Acousto-optic collinear diffraction of arbitrary polarized light

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Collinear acousto-optic diffraction of arbitrary polarized light is studied theoretically and experimentally. It is shown that the diffraction spectrum at the output of a collinear acousto-optic cell contains in the general case four optical components which have different polarization and frequency. The frequency shift is caused by the Doppler effect. Beating of these four components leads to modulation of light intensity passed through the output analyzer. In this work, the amplitudes of the modulation components are calculated as functions of frequency and power of the acoustic wave for different polarizer and analyzer orientations. The dependences of the optical beam intensity on the analyzer orientation are examined experimentally for different values of the acoustic power.

1 Introduction

In practical use of collinear acousto-optic (AO) interaction a reasonable question of choosing the incident light beam polarization arises. The choice depends on the type of the medium where the light beam and the acoustic wave propagate. In other words, the type of the material which the AO cell is fabricated from should be taken into account. In modern acousto-optics, solid materials such as crystals and glasses are mainly used. In these materials, the axes of anisotropy which define the polarization of optical eigenmodes either are predetermined by crystal symmetry or appear under the action of ultrasound excited in the medium. However, in any case the magnitude of the AO effect strongly depends on the incident light polarization [1,2]. Therefore, the correct choice of the input light polarization is very important in any AO experiment. Usual recommendations amount to the following: in an anisotropic medium the incident radiation has to have the polarization of one of the medium eigenmodes, whereas in an isotropic medium the polarization vector has to be directed along one of the sound-induced anisotropy axes.

However, AO interaction of an arbitrary polarized light is undoubtedly of theoretical and practical interest as well. Analyzing this problem, the authors [3,4] have shown that in the Raman-Nath regime of diffraction the rotation of the polarization plane can occur through an angle depending on the acoustic power. A similar result has been obtained in [5] with respect to the 1st order of the Bragg diffraction. As for the intermediate regime of diffraction which corresponds better to a real situation, the situation is much more complicated. In this case the additional phase shift appears in all diffraction orders [6-8] which has to be taken into consideration at the analysis of the output light polarization. Due to this effect, the linearly polarized optical beam becomes elliptically polarized [9-11]. Changing the power or the frequency of the acoustic wave, one can control the light polarization.

In all papers mentioned only quasi-orthogonal geometry of AO interaction was examined. The question about the influence of light polarization on collinear diffraction characteristics is open until now. The given work presents results of such an investigation. The calculations have been made in the plane-wave approximation. Preliminary experiments are fulfilled with an AO collinear cell made of a calcium molybdate ($CaMoO_4$) single crystal.

2 Basic relationships

The distinguishing peculiarity of the collinear AO interaction is that the incident and diffracted optical beams and the acoustic wave propagate in an anisotropic medium along the same direction. The principle scheme for realization of collinear diffraction is shown in Fig. 1 [12,13]. In the case of a $CaMoO_4$ cell, an acoustic wave excited by a piezoelectric transducer propagates first along the *Z* crystallographic axis and then, after reflection from the input optical face of the cell, is transformed into a shear mode propagating along the *X* axis. The regime of traveling acoustic wave is provided by an acoustic absorber placed at the output end of the cell. A laser beam passes through the cell near the *X* axis and diffracts in the acoustic field, changing its polarization to the orthogonal one. At the conventional applications of the collinear cell as a spectral filter, the polarizer is oriented in such a manner that the input radiation has ordinary or extraordinary polarization, while the analyzer is crossed with the polarizer. Due to this geometry, the diffracted radiation is separated from the incident one. However, if the incident light is not polarized, half the light power is lost in this process. In this work, we examine the case of arbitrary polarization of the incident light.

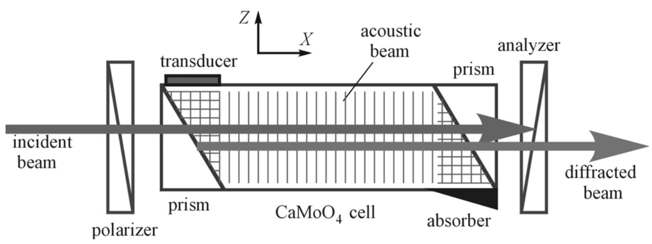


Fig.1. Principle scheme of collinear AO interaction

Let us suppose that the incident radiation is linearly polarized at the angle α with respect to the *Y* axis (Fig. 2). Entering the crystal, the optical wave E_i is split into two waves E_i^Y and E_i^Z polarized along the *Y* and *Z* axes. It is clear that in the general case these two waves are not equal in amplitude. However, if the incident light is nor polarized at all, these components are equal to each other as at $\alpha = 45^\circ$. Thus, our consideration includes the cases of linearly polarized and non-polarized light.

Since the phase matching condition is fulfilled for the both components equally, they diffract in the acoustic field independently from each other. In this case the ordinary wave E_i^Y diffracts into +1st order, forming the waves E_0^Y

(zero order) and E_1^Z (+1st order), while the extraordinary wave E_i^Z diffracts into –1st order, originating the waves E_0^Z (zero order) and E_{-1}^Y (–1st order). The waves E_0^Y and E_0^Z have the same frequency ω as the incident light, whereas the waves E_1^Z and E_{-1}^Y, due to the Doppler effect, have shifted frequencies $\omega + \Omega$ and $\omega - \Omega$ respectively.

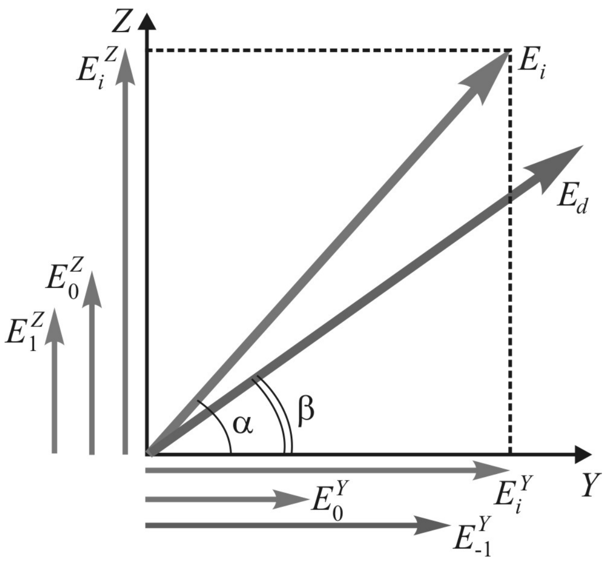


Fig. 2. Polarization of incident and diffracted waves

The analyzer oriented at the angle β let pass only a part of every component. Thus, at the system output the four components can be written as

$$E_{d1} = E_0^Y \cos\beta = E_i \cos\alpha \cos\beta \left(\cos\frac{\mathrm{K}}{2} - j\frac{R}{2}\mathrm{sinc}\frac{\mathrm{K}}{2\pi} \right) \exp\left[j\left(\omega t - k_o l + \frac{R}{2} \right) \right], \quad (1)$$

$$E_{d2} = E_1^Z \sin\beta = -E_i \frac{A}{2} \cos\alpha \sin\beta\, \mathrm{sinc}\frac{\mathrm{K}}{2\pi} \exp\left[j\left((\omega + \Omega)t - k_e l - \frac{R}{2} \right) \right], \quad (2)$$

$$E_{d3} = E_0^Z \sin\beta = E_i \sin\alpha \sin\beta \left(\cos\frac{\mathrm{K}}{2} + j\frac{R}{2}\mathrm{sinc}\frac{\mathrm{K}}{2\pi} \right) \exp\left[j\left(\omega t - k_e l - \frac{R}{2} \right) \right], \quad (3)$$

$$E_{d4} = E_{-1}^Y \cos\beta = E_i \frac{A}{2} \sin\alpha \cos\beta\, \mathrm{sinc}\frac{\mathrm{K}}{2\pi} \exp\left[j\left((\omega - \Omega)t - k_o l + \frac{R}{2} \right) \right], \quad (4)$$

where A is the Raman-Nath parameter proportional to the acoustic wave amplitude, R is the dimensionless phase mismatch [1], $\mathrm{K} = \sqrt{A^2 + R^2}$, k_o and k_e are the propagation constants for the ordinary and extraordinary optical waves accordingly, l is the AO interaction length. The phase mismatch R depends on the optical wavelength λ and the acoustic frequency f:

$$R = 2\pi l \left(\frac{f}{V} - \frac{n_e - n_o}{\lambda} \right) = \frac{2\pi l}{V}\left(f - f_0 \right) \quad (5)$$

where V is the ultrasound velocity, $n_o = k_o \lambda / 2\pi$ and $n_e = k_e \lambda / 2\pi$ are the refractive indices, f_0 is the frequency of collinear phase matching.

At the system output, these four waves interfere with each other. Beatings of shifted (2),(4) and unshifted (1),(3) components result in appearing intensity light modulation with the acoustic frequency Ω, while the beatings of differently shifted components (2) and (4) give intensity modulation with the frequency 2Ω. Therefore, the output light intensity contains three components and can be written in the form

$$I = E_i^2 \left[I_0 + I_1 \cos(\Omega t + \varphi_1) + I_2 \cos 2(\Omega t + \varphi_2) \right] \quad (6)$$

These components can be separated from each other and measured in the experiment.

3 Results of calculations

Below results of computations of the normalized intensities I_0, I_1 and I_2 are presented for different values A and R. The calculations have been fulfilled for a fixed polarization of the incident light ($\alpha = 45^\circ$) and a discrete set of analyzer orientations ($\beta = 0^\circ, 11.2^\circ, 22.5^\circ, 45^\circ$).

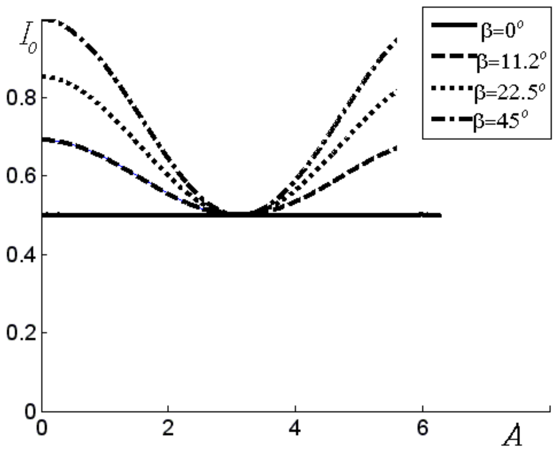
Fig. 3 demonstrates the dependence of I_0, I_1 and I_2 on the Raman-Nath parameter (in fact, on the acoustic wave amplitude) at the frequency of phase matching f_0 (when $R = 0$). Firm curves correspond to the case when the analyzer lets pass the radiation polarized along the Y axis. It is seen that the constant component is always equal to 0.5, the second harmonic is absent completely and the first harmonic changes sinusoidally, reaching maximum value 0.5 at the points $A = \pi/2,\ 3\pi/2,\ \ldots$ This means that at these points the light intensity varies harmonically with the frequency Ω from zero to the incident light intensity E_i^2. The AO cell produces 100% modulation of the optical beam without any light losses. However, the acoustic power required in this case is 4 times less than in the conventional variant of collinear diffraction, when the incident light polarization is chosen along the proper axes of the crystal.

Another interesting variant takes place at $\beta = 45^\circ$ (chain lines). In this case, the constant component changes from 1 to 0.5, the first harmonic is absent and the second harmonic attains extremum at the point $A = \pi$. Thus, at this geometry one can also obtain 100% modulation without light losses, but at the frequency 2Ω.

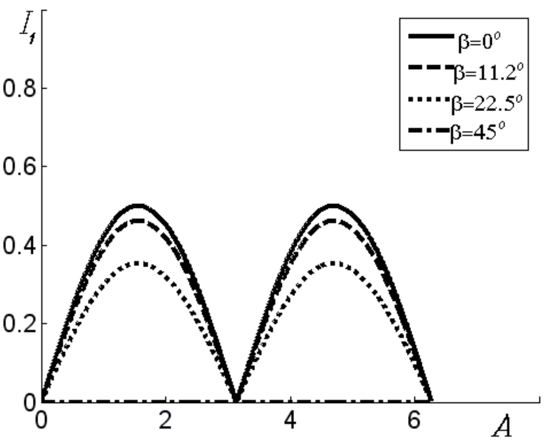
Fig. 4 displays mismatch characteristics obtained at fixed values $A = \pi/2$. As mentioned above, the mismatch R can be varied in experiments by means of changing either the acoustic frequency or the optical wavelength. In the latter case, the obtained curves may be considered as transmission functions of the collinear AO filter [1,2].

The case $\beta = 0^\circ$ is of most interest. Here the constant component does not depend on the mismatch R. The second harmonic is absent at all. Thus, only registering the first harmonic, one can perform the spectral analysis of optical radiation at the given disposition of the polarizers. The spectral transmission function differs from the sinc^2-function that is typical for the conventional collinear filter: in its central part there is rather a broad area with a practically constant transmission coefficient. At the point of phase matching ($R = 0$) the output beam is 100%-modulated without any optical losses. As mentioned above, the required acoustic power is 4 times less; this peculiarity should be considered as an important advantage. However, the variant discussed has also a disadvantage – too large side lobes of the transmission function in comparison to the situation when analyzer and polarizer are crossed (conventional filter). The plots in Fig. 4c are calculated for

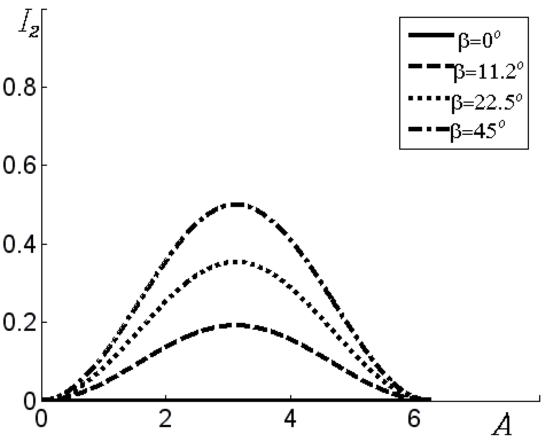
$A=\pi/2$; in the case $A=\pi$ the values I_2 are two times higher. In the case $\beta=45^\circ$, the first harmonic is absent,



(a)

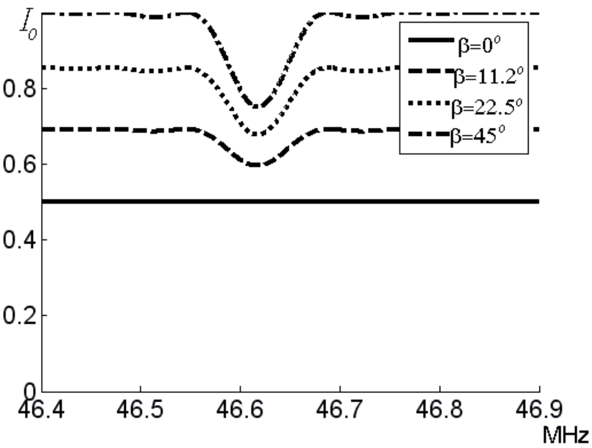


(b)

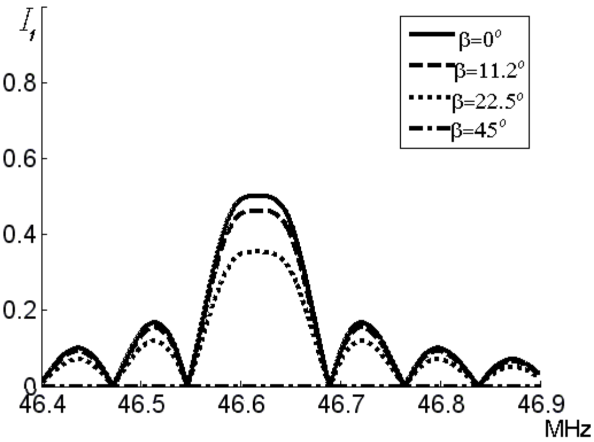


(b)

Fig. 3. Normalized intensities I_0 (a), I_1 (b) and I_2 (c) as functions of Raman-Nath parameter at $R=0$.



(a)



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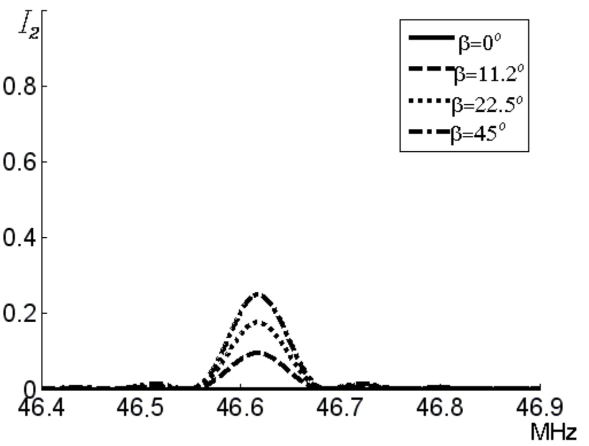

(c)

Fig. 4. Normalized intensities I_0 (a), I_1 (b) and I_2 (c) as functions of mismatch parameter at $A=\pi/2$.

however the second harmonic can be used effectively for optical signal filtration. The transmission function is the same as for the conventional filter, but one can obtain a gain of 2 times in output optical intensity when the incident radiation is not polarized because of no losses in light.

4 Experimental results

An experiment was carried out to verify the theoretical results. In the experiment we used an AO cell fabricated of a $CaMoO_4$ single crystal. An optical radiation of the He-Ne laser with the wavelength $\lambda = 633$ nm together with a shear acoustic wave propagates along the *X* axis of the crystal. The AO interaction length *l* was about 4 cm. The experiment was executed at the acoustic frequency $f_0 = 46.6$ MHz which is the frequency of the collinear phase matching for calcium molybdate. The input polarization was chosen at the angle $\alpha = 45^\circ$ to the *Y* and *Z* axes. In the experiment, we measured the dependence of I_0 and I_1 components of the diffracted optical beam on the angle β in the range from zero to 180 degrees. The measurements were carried out for two values of acoustic power which corresponded to the Raman-Nath parameter magnitudes $A = 1.4$ and $A = 1.8$. Fig. 5a presents these dependences for the constant component I_0. It is seen that I_0 changes with the angle β according to the cosine law and reaches zero at the points $\beta = \pi/4, 3\pi/4 \ldots$. The maximum value I_0 is 0.5. Comparing the theoretical and experimental curves, one can mark a good agreement between theory and experiment. Analogous curves for the first harmonic amplitude I_1 are represented in Fig. 5b.

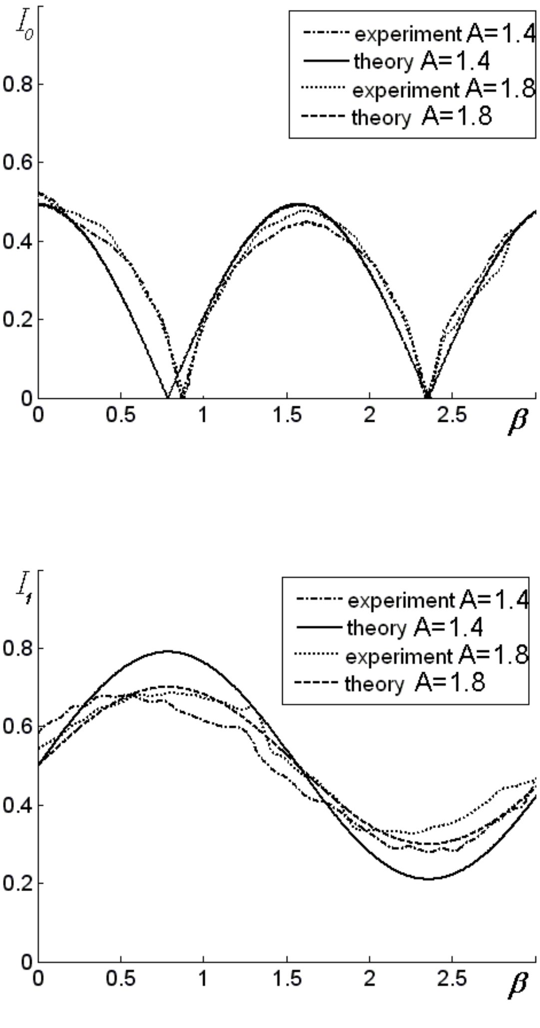

Fig. 5. The constant component I_0 and the 1st harmonic I_1 as functions of the analyzer orientation

5 Conclusion

The paper presents the first analysis of the polarization effects that appear at the collinear AO interaction in the case when the incident optical beam has an arbitrary polarization. Entering the AO cell, the optical wave is split into two components which diffract independently, forming four components of the zero, +1st and –1st orders. Because of the Doppler effect the components of the +1st and –1st orders have shifted frequencies. Beatings of all the components lead to intensity modulation of the light beam at the output of the analyzer. It should be noticed that this is the only case of diffracted light modulation when the light is scattered by the traveling acoustic wave. Depending on the analyzer orientation, one can get 100% modulation at the frequency of ultrasound or at the doubled frequency.

Acknowledgments

This work has been supported in part by the Russian Foundation for Basic Research, grants № 06-07-89309 and № 08-07-00498.

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