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Number of reflecting layers as a dominating factor of the influence of an acoustic grating on the coherence degree of an optical field

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Abstract. **The effect of two main regimes of the anisotropic Bragg acoustooptic (AO) diffraction on the coherence degree of an optical field from the point of view of the number of acoustic grating layers intersected by an optical beam is analysed. It is shown based on the AO interaction in a TeO_2 single crystal that despite a substantial difference (approximately by five times) between acoustic frequencies used in the regimes of large and small angles of light incidence with respect to the acoustic wave front, the character of the speckle pattern is almost the same.**

Keywords: *acoustooptic diffraction, Bragg regime, coherence degree of an optical field.*

The effect of the acoustooptic (AO) Bragg diffraction on the degree of the spatial coherence of a partially coherent optical field was studied in [1 – 3]. It was shown that the regime of anisotropic diffraction most strongly influences it, when optical radiation is incident at a large angle on the front of the acoustic wave (the regime of large angles [3] unlike the regime of small angles, when the angle of incidence is small [4 – 6]). This effect was explained by the fact that the light intersects a great number of layers of the acoustic grating in the regime of large angles. To verify this fact, we compared directly in this paper the effect of these two basic regimes of the anisotropic diffraction at different frequencies (in our experiment the frequencies differed by approximately five times) but for the same number of intersected layers of the acoustic grating on the degree of the spatial coherence of optical radiation.

Let L be the length of the AO interaction. Then the number of the layers of the acoustic grating is

$$N = \frac{L \tan \Theta}{\Lambda} = \frac{Lf \tan \Theta}{\upsilon}, \qquad (1)$$

where Λ, f, υ are the wavelength, frequency and the speed of sound, respectively; Θ is the angle of inclination of the wave light vector $\boldsymbol{k}$ to the front of the acoustic wave. For two different angles of incidence (Θ_1 and Θ_2), the number N of layers remains the same (L and υ are considered constant) only if the condition

$$f_1 \tan \Theta_1 = f_2 \tan \Theta_2 \qquad (2)$$

is fulfilled, where f_1 and f_2 are acoustic waves in the regimes under study.

Figure 1a presents a vector diagram of two regimes of the AO diffraction in a uniaxial positive crystal – the regime of small angles (the incident radiation with the wave vector $\boldsymbol{k}_{\rm i1}$ diffracts in the direction $\boldsymbol{k}_{\rm d1}$ upon interaction with the acoustic wave with the wave vector $\boldsymbol{q}$) and the regime of large angles (radiation with the wave vector $\boldsymbol{k}_{\rm i2}$ diffracts in the direction $\boldsymbol{k}_{\rm d2}$ upon interaction with the same wave). Here, the sound wave propagates perpendicular to the optical axis Z of the crystal. Figure 1b shows the propagation of radiation with the vectors $\boldsymbol{k}_{\rm i1}$ and $\boldsymbol{k}_{\rm i2}$ through the acoustic grating of width L. We assume that the incident beams are 'ordinary' ones and Θ_1 and Θ_2 are the angles

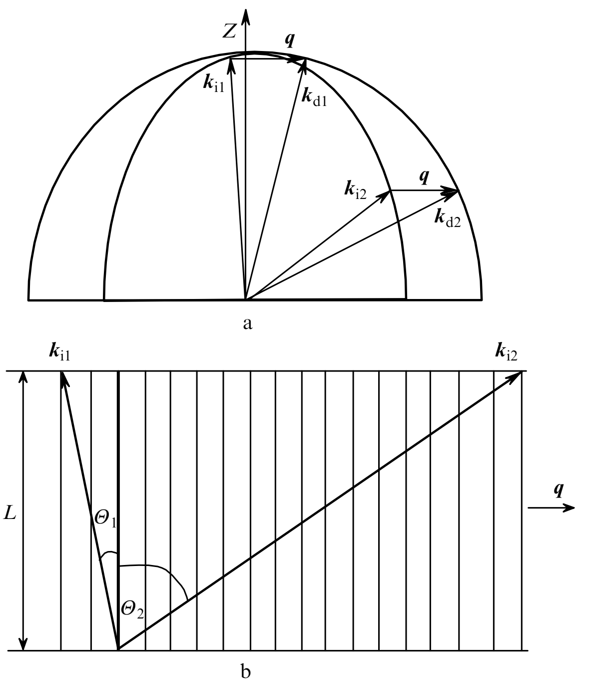

Figure 1. Vector diagram of two regimes of anisotropic AO diffraction (a) and propagation of incident beams through the acoustic grating (b).

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between the wave vectors $\boldsymbol{k}_{i1}$, $\boldsymbol{k}_{i2}$ and the front of the acoustic wave, respectively.

The frequency and the corresponding angle cannot be chosen arbitrarily because they are related by the Bragg matching condition. In our case, this relation is described by the expression [4–6]

$$f_1 = \frac{\upsilon}{\lambda_0} \sin \Theta_1 (n_e + n_o) \tag{3}$$

for the regime of small angles of incidence and

$$f_2 = \frac{\upsilon}{\lambda_0} \sin \Theta_2 (n_e - n_o) \tag{4}$$

for the regime of large angles. Here, λ_0 is the light wavelength; n_o, n_e are the principal refractive indices of the crystal. By solving (3), (4) and (2) together, we obtain the equation relating frequencies f_1 and f_2:

$$f_2^4 + A\lambda_0^2 f_2^2 - A\upsilon^2 (n_e - n_o)^2 = 0, \tag{5}$$

where

$$f_2^2 = \left[\left(\frac{A\lambda_0^2}{2} \right)^2 + A\upsilon^2 (n_e - n_0)^2 \right]^{1/2} - \frac{A\lambda_0^2}{2}; \tag{6}$$

$$A = \frac{f_1^4}{\upsilon^2 (n_e + n_0)^2 - f_1^2 \lambda_0^2}. \tag{7}$$

Based on the parameters of the TeO_2 crystal for the emission at a wavelength $\lambda_0 = 0.63 \times 10^{-4}$ cm ($\upsilon = 0.6 \times 10^5$ cm s^{-1}, $n_o = 2.26$ and $n_e = 2.41$), it is easy to show by analysing (6) and (7) that the ratio f_1/f_2 of the frequencies remains virtually invariable and is ~ 5.6 upon changing the frequency f_1 from 50 to 200 MHz. Taking into account the gyrotropy of the TeO_2 crystal, the above calculations become more complicated; however, their influence on the final results is insignificant. In particular, the ratio of the frequencies becomes equal to ~ 5. Figure 2 presents the dependences of the number N of layers of the acoustic grating on the sound frequency obtained for the same parameters by using relation (1). In the calculations L was set equal to 0.5 cm (which corresponded to the experimental conditions).

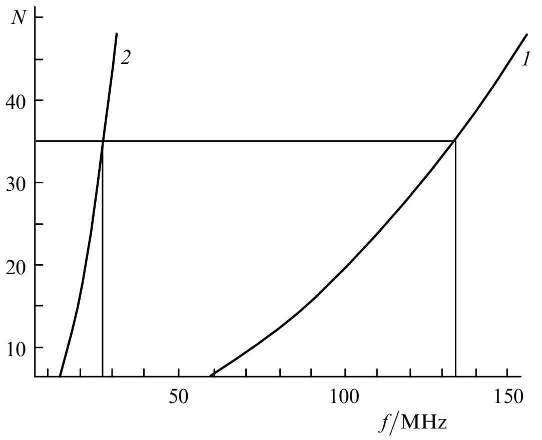

Figure 2. Dependences of the number N of intersected optical beams on the acoustic wave frequency for the regime of small (*1*) and large (*2*) angles.

By setting the number of layers $N = 35$ in Fig. 2, we obtain $f_1 \sim 133$ MHz and $f_2 \sim 27$ MHz. We used these frequencies in the experiment to verify the equivalence of the speckle pattern formed due to the AO diffraction in the regimes of large and small angles. We fabricated a TeO_2 AO cell in which a transverse acoustic wave was generated at the first harmonic frequency ~ 26.5 MHz and bandwidth $\sim 15\,\%$ and at the fifth harmonic frequency ~ 133 MHz and the bandwidth $\sim 1\,\%$.

The optical scheme of the experimental setup is shown in Fig. 3. Radiation from LGN-207A He–Ne laser (*1*) at 0.63×10^{-4} cm and the coherence length ~ 20 cm propagated through glass plate (*2*), one side of which was polished with the M5 powder. Partially coherent radiation appearing after propagation through the plate was transformed by lenses (*3*) into a weakly converging beam. The radiation divergence was $\sim 0.5°$ and the waist diameter was ~ 0.8 cm. Radiation was directed to AO cell (*5*), which was in the beam waist. The distance from lenses (*3*) to the beam waist was ~ 50 cm. Diaphragm (4) was placed directly in front of the AO cell to decrease the parasitic noises. Screen (*6*) mounted at a distance of ~ 150 cm from the AO cell was used to observe diffraction spots, whose pictures were taken by using 'Zenith' film camera (*7*), which allowed us to take photographs with a high spatial resolution.

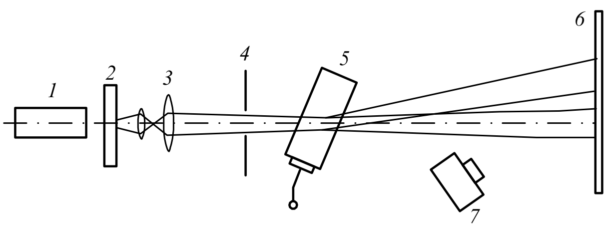

Figure 3. Optical scheme of the experiment.

Figure 4 presents the photographs of the speckle pattern of radiation diffracted at frequencies $f_2 = 27$ MHz and $f_1 = 133$ MHz. Note, first of all, that the half widths of the diffracted spots are different. This is explained by the change in the angular divergence of the sound wave with increasing the frequency: $\Delta\varphi_{ac} \approx \Lambda/D = \upsilon/(fD)$, where D is the converter aperture. When the frequency changes by five times, the half width of the spot should change by the same value. However, it changed only by two–three times in the experiment. The discrepancy with the experiment is explained by the fact that at small sound frequencies the divergence of the incident light wave, which is smaller than the divergence of the sound wave, is the key factor, and at large sound frequencies, the situation is opposite, i.e. the divergence of the sound wave, which becomes smaller than the divergence of the incident radiation, is the key factor. The divergence of the diffracted radiation, as is known [7], is determined by the smallest divergence of the incident light and sound waves.

Figure 4c, d presents typical profiles of speckle patterns of Figs 4a, b in the cross sections of the beams close to the central section after digital processing. One can see that the oscillation periodicity, the distance between the maxima and the depth of curve modulation in Figs 4c, d are close to each

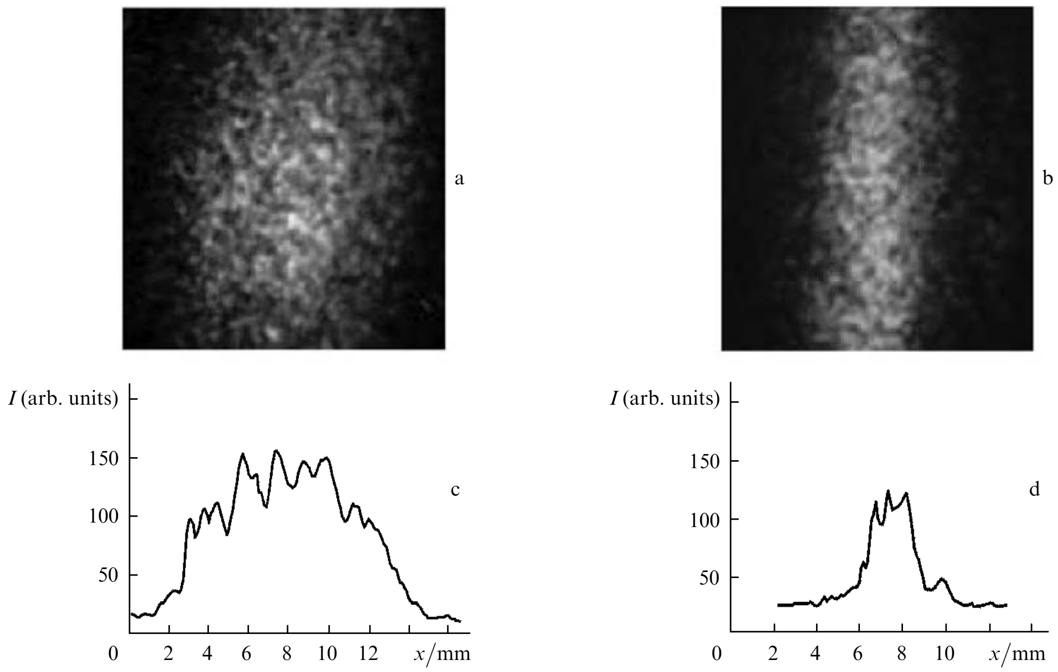

Figure 4. Photographs of the radiation speckle pattern obtained due to the AO diffraction in the regimes of large (a) and small (b) angles and characteristic intensity profiles of diffracted radiation (c, d) corresponding to these speckle patterns obtained near the central cross section of the beam.

other, i.e. in our opinion the parameters of the speckle structures coincide with a good accuracy.

For a quantitative estimate of the coherence degree of the optical field, advantage can be taken of the Gauss – Sheel model [3, 8] according to which the field is represented by a set of randomly distributed Gaussian beams. Mathematically it can be written as

$$I(x_1, x_2) = \frac{2I_0}{\pi\omega^2}\exp\left[-\frac{x_1^2 + x_2^2}{\omega^2}\right]\exp\left[-\frac{(x_1 - x_2)^2}{2\sigma^2}\right]. \quad (8)$$

Here, I, I_0 are the distribution of the field and the total intensity, respectively; x_1 and x_2 are arbitrary points in the fixed plane of the screen; ω and σ determine the beam half width at the e^{-2} intensity level and a modulus of the complex degree of spatial coherence (at the $e^{-0.5}$ level), respectively. We will assume that the divergences of partial Gaussian beams are equal and coincide with the radiation divergence of the He – Ne laser, i.e. $\omega \approx 0.5$ mm. This value well describes the maxima in Fig. 4a, b. To estimate the degree σ of the spatial coherence entering expression (8), we will use the mean distance between adjacent maxima, which are equal to ~ 1 mm. In other words, at a distance of 1 mm adjacent beams do not 'feel' each other already. This gives $\sigma \approx 0.25$ mm. Note that the speckle pattern of incident radiation noticeably differs from the speckle structure of diffracted radiation: the distance between the adjacent maxima for the initial radiation is significantly lower. According to our estimates, $\sigma \approx 0.1$ mm for incident radiation. Detailed studies devoted to the comparison of speckle patterns of an incident beam and a beam diffracted due to Bragg AO diffraction in the TeO_2 single crystal, were performed in [3].

Therefore, in this paper

(i) two main regimes of anisotropic AO diffraction have been considered (from the point of view of the number of layers of the acoustic grating intersected by an incident light wave), the technique of search for frequency-angular parameters of such regimes has been elaborated, numerical calculations have been performed;

(ii) in accordance with the calculations the experiment is performed by using a TeO_2 single crystal;

(iii) experimental results show that the character of the spectral pattern of the optical field diffracted in the regime of large angles coincides with the character of the field diffracted in the regime of small angles, if the number of layers of the acoustic grating intersected by light is the same. In this case, the acoustic frequencies and divergences of diffracted beams can differ several-fold.

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