interaction plane around the $Y$ axis:

\[
p_{\text{eff}}^{(\text{VIII})} = \left\{ \begin{array}{l}
-0.5(p_{12} - p_{11})\sin^2\varphi_Y - p_{13}\cos^2\varphi_Y)\sin 2\varphi + p_{14}\cos 2\varphi \cos \varphi_Y \sqrt{1 - \frac{\sin \theta \sin \varphi_Y}{\sqrt{1 - \sin^2 \theta \cos^2 \varphi_Y}}} \\
-\frac{p_{66} \cos 2\varphi \sin \varphi_Y - 0.5p_{14} \sin 2\varphi \sin \varphi_Y}{\sqrt{1 - \sin^2 \theta \cos^2 \varphi_Y}} \sin \theta \cos \varphi_Y \\
+[-0.5p_{44} \sin 2\varphi \sin \varphi_Y + p_{41} \cos 2\varphi \sin \varphi_Y] \sqrt{1 - \frac{\sin \theta \sin \varphi_Y}{\sqrt{1 - \sin^2 \theta \cos^2 \varphi_Y}}} \\
-0.5(p_{12} \sin^2 \varphi_Y - p_{11} - p_{13} \cos^2 \varphi_Y)\sin 2\varphi_Y - p_{14} \cos 2\varphi_Y \cos \varphi_Y \sqrt{1 - \frac{\sin \theta \sin \varphi_Y}{\sqrt{1 - \sin^2 \theta \cos^2 \varphi_Y}}} \\
+0.5[p_{44} \cos 2\varphi \cos \varphi_Y - p_{41} \sin 2\varphi_Y (1 + \sin^2 \varphi_Y)] \sqrt{1 - \sin^2 \theta \cos^2 \varphi_Y}
\end{array} \right\} ^2, \tag{30}
\]

(iii) the rotation of the interaction plane around the $Z$ axis:

\[
p_{\text{eff}}^{(\text{IX})} = \left\{ \begin{array}{l}
[(p_{11} - p_{12}) 0.5 \cos \chi \sin 2\varphi_Z - p_{14} \sin \chi \cos \varphi_Z] \sin \theta \\
+ \left[ p_{66} \cos \chi \cos 2\varphi_Z - p_{14} \sin \chi \sin \varphi_Z \right] \sin \theta + [-p_{44} \sin \chi \sin \varphi_Z + p_{41} \cos \chi \cos 2\varphi_Z] \cos \theta \right\} ^2, \tag{31}
\]

(ii) the rotation of the interaction plane around the $X$ axis:

\[
p_{\text{eff}}^{(\text{IX})} = \left\{ \begin{array}{l}
-(-p_{12} + p_{13}) \sin \chi \sin 2\varphi_X - p_{14} \sin \chi \cos 2\varphi_X \sqrt{1 - \frac{\sin \theta \sin \varphi_X}{\sqrt{1 - \sin^2 \theta \cos^2 \varphi_X}}} \\
-\frac{p_{66} \cos \varphi_X - p_{14} \sin \varphi_X}{\sqrt{1 - \sin^2 \theta \cos^2 \varphi_X}} \cos \chi \sqrt{1 - \sin^2 \theta \cos^2 \varphi_X} \\
+[-p_{44} \sin \varphi_X + p_{41} \cos \varphi_X] \cos \chi \sqrt{1 - \sin^2 \theta \cos^2 \varphi_X} \\
-\left[ (-p_{11} + p_{12}) \sin \chi \sin 2\varphi_X + p_{14} \sin \chi \cos 2\varphi_X \right] \sin \theta \sin \varphi_X \sqrt{1 - \sin^2 \theta \cos^2 \varphi_X} \\
+[-p_{44} \cos 2\varphi_X - p_{41} \sin 2\varphi_X] \sin \chi \sqrt{1 - \sin^2 \theta \cos^2 \varphi_X}
\end{array} \right\} ^2, \tag{32}
\]

(iii) the rotation of the interaction plane around the $Y$ axis:

\[
p_{\text{eff}}^{(\text{IX})} = \left\{ \begin{array}{l}
-(-p_{11} + p_{13}) \sin \chi \sin 2\varphi_Y - p_{14} \cos \chi \sin \varphi_Y \sqrt{1 - \frac{\sin \theta \sin \varphi_Y}{\sqrt{1 - \sin^2 \theta \cos^2 \varphi_Y}}} \\
-\frac{p_{66} \cos \varphi_Y - p_{14} \sin \varphi_Y}{\sqrt{1 - \sin^2 \theta \cos^2 \varphi_Y}} \cos \chi \sqrt{1 - \sin^2 \theta \cos^2 \varphi_Y} \\
+[-p_{44} \sin \varphi_Y + p_{41} \cos \varphi_Y] \cos \chi \sqrt{1 - \sin^2 \theta \cos^2 \varphi_Y} \\
-\left[ (-p_{12} + p_{13}) \sin \chi \sin 2\varphi_Y + p_{14} \cos \chi \sin \varphi_Y \right] \sin \theta \sin \varphi_Y \sqrt{1 - \sin^2 \theta \cos^2 \varphi_Y} \\
+[-p_{44} \cos \varphi_Y - p_{41} \sin \varphi_Y] \cos \chi \sqrt{1 - \sin^2 \theta \cos^2 \varphi_Y}
\end{array} \right\} ^2. \tag{33}
\]
Now one has to account for the dependence of AW velocities on the wave vector direction, which has earlier been described in detail in the work [13]. Then, we obtain the following relations for the AOFM:

\[
M_{2}^{(VII)} = \frac{n^{2}e^{2} \gamma^{(VII)}_{ef} \rho_{QL}^{(VII)}}{\rho} \sin^{2} \theta \cos^{2} \phi \sin \phi X + \sin \phi Y + \sin \phi Z,
\]

\[
M_{2}^{(VIII)} = \frac{n^{2}e^{2} \gamma^{(VIII)}_{ef} \rho_{QT1}^{(VIII)}}{\rho} \sin^{2} \theta \cos^{2} \phi \sin \phi X + \sin \phi Y + \sin \phi Z,
\]

\[
M_{2}^{(IX)} = \frac{n^{2}e^{2} \gamma^{(IX)}_{ef} \rho_{QT2}^{(IX)}}{\rho} \sin^{2} \theta \cos^{2} \phi \sin \phi X + \sin \phi Y + \sin \phi Z.
\] (34)

Here, \(v_{QL}(\chi, \varphi_{X,Y,Z}), v_{QT1}(\chi, \varphi_{X,Y,Z})\), and \(v_{QT2}(\chi, \varphi_{X,Y,Z})\) define the change in the AW velocity occurring in different interaction planes. Finally, the modified refractive indices are as follows:

\[
n_{e}^{*} = \frac{n_{e}^{2} n_{e}^{*}}{\sqrt{n_{e}^{2} \cos^{2} \theta + n_{e}^{2} \sin^{2} \theta}},
\]

\[
n_{o}^{*} = \frac{n_{o}^{2} n_{o}^{*}}{\sqrt{(n_{o}^{2} - n_{e}^{2}) \cos^{2} \phi + n_{o}^{2} \sin^{2} \phi}}. \] (35)

They are actual, respectively, for the cases of rotations, by the angles \(\varphi_{X}\) or \(\varphi_{Y}\), of the interaction plane around the \(Z\) axis.

**Fig. 2.** Dependences of AOFM (a), (c), (e) and EEC (b), (d), (f) on the \(\theta + \gamma\) angle for the type VII of AO interactions occurring at \(\varphi_{Z} = 30\) deg.
3. RESULTS AND DISCUSSION

Figures 2–4 represent the dependences of the AOFM and the effective EEC on the angle $\theta + \gamma$ for the types VII, VII, and IX of AO interactions. Here, we restrict our consideration to those interaction planes for which the maximum AOFM values can be reached. The maximal AOFM ($3.6 \times 10^{-15} \text{s}^3/\text{kg}$) for the type VII of AO interactions with the quasi-longitudinal AW is peculiar for the diffraction in the interaction plane $X'Z$ rotated around the $Z$ axis by 30 deg [see Figs. 2(a) and 2(e); Table 1]. This kind of diffraction can be observed in the two different geometries:

1. the incident optical wave propagates along the direction inclined by 70.0 deg with respect to the $X'$ axis, while the diffracted wave propagates under the angle 234 deg with respect to the $X'$ axis; in this case, the AW propagates under the angle $\chi = 242.0$ deg with respect to the $X'$ axis;
2. the incident optical wave propagates under the angle 250.0 deg with respect to $X'$ axis, while the diffracted wave under the angle 54.0 deg with respect to $X'$ axis; in this case, the AW wave propagates under the angle $\chi = 62.0$ deg with respect to the $X'$ axis.

Note that the diffraction type under analysis is close to the collinear diffraction when the incident and diffracted waves are

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Fig. 3. Dependences of AOFM (a), (c), (e) and EEC (b), (d), (f) on the $\theta + \gamma$ angle for the type VIII of AO interactions occurring at $\varphi_Z = 90$ deg.
oppositely directed. Obviously, these diffractions can be implemented at high enough AW frequencies ($f_a \approx 47$ GHz). Efficient collinear diffractions can be realized under the following conditions: (1) $\theta_1/\theta_2 = 0.136\gamma/70$ deg; (2) $\theta_1/\theta_2 = 0.135\gamma/250$ deg; (3) $\theta_1/\theta_2 = 70$ deg; (4) $\theta_1/\theta_2 = 250$ deg; and (5) $\theta_1/\theta_2 = 70$ deg. However, the AOFM for the collinear diffraction appears to be somewhat lower if compared with the noncollinear case described above, being equal only to $3.4 \times 10^{-15}$ s$^3$/kg. It is worthwhile that, in the case of collinear diffraction at $\gamma = 0$, the angular width of the AOFM extremum is narrow. As shown in the study [25], this is mainly caused by extremely strong dependence of EEC on the angle $\theta$ in the vicinity of $\gamma = 0$. Comparing Figs. 2(a), 2(c), 2(e) and Figs. 2(b), 2(d), 2(f), one can conclude that the AOFM anisotropy is mainly caused by the anisotropy of the effective EEC.

For the type VIII of AO interactions with the QT$^1$ AW, i.e., the AW polarized in the plane of interaction, the maximum AOFM value ($15.1 \times 10^{-15}$ s$^3$/kg) is achieved in the $Y$–$Z$ interaction plane, namely, under the conditions when the $X$–$Z$ interaction plane is rotated by 90 deg around the $Z$ axis [see Fig. 3(c) and Table 1]. Then, the AW propagates under the angle 79.8 deg with respect to the $Y$ axis (or the $X'$ axis), while the incident and diffracted optical waves propagate under the

![Fig. 4. Dependences of AOFM (a), (c), (e) and EEC (b), (d), (f) on the $\theta + \gamma$ angle for the type IX of AO interactions occurring at $\varphi_x = 60$ deg.](image-url)
angles 150.0 and 145.0 deg with respect to the same axis. The frequency of the AW at this “tangential” type of AO interaction is equal to $f_a = 24.7$ MHz.

In case of the type IX of AO interactions with the QT$_2$ AW polarized perpendicular to the interaction plane, the maximum AOFM is equal to $15.9 \times 10^{-15}$ s$^3$/kg [see Fig. 4(e) and Table 1]. The maximal AOFM value for the LiNbO$_3$ crystals is then reached under rotation by 60 deg of the interaction plane $XZ$ around the $X$ axis. The incident optical wave propagates under the angle of 260.0 deg with respect to the $X$ axis, while the diffracted one under the angle of 74.0 deg with respect to the same axis. Thus, this kind of AO diffraction is close to the collinear one occurring at the diffraction angle $\gamma = 186$ deg, which is close to the condition of a “reflecting AO grating” (i.e., $\gamma = 180$ deg) and can be realized at high enough AW frequencies ($f_a = 24.6$ GHz). At the type IX of AO interactions, almost the same AOFM values can be reached with a number of diffraction geometries. For example, the AOFM value equal to $15.6 \times 10^{-15}$ s$^3$/kg [see Fig. 4(a)] can be achieved at the “tangential phase-matching condition” ($\theta = 80.0$ deg, $\theta + \gamma = 73.0$ deg, and the AW propagates under the angle 2.1 deg with respect to the $X$ axis). For this diffraction case, the AW frequency should be equal to $f_a = 1.4$ GHz.

As in the cases of the type VIII and IX of AO interactions, the anisotropy of AOFM is determined by the anisotropy of the EEC [see Figs. 3(b) and 4(b)].

Let us compare our results with those known from the earlier literature on the subject. As previously mentioned, the maximum AOFM value obtained in the work [19] is equal to $20 \times 10^{-15}$ s$^3$/kg for the diffraction implemented in the $Z$–$Y$ plane under propagation of the fast quasi-transverse AW under the angle of 60 deg with respect to the $Y$ axis. In our notation, this kind of AO diffraction corresponds to the type VIII of interactions, which is realized in the $Z$–$Y$ plane (see Fig. 3). Note that we have also obtained high AOFM values in this interaction plane. However, they are still smaller than the AOFM obtained in [19]. Moreover, the propagation direction for the AW in our case is equal to 79.8 deg with respect to the $Y$ axis rather than 60 deg as reported in [19]. Of course, this difference can be caused by different constitutive coefficients (the elasto-optic coefficients, the elastic stiffness coefficients, and the refractive indices) used in the calculations of our work and the study [19]. Unfortunately, the authors of [19] have not presented these coefficients.

As previously mentioned, the AOFM value equal to $22 \times 10^{-15}$ s$^3$/kg has been reported in the work [20] for the interaction in the $Y$–$Z$ plane with the slow AW that propagates at the angle 120 deg with respect to the $Y$ axis and is polarized parallel to the $X$ axis. This kind of AO diffraction corresponds to our interaction type IX. According to our data, the AOFM in this interaction plane does not exceed $\sim 13 \times 10^{-15}$ s$^3$/kg. This is almost two times smaller than the value reported in [20].

The AOFM value obtained in [21] ($15.9 \times 10^{-15}$ s$^3$/kg) is the closest to our results. Let us remind that our maximal value is exactly the same. Note also that both of the AOFM values correspond to the type IX of AO interactions. Nonetheless, the geometries peculiar for those interactions differ essentially.

### Table 1. Geometries of AO Interaction at Which the Maximum Values of AOFM at Different Types of Anisotropic Interaction Are Reached in LiNbO$_3$ Crystals

| Type of Interaction | Orientation of the Interaction Plane $\varphi_X$ | $\varphi_Z$ | $\varphi_{Z'}$ | $\psi_{X'}$ | $\psi_{Z'}$ | $\psi_{Z''}$ |
|---------------------|---------------------------------------------|------------|-------------|-------------|------------|-------------|
| VII                 | $\varphi_X = 30$                           | 79.8 deg. | 69.8 deg.   | $\psi_{X'} = 60$   | 260.0 deg. | 78.4 deg.   |
| VIII                | $\varphi_Z = 90$                           | 90.0 deg. | 90.0 deg.   | $\psi_{Z'} = 90$   | 150.0 deg. | 150.0 deg.  |
| IX                  | $\varphi_{Z'} = 90$                         | 90.0 deg. | 90.0 deg.   | $\psi_{Z''} = 90$  | 90.0 deg. | 90.0 deg.   |

**Optical Wave**
- **Wave Polarization**
- **Propagation Direction of Optical Incident Wave**
- **Propagation Direction of Optical Diffracted Wave**

**AOFM**
- $10^{-15}$ s$^3$/kg

**Angles**
- $\varphi_X$, $\varphi_Z$, $\psi_{X'}$, $\psi_{Z'}$, $\psi_{Z''}$
- Degrees
Namely, the AO interaction described in [21] occurs in the $Y$–$Z$ plane while, according to our results, the interaction plane is rotated by the angle $\phi \approx 60$ deg around the $X$ axis. Of course, such a difference can be caused by differences among the elasto-optic tensor components, which are used in our work and in [21]. Nonetheless, no relations for the EEC have been presented in [21], which makes it impossible to clarify the reasons for the difference of the experimental geometries. In addition, the polarization of the diffracted optical wave for the interaction geometry at which the maximum AOFM value is obtained in [21] includes a nonzero longitudinal component, which has no physical meaning. Besides, it should be noted that the AOFM value obtained using our method with a set of our elasto-optic and other constitutive coefficients for the interaction geometry mentioned in [21] is equal to $4.6 \times 10^{-15}$ s$^3$/kg. It is equal to $11.3 \times 10^{-15}$ s$^3$/kg if we use the coefficients of [21] but not $15.9 \times 10^{-15}$ s$^3$/kg. The difference between our calculation results and those presented in [20] can be caused by the difference of elasto-optic coefficients used. For example, we have the values $p_{33} = 0.007$ in [20] and $p_{33} = 0.141$ in our recent work [23], $p_{44} = -0.15$ in [20] and $p_{44} = -0.051$ in [23], while for the coefficient $p_{14}$ the values $-0.08$ and $0.057$ have been reported in [20] and [23], respectively.

Now let us compare the results of our analysis with the experimental data available in the literature. Unfortunately, the experimental data available on the relative AOFM values occurring under the conditions of anisotropic diffraction in the LiNbO$_3$ crystals are quite pure. As far as we know, the only data are available for the collinear diffraction at which all three AWs propagate along the directions close to the optic axis [26]. Then, the quasi-transverse AW $v_{35}$ perturbs the refractive indices, with activating the EOC $p_{14}$, while the incident and diffracted optical waves have the polarizations parallel to the $X$ and $Y$ axes, respectively. In our notation, this diffraction belongs to the type VIII of AO interactions ($\phi = 90$ deg and $\theta = \theta + \gamma = 90$ deg). The AOFM obtained in [26] is equal to $2.92 \times 10^{-15}$ s$^3$/kg. According to our data, this value corresponds to the angle $\theta + \gamma \approx 84$ deg. Note that, exactly under the condition $\theta = \theta + \gamma = 90$ deg, the anisotropic diffraction is impossible in principle because we deal with the direction of the optic axis. Following from Eq. (28), the EEC under this interaction geometry is equal to the EEC $p_{14}$, as noted in [26]. According to our data [23], the coefficient $p_{14}$ is then equal to $0.057 \pm 0.004$. According to our analysis, the EEC is equal to $0.066$ at $\theta + \gamma \approx 84$ deg, whereas according to the data in [26] obtained using the Dixon–Cohen method, the EEC is equal to 0.070. Hence, one can see good agreement between the results of our analysis and the experimental data [26] after accounting for the experimental errors $\pm 5$–10%.

4. CONCLUSIONS

In the present work, we have developed a method for the analysis of AOFM anisotropy, which is valid for the case of anisotropic diffractions in crystals belonging to the point symmetry groups 3m, 32, and 3m. We have performed our analysis on the example of LiNbO$_3$ crystals. The relations for the EEC and the AOFM have been obtained for the three types of anisotropic AO interactions. We have shown that the maximal AOFM proper for the type VII of AO interactions with the quasi-longitudinal AW is equal to $3.6 \times 10^{-15}$ s$^3$/kg. This type of interaction is realized at the almost collinear reflection geometry of AO diffraction. At the type VIII of AO interactions with the AW QT$_1$, which is polarized in the plane of interaction, the maximum AOFM ($15.1 \times 10^{-15}$ s$^3$/kg) is achieved in the interaction plane $Y$–$Z$. The highest AOFM value for the LiNbO$_3$ crystals is reached at the type IX of AO interactions with the AW termed as QT$_2$ and polarized perpendicular to the interaction plane. The interaction plane is then rotated by 60.0 deg around the $X$ axis with respect to the $X$–$Z$ plane. The appropriate AOFM is equal to $15.9 \times 10^{-15}$ s$^3$/kg. By comparing our results with the available experimental data, we have found good agreement that suggests a correctness of our theoretical approach.

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