Influence of Faraday elliptical birefringence on the acousto-optic diffraction efficiency: a case of isotropic interaction with quasi-longitudinal acoustic waves in KH_2PO_4 crystals

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Abstract. It is shown for the first time that acousto-optic efficiency can be enhanced by the magnetic field-induced ellipticity of optical eigenwaves due to a Faraday effect. We find that the acousto-optic figure of merit for KH_2PO_4 crystals can be increased about two times when a magnetic field is applied along the optic axis and the incident and diffracted optical waves propagate along the directions close to the optic axis with the polarizations being the same as the magnetically induced polarizations of elliptical eigenwaves. We also analyze the angular behaviour of the peaks of effective elasto-optic coefficients and their full-width half maximums with changing magnetic field. Our results demonstrate that it is possible to control the efficiency of the acousto-optic Bragg diffraction using the magnetic field. The magnetic field needed for enhancing the acousto-optic figure of merit depends on the Faraday-tensor component of a material.

Keywords: acousto-optics, Faraday effect, ellipticity of eigenwaves, diffraction efficiency, KH_2PO_4 crystals

UDC: 535.43, 535.551, 535.562, 534-16

1. Introduction

Acousto-optic (AO) interaction is a well-known phenomenon [1, 2] that consists in diffraction of optical waves on the phase grating caused by an acoustic wave (AW) through elasto-optic (EO) coupling [3]. AO diffraction has found its applications in a lot of technologies and devices such as light scanning, deflection, modulators, tunable AO filters, etc. [4–6]. One of the most important parameters which characterizes the AO diffraction is its efficiency $\eta = I_d / I_0$. It describes the ratio of the intensities of incident (I_0) and diffracted (I_d) waves. If the efficiency of the Bragg-type diffraction is low enough, it can be found from the relation

$$\eta = M_2 \frac{\pi^2 L}{2H\lambda^2 \cos^2 \theta_B} P_a , \quad (1)$$

where λ is the wavelength of optical radiation in vacuum, L the interaction length, H the height of the acoustic beam, θ_B the Bragg angle, and P_a the AW power.

As seen from Eq. (1), the AO efficiency is determined by the proportionality coefficient M_2 which is called an AO figure of merit:

$$M_2 = \frac{n_i^3 n_d^3 p_{eff}^2}{\rho v^3} . \quad (2)$$

The latter depends on the constitutive parameters of a material, i.e. the refractive indices of the incident (n_i) and diffracted (n_d) optical waves, the velocity $.v.$ of the AW, the effective EO coefficient p_{eff}, and the density ρ of the material. Since the AO figure of merit determines the diffracted portion of the input optical intensity, this parameter is very important from the viewpoint of energy consumption. In other words, it determines the acoustic power needed for reaching a required level of intensity of the diffracted beam. The AO figure of merit can be increased by accounting for the anisotropy of AW velocities and EO coefficients (see, e.g., Refs. [7, 8]). However, in many cases this approach leads to inconvenient geometries of AO interactions.

It is a known fact that consideration of optical activity in one of the most efficient AO materials, TeO_2 crystal, gives rise to increasing AO figure of merit from (600–800)×10^{-15} s^3/kg for the linearly polarized optical waves up to 1200×10^{-15} s^3/kg for the circularly polarized waves [9], whenever the incident and diffracted optical beams propagate in the vicinity of optic axis. Paratellurite is not the only material where consideration of the optical activity can increase the AO figure of merit. In the recent work [10], it has been found that the diffraction efficiency in optically active α-HIO_3 crystals increases significantly when the incident and diffracted optical waves propagate along the directions close to the optic axis.

In our recent work [11] we have demonstrated that essential enhancement of the AO efficiency in the presence of natural optical activity is caused by the ellipticity of optical eigenwaves. The latter effect imposes contributions of extra components of the EO tensor to the effective EO coefficient. It has been assumed in Ref. [11] that the optical activity induced by either electric or magnetic field due to an electro-gyration or a Faraday effects can also increase the effective EO coefficients and the diffraction efficiency. The aim of the present work is to analyze the influence of a magnetic field-induced ellipticity of optical eigenwaves on the effective EO coefficients and the AO figure of merit. Here we choose canonical KH_2PO_4 crystals as an example.

2. Method of analysis

The KH_2PO_4 crystals chosen for our analysis are well known as a material used as a working element of many optoelectronic devices. The AO figure of merit for KH_2PO_4 is not high enough. Its highest value, 7.1×10^{-15} s^3/kg, is achieved in the case of isotropic AO interaction. Then the optical wave polarized inside the *XY* plane propagates along the $[\bar{1}10]$ direction and interacts with the longitudinal AW propagating in the same plane along the [110] direction [8]. The KH_2PO_4 crystals are not optically active when the light propagates along the four-fold symmetry axis or in the mirror planes. Their only nonzero gyration-tensor components are g_{11} and $g_{22} = -g_{11}$.

When calculating the efficient EO coefficient, we neglect the ellipticity of eigenwaves caused by the natural optical activity in case when the light propagates along the *X* axis. This is a reasonable approximation since the effect is very small and, moreover, it is masked by a much larger linear birefringence. The refractive indices are equal to n_o = 1.5073 and n_e = 1.4668 at the wavelength 632.8 nm of optical radiation [12]. In the present work, we will consider an isotropic AO interaction in the (010) and (110) planes with a quasi-longitudinal AW. The Bragg angle has been chosen to be equal to $\theta_B = 0.1$ deg at the AW frequency ~ 46 MHz. The EO-tensor components involved in this type of AO interactions are as follows: p_{11} = 0.238±0.024, p_{12} = 0.249±0.013, p_{13} = 0.242±0.012, p_{31} = 0.227±0.011, and p_{33} = 0.242±0.024 (at λ = 632.8 nm) [13]. Note that these coefficients are much larger than the EO components p_{44} = –0.021±0.0021 and p_{66} = –0.068±0.003 [13] which are responsible for the AO interaction with quasi-transverse AWs. The AW velocities have been calculated using a known Christoffel equation and the data for the elastic-stiffness coefficients ($C_{11} = C_{22}$ = 71.4±0.8, C_{33} = 56.15±0.3, C_{12} = –4.9±1.0, $C_{13} = C_{23}$ = 12.9±0.3, C_{44} = 12.7±0.1, and C_{66} = 6.24±0.05 GPa [14] – see Ref. [8]). All of those coefficients have been determined under the condition of constant electric induction. The density of the KH_2PO_4 crystals is equal to $\rho = 2338$ kg/m^3 [15].

The specific Faraday rotation is determined by the formula

$$\rho_i = \frac{\pi n_o^3}{\lambda} F_{il} H_l \,, \tag{3}$$

where F_{il} is the Faraday tensor and H_l the magnetic field. In our calculations, we assume that the magnetic field is applied along the Z axis. The Verdet constant for KH_2PO_4 is equal to $V = 207$ deg×m^{-1}×T^{-1} at 632.8 nm [16]. Then the relevant Faraday-tensor component is equal to $F_{33} = 2.15\times10^{-11}\,\mathrm{Oe}^{-1}$. The ellipticities of the eigenwaves and the effective EO coefficients can be obtained similarly to the derivation in Ref. [11]. The ellipticity of the optical eigenwaves is defined as

$$\chi(\theta) = \frac{1}{2F'_{33}(\theta)H_3}\left(n_o^2 - n_e^{*2} - \sqrt{(n_o^2 - n_e^{*2})^2 + 4(F'_{33}(\theta)H_3)^2}\right) \approx \frac{F'_{33}(\theta)H_3}{n_o^2 - n_e^{*2}} \,, \tag{4}$$

where

$$n_e^* = \sqrt{\frac{n_o^2 n_e^2}{n_e^2\cos^2(\theta_B+\theta) + n_o^2\sin^2(\theta_B+\theta)}} \,, \tag{5}$$

$$F'_{33}(\theta) = F_{33}\cos^2(\theta+\theta_B) \,, \tag{6}$$

and θ implies the angle between the wavevector of the incident optical wave and the Z axis. Then the efficient EO coefficients for the type I (the optical waves are n_o-polarized) and the type II (the optical waves are n_e-polarized) of isotropic AO interactions with the quasi-longitudinal AW read as

$$p_{eff}^{2(I)} = \left(p_{12}\cos\theta\cos\zeta_2 + p_{13}\sin\theta\sin\zeta_2\right)^2 + 0.5\chi^2 \begin{pmatrix} \left(p_{11}\cos\theta\cos\zeta_2 + p_{13}\sin\theta\sin\zeta_2\right)^2\cos^4\theta \\ +\left(p_{31}\cos\theta\cos\zeta_2 + p_{33}\sin\theta\sin\zeta_2\right)^2\sin^4\theta \\ +0.5\left(p_{44}\sin(\zeta_2+\theta)\right)^2\sin^2 2\theta \\ +\left(p_{11}\cos\theta\cos\zeta_2 + p_{13}\sin\theta\sin\zeta_2\right) \\ \times\left(p_{44}\sin(\zeta_2+\theta)\right)\sin 2\theta\cos^2\theta + \left(p_{44}\sin(\zeta_2+\theta)\right) \\ \times\left(p_{31}\cos\theta\cos\zeta_2 + p_{33}\sin\theta\sin\zeta_2\right)\sin 2\theta\sin^2\theta \end{pmatrix} , \tag{7}$$

$$\begin{aligned} p_{eff}^{2(II)} = {} & \cos^2(\theta_B+\theta)\begin{bmatrix} (p_{11}\cos\theta\cos\zeta_2 + p_{13}\sin\theta\sin\zeta_2)^2\cos^2\theta \\ +(p_{44}\sin(\zeta_2+\theta))^2\sin^2\theta \end{bmatrix} \\ & +(p_{44}\sin(\zeta_2+\theta))\sin 2\theta \\ & \times\begin{bmatrix} (p_{11}\cos\theta\cos\zeta_2 + p_{13}\sin\theta\sin\zeta_2)\cos^2\theta \\ +(p_{31}\cos\theta\cos\zeta_2 + p_{33}\sin\theta\sin\zeta_2)\sin^2\theta \end{bmatrix} \\ & +\sin^2(\theta_B+\theta)\begin{bmatrix} (p_{44}\sin(\zeta_2+\theta))^2\cos^2\theta \\ +(p_{31}\cos\theta\cos\zeta_2 + p_{33}\sin\theta\sin\zeta_2)^2\sin^2\theta \end{bmatrix} \\ & +\chi^2\left[(p_{12}\cos\theta\cos\zeta_2 + p_{13}\sin\theta\sin\zeta_2)^2\right] \end{aligned} . \tag{8}$$

Here ζ_2 represents the angle of deviation of the AW polarization from the purely longitudinal state, which is given by the relation $\tan 2\zeta_2 = \dfrac{(C_{13}+C_{44})\sin 2\Theta}{(C_{11}-C_{44})\cos^2\Theta+(C_{44}-C_{33})\sin^2\Theta}$, when the AW propagates in the (010) plane. The second terms in the r. h. s. of Eqs. (8) determine the increments of the effective EO coefficients (Δp_{eff}^2) due to a nonzero ellipticity of the optical eigenwaves. The AW velocities depend on the angle Θ between the wavevector of the AW and the X as follows:

$$v_{QL}(\Theta)=\frac{1}{2}\left(\begin{array}{l}(C_{11}+C_{44})\cos^2\Theta+(C_{44}+C_{33})\sin^2\Theta\\ \hline +\sqrt{\left((C_{11}-C_{44})\cos^2\Theta+(C_{44}-C_{33})\sin^2\Theta\right)^2+(C_{13}+C_{44})\sin^2 2\Theta}\end{array}\right). \quad (9)$$

We have analyzed the dependence of the effective EO coefficient and the AO figure of merit for the interaction plane (110), too. The dependence of the AW velocity on the angle Θ between the bisector of the X and Y axes (i.e., the X' axis) and the wavevector of the AW can be written as

$$v_{QL}(\Theta)=\frac{1}{2}\left(\begin{array}{l}(0.5(C_{11}+C_{12}+2C_{66})+C_{44})\cos^2\Theta+(C_{44}+C_{33})\sin^2\Theta\\ \hline +\sqrt{\begin{array}{l}\left((0.5(C_{11}+C_{12}+2C_{66})-C_{44})\cos^2\Theta+(C_{44}-C_{33})\sin^2\Theta\right)^2\\ +(C_{13}+C_{44})\sin^2 2\Theta\end{array}}\end{array}\right). \quad (10)$$

The squared effective EO coefficients found for the case of AO interactions in the (110) plane are as follows:

$$p_{eff}^{2(I)}=\left(p_{12}\cos\theta\cos\zeta'_2+p_{13}\sin\theta\sin\zeta'_2\right)^2$$
$$+0.5\chi^2\left(\begin{array}{l}\left(0.5(p_{11}+p_{12}+0.5p_{66})\cos\theta\cos\zeta'_2+p_{13}\sin\theta\sin\zeta'_2\right)^2\cos^4\theta\\ +\left(p_{31}\cos\theta\cos\zeta'_2+p_{33}\sin\theta\sin\zeta'_2\right)^2\sin^4\theta\\ +0.5\left(p_{44}\sin(\zeta'_2+\theta)\right)^2\sin^2 2\theta\\ +\left(0.5(p_{11}+p_{12}+0.5p_{66})\cos\theta\cos\zeta'_2+p_{13}\sin\theta\sin\zeta'_2\right)\\ \times\left(p_{44}\sin(\zeta'_2+\theta)\right)\sin 2\theta\cos^2\theta+\left(p_{44}\sin(\zeta'_2+\theta)\right)\\ \times\left(p_{31}\cos\theta\cos\zeta'_2+p_{33}\sin\theta\sin\zeta'_2\right)\sin 2\theta\sin^2\theta\end{array}\right), \quad (11)$$

$$p_{eff}^{2(II)}=\cos^2(\theta_B+\theta)\left[\begin{array}{l}(0.5(p_{11}+p_{12}+0.5p_{66})\cos\theta\cos\zeta'_2+p_{13}\sin\theta\sin\zeta'_2)^2\cos^2\theta\\ +(p_{44}\sin(\zeta'_2+\theta))^2\sin^2\theta\end{array}\right]$$
$$+(p_{44}\sin(\zeta'_2+\theta))\sin 2\theta$$
$$\times\left[\begin{array}{l}(0.5(p_{11}+p_{12}+0.5p_{66})\cos\theta\cos\zeta'_2+p_{13}\sin\theta\sin\zeta'_2)\cos^2\theta\\ +(p_{31}\cos\theta\cos\zeta'_2+p_{33}\sin\theta\sin\zeta'_2)\sin^2\theta\end{array}\right], \quad (12)$$
$$+\sin^2(\theta_B+\theta)\left[\begin{array}{l}(p_{44}\sin(\zeta'_2+\theta))^2\cos^2\theta\\ +(p_{31}\cos\theta\cos\zeta'_2+p_{33}\sin\theta\sin\zeta'_2)^2\sin^2\theta\end{array}\right]$$
$$+\chi^2\left[(p_{12}\cos\theta\cos\zeta'_2+p_{13}\sin\theta\sin\zeta'_2)^2\right]$$

where $\tan 2\zeta'_2=\dfrac{(C_{13}+C_{44})\sin 2\Theta'}{(0.5(C_{11}+C_{12}+2C_{66})-C_{44})\cos^2\Theta'+(C_{44}-C_{33})\sin^2\Theta'}$ and Θ' implies the angle between the [110] direction and the AW vector.

3. Results and discussion

As seen from Fig. 1, peak-like angular anomalies of the squared effective EO coefficients and the AO figure of merit appear when the AW propagates along the *X* axis and the magnetic field H_3 is applied. This happens at the AO interactions of both types I and II. The magnetic fields 10^6–10^7 Oe evidently increase the effective EO coefficient. For instance, we have the coefficients 0.25 and 0.35 respectively at $H_3 = 0$ and $H_3 = 10^6$ Oe in case of the type I of AO interactions (Fig. 1a). Then the AO figure of merit increases from 1.84×10^{-15} s^3/kg at a zero magnetic field up to 3.52×10^{-15} s^3/kg at $H_3 = 10^6$ Oe (Fig. 1b). In case of the AO interactions of the type II, the effective EO coefficient increases from 0.24 up to 0.35 (Fig. 1c), while the AO figure of merit changes from 1.68×10^{-15} s^3/kg up to 3.52×10^{-15} s^3/kg under the same conditions (Fig. 1d). Hence, the effective EO coefficient increases by ~ 30%, while the AO figure of merit becomes ~ 50% higher under the influence of the magnetic field.

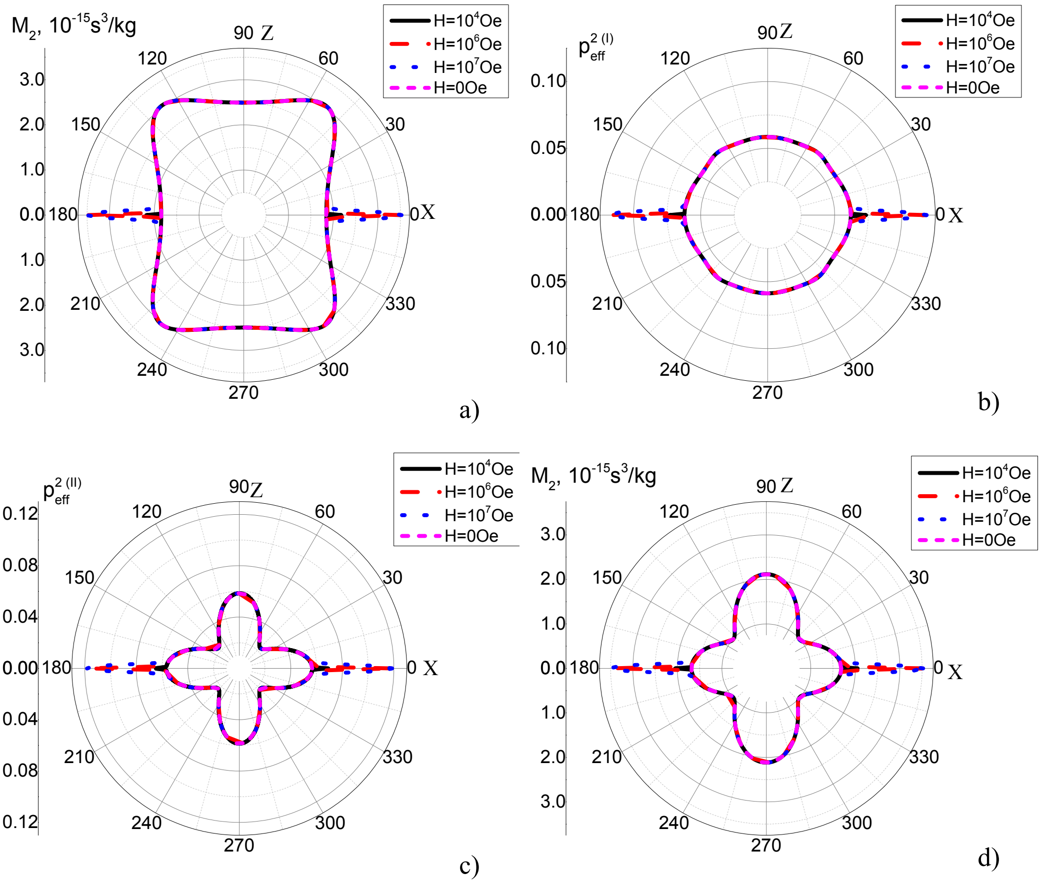

Fig. 1. Dependences of squared effective EO coefficient (a, c) and AO figure of merit (b, d) for AO interactions of the types I (a, b) and II (c, d) on the angle Θ between the wavevector of the AW and the *X* axis.

The increment of the squared effective EO coefficient increases rapidly with increasing magnetic field and saturates at $H_3 = 10^6$ Oe (Fig. 2a, c). The behaviour of the full width at half maximum (FWHM) of an angular peak peculiar for the effective EO coefficient is not monotonous (Fig. 2 b, d). For both types of the AO interactions, the FWHM rapidly increases from zero to 1.04 deg when the magnetic field increases from zero to 10^4 Oe. It remains almost invariable up to the magnetic field strengths ~ 10^6 Oe. Then the FWHM increases almost linearly with further increase in the magnetic field. Thus, the increment of the effective EO coefficient ceases to increase above $H_3 = 10^6$ Oe although the peak of this coefficient broadens.

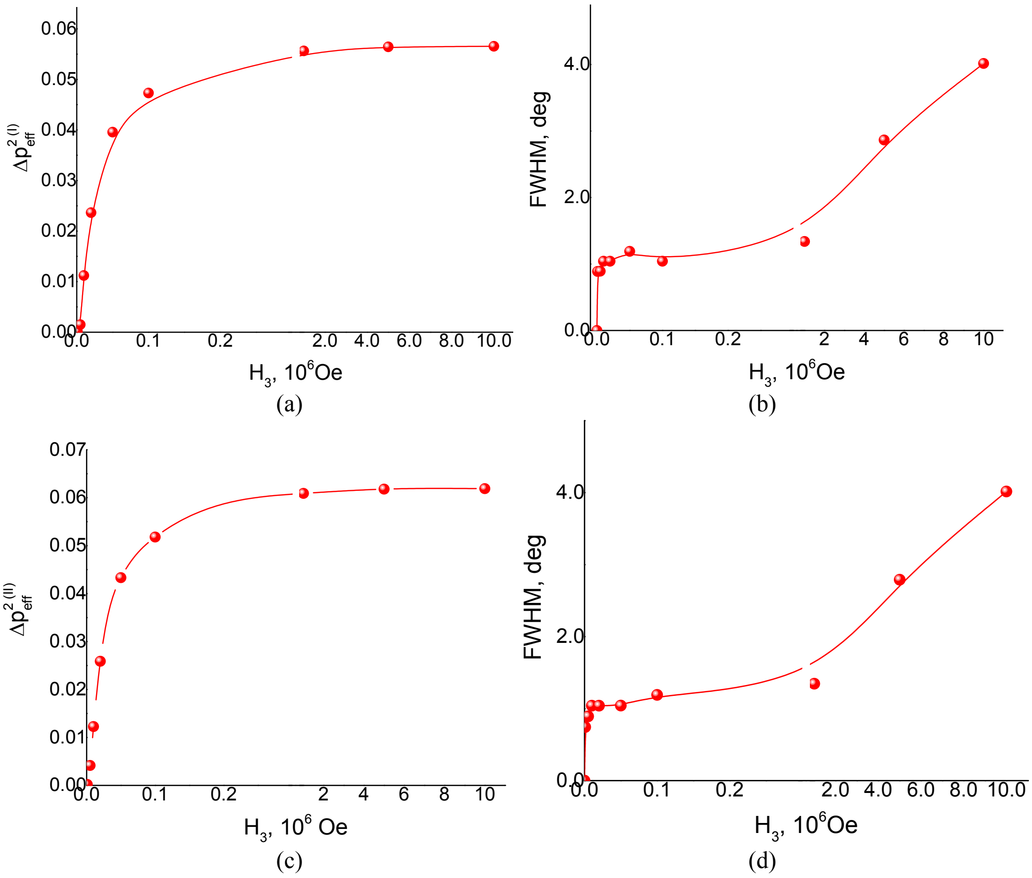

Fig. 2. Increment of the squared effective EO coefficient (a, c) and FWHM of angular peak of the effective EO coefficient (b, d) as functions of the magnetic field H_3, as found for AO interactions of the types I (a, b) and II (c, d).

It has been shown in our recent work [8] that the minimal AW velocity for the quasi-longitudinal AW in the KH_2PO_4 crystals corresponds to its propagation along the [110] direction. Then the AW velocity is equal to 4110 m/s. This is the reason why the AO figure of merit reaches its highest value, 7.1×10^{-15} s^3/kg, in case of the interaction with this AW [8]. However, a consideration in Ref. [8] has addressed the interaction (001) plane. If we analyze the influence of the Faraday rotation on the AO figure of merit for the case of the AO interactions occurring in the (001) plane, the ellipticity of optical eigenwaves remains negligibly small due to a high linear birefringence. This is why we consider the AO interaction in the (110) plane with the slowest quasi-longitudinal AW that propagates along the [110] direction. In this case, the optical waves propagate along the directions close to the optic axis where the magneto-induced ellipticity of the eigenwaves is high enough. As seen from Fig. 3a, c, the effective EO coefficient then increases from 0.25 to 0.37 for the type I of AO interactions and from 0.23 to 0.34 for the type II of AO interactions, whenever the magnetic field is applied. Under these conditions, the AO figures of merit increases from 4.48×10^{-15} to 8.18×10^{-15} s^3/kg and from 3.7×10^{-15} to 8.18×10^{-15} s^3/kg respectively for the OA interactions of the types I and II.

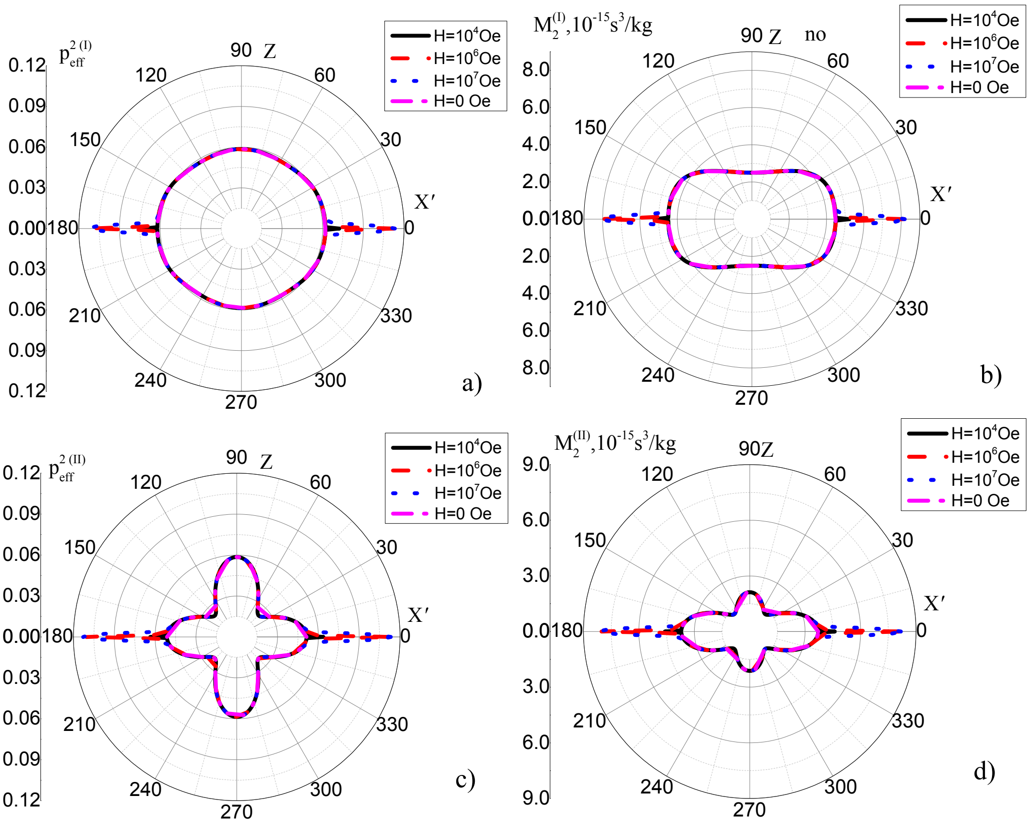

Fig. 3. Dependences of effective EO coefficients (a, c) and AO figures of merit (b, d) on the angle Θ' between the AW vector and the X' axis (i.e., the [110] direction), as calculated for AO interactions of the types I (a, b) and II (c, d) in the (110) plane.

4. Conclusion

In the present work, we have revealed for the first time that the AO efficiency can be enhanced by the magnetic field which induces the ellipticity of the optical eigenwaves due to the Faraday effect. The analysis has been carried out on the particular example of KH_2PO_4. The latter crystals do not manifest the natural optical rotation at the light propagation along the optic axis, which corresponds to the isotropic AO interactions with the quasi-longitudinal AW. It has been found that the AO figure of merit can be increased about two times whenever the magnetic field is applied along the optic axis and the incident and diffracted optical waves propagate along the directions close to the optic axis with the polarizations that coincide with those of magnetically induced polarizations of the elliptical eigenwaves.

We have demonstrated that the angular peaks of the effective EO coefficients increase with increasing magnetic field and reach their saturation at $H_3 = 10^6$ Oe. We have also shown that the FWHM of the angular peak of the effective EO coefficient behaves non-monotonously with increasing magnetic-field strength. Namely, the FWHM increases rapidly from zero to 1.04 deg when the magnetic field increases from zero to 10^4 Oe and then remains almost invariable up to the magnetic fields 10^6 Oe. After that, the FWHM increases almost linearly with further increase in the magnetic field. Above $H_3 = 10^6$ Oe, the magnetically induced increment of the effective EO coefficient ceases to increase and the appropriate angular peak of this coefficient broadens. Our results testify the possibilities for controlling the efficiency of the AO Bragg diffraction with the aid of the magnetic field. The magnetic fields needed for reaching saturation of the AO figure of merit depend on the Faraday-tensor components of a material under test. From this viewpoint, magnetically ordered materials seem to be particularly efficient.

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Анотація. *Вперше показано, що акустооптичну ефективність можна підвищити за рахунок індукованої магнітним полем еліптичності оптичних власних хвиль внаслідок ефекту Фарадея. Ми виявили, що акустооптичну ефективність кристалів* KH_2PO_4 *можна збільшити приблизно вдвічі, якщо прикласти магнітне поле вздовж оптичної осі, падаюча та дифрагована оптичні хвилі поширюються вздовж напрямків, близьких до оптичної осі, а їхні поляризації є такими ж, як магнітоіндукована поляризація еліптичних власних хвиль. Також проаналізовано кутову поведінку піку ефективних пружнооптичних коефіцієнтів та його повної ширини на половині максимуму зі зміною магнітного поля. Наші результати демонструють, що ефективністю акустооптичної дифракції Брегга можна керувати за допомогою магнітного поля. Магнітне поле, необхідне для підвищення акустооптичної ефективності, залежить від компонента тензора Фарадея даного матеріалу.*

Ключові слова: *акустооптика, ефект Фарадея, еліптичність власних хвиль, дифракційна ефективність, кристали* KH_2PO_4