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Multiplication of the frequency shift of optical radiation by means of cascade acousto-optic interaction

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Abstract. A method for increasing the frequency shift of optical radiation by means of cascade acousto-optic diffraction of light is proposed and studied. The method is based on special features of anisotropic diffraction in an anisotropic medium and optical properties of gyrotropic media. Five-cascade diffraction of radiation from a He – Ne laser ($\lambda = 0.633$ μm) in a $\mathrm{TeO_2}$ single crystal with an efficiency of 8% was obtained experimentally.

The frequency shift due to acousto-optic (AO) interaction is used extensively for frequency modulation in optical fibre communication links [1], for optical heterodyning [2], and in various physical sensors, such as anemometers [3], gyroscopes [4], etc. The use of AO diffraction is attractive for such applications because of the ease of obtaining a frequency shift by this method, which is produced by the reflection of an optical beam from a travelling acoustic wave. In the Bragg diffraction regime (only this regime is considered in this paper), the frequency ω_{d} of the diffracted beam is determined by the expression $\omega_{\mathrm{d}} = \omega_{\mathrm{i}} \pm \Omega$, where ω_{i} is the frequency of the incident beam and Ω is the frequency of the acoustic wave [5, 6].

It is often important in practice that the frequency shift of an optical signal be increased considerably. The simplest way to do this is to use the Raman – Nath AO diffraction [5, 6], in which the beams diffracted into higher orders are shifted in frequency by $n\Omega$, where n is the diffraction order. However, this process is characterised by high optical loss because the intensity of higher orders is, as a rule, low, which makes the method inefficient. As a result, it would be more advantageous to solve the problem of frequency shift multiplication by using Bragg diffraction.

Note that several methods for solving this problem are described in the literature. In particular, two-frequency [6, 7] and mutifrequency (three- and four-photon) [8] Bragg scattering of light by elastic waves was studied. However, the experimental realisation of frequency shift multiplication by a factor of more than four by using Bragg diffraction with one AO cell is unknown.

In Ref. [9] the AO diffraction was analysed theoretically for the case where a light beam is reflected successively from four lateral faces of an acousto-optic guide and is virtually always found in the field of an acoustic wave. According to the estimates made there, the frequency shift may exceed 530 f, where f is the acoustic frequency. However, it is very difficult to fabricate such a cell because the fabrication of multipass optical elements (interferometers, etalons, Lummer – Gehrke plates, etc. (see, e.g., Ref. [10]), especially in the case of large-size ($\sim$10 cm) elements, considerably increases the requirements imposed on the optical homogeneity of a material, its temperature stability and tempera-ture uniformity during the operation, and geometric and technological characteristics of working faces (such as planeness, roughness, etc.).

In this paper, we propose and demonstrate experimentally the cascade AO diffraction method, which consists of multiple, successive diffraction of an optical beam by the same acoustic wave and makes it possible, in principle, to shift the optical frequency by a value exceeding the acoustic frequency by more than an order of magnitude. The method is based on a well-known feature of AO diffraction in an anisotropic medium, which consists of the difference of angles of incidence and scattering of light in the case of anisotropic AO interaction. Fig. 1 presents the vector diagram of anisotropic diffraction in a uniaxial crystal. The incident optical radiation with the vector $\boldsymbol{K}_{\mathrm{i}}$ (for definiteness, it is assumed to be an ordinary beam) travels at the angle Θ_{i} to the z axis and diffracts from the acoustic wave with the wave vector $\boldsymbol{q}$ in the direction $\boldsymbol{K}_{\mathrm{d}}$ (an extraordinary ray) at the angle Θ_{d} to the z axis. We assume that $\boldsymbol{q} \perp z$. The angle Θ_{i} and Θ_{d} are determined by Dixon relations [11]

$$\begin{aligned} \sin\theta_{\mathrm{i}} &= \frac{\lambda_0}{2Vn_{\mathrm{i}}}\left[f + \frac{V^2}{f\lambda_0^2}\left(n_{\mathrm{i}}^2 - n_{\mathrm{d}}^2\right)\right], \\ \sin\theta_{\mathrm{d}} &= \frac{\lambda_0}{2Vn_{\mathrm{d}}}\left[f - \frac{V^2}{f\lambda_0^2}\left(n_{\mathrm{i}}^2 - n_{\mathrm{d}}^2\right)\right], \end{aligned} \tag{1}$$

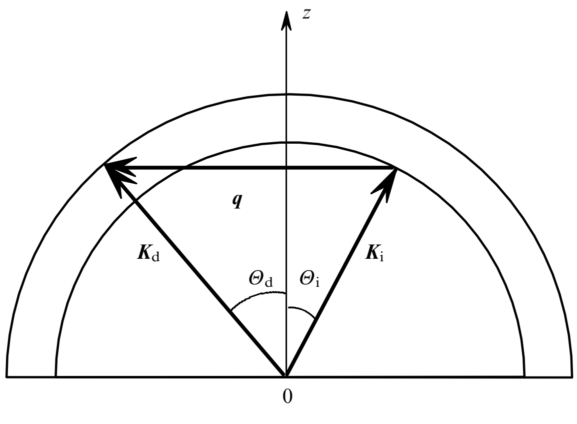

Figure 1. Vector diagram of anisotropic AO diffraction.

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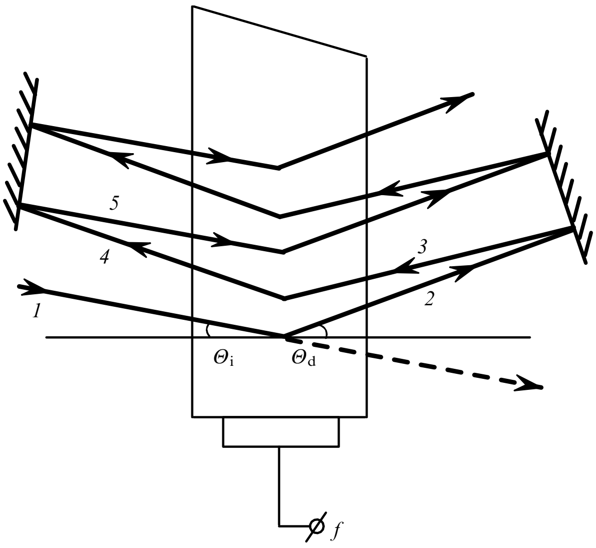

Figure 2. Schematic optical diagram of the system for obtaining the frequency shift by using cascade diffraction in an AO cell.

where λ_0 is the wavelength of optical radiation, n_i and n_d are the refractive indices for incident and diffracted beams, respectively, and f and V are the frequency and velocity of the acoustic wave. In particular, one can see from Eqns (1) that the larger the difference $n_i^2 - n_d^2$, the larger the difference between Θ_i and Θ_d.

Fig. 2 presents the schematic optical diagram of the method proposed for the cascade multiplication of the frequency shift. The initial optical radiation 1 (for definiteness, it is assumed to be the ordinary ray) is incident at an angle Θ_i to the direction of propagation of the acoustic wave in an AO cell and diffracts in the direction of beam 2 at the angle $\Theta_d \neq \Theta_i$. Beam 2 is reflected from a mirror, which is oriented so that the reflected radiation (beam 3) is incident at an angle Θ_i to the direction of the acoustic wave and be diffracted at an angle Θ_d in the direction of beam 4. Beam 4 reflected from the second mirror in the direction of beam 5, which also makes the angle Θ_i with the direction of the acoustic wave, and so on. One can see from Fig. 2 that the beams diffract at different points of the crystal. This provides an easy control of the number of AO reflections and makes it possible to couple out the resulting optical signal from the AO element by simply choosing sizes of the mirrors.

We emphasise that the optical beam at each diffraction stage shown in Fig. 2 is found in exact Bragg synchronism with the acoustic wave; i.e., in the case of 100% diffraction efficiency, the intensity of the beam that has diffracted n times from the acoustic wave should be equal to the initial radiation intensity. It is evident that this ideal situation is not realised in practice because of the impossibility of obtaining 100% diffraction efficiency, loss inside the crystal, loss through secondary reflections from the crystal faces and mirrors, etc.

It is important to fulfil one more condition when using this method to obtain a high diffraction efficiency. The mirrors should not only reflect the beams at an angle Θ_i to the direction of the acoustic wave, but also change their polarisation to the orthogonal one (i.e., the extraordinary ray should be transformed into the ordinary one). If an AO medium represents a gyrotropic TeO_2 crystal, this transformation is realised automatically. Indeed, because the natural waves of optical radiation travelling in a TeO_2 crystal near its optic axis are elliptically polarised and their polarisation, is nearly circular, the reflection from a mirror transforms the left-hand circular polarisation into the right-hand polarisation and vice versa. In other words, the reflection transforms a circularly polarised wave into a wave with a mutually orthogonal polarisation.

If AO diffraction in TeO_2 is realised at high frequencies, the polarisation of natural waves may be substantially different from circular polarisation. In this case, it may be of primary importance to analyse the efficiency of n-cascade Bragg diffraction taking into account the ellipticity of natural waves. Considering this question in greater detail, let an AO medium be a uniaxial positive TeO_2 crystal possessing gyrotropy. As noted above, in the general case, the natural waves of optical radiation travelling near the optic axis of the TeO_2 crystal have an elliptic polarisation, whose ellipticity ρ_0 can written in the form [12]

$$\rho_0 = \frac{1}{G_{33}}\left\{\left[\sin^4\Theta\left(\frac{1}{n_o^2}-\frac{1}{n_e^2}\right)^2 + 4G_{33}^2\cos^4\Theta\right]^{1/2} - \sin 2\Theta\left(\frac{1}{n_o^2}-\frac{1}{n_e^2}\right)^2\right\}, \qquad (2)$$

where G_{33} is the gyration pseudotensor component; n_o and n_e are the principal indices of refraction of the crystal, and Θ is the angle between the optic axis z of the crystal and the direction of propagation of light. The reflection from an external mirror only changes the direction of polarisation rotation, but does not change the orientation of axes of the polarisation ellipse [13, 14]. In other words, the reflection does not transform the elliptic polarisation into the mutually orthogonal polarisation. In the general case, this leads to a decrease in the diffraction efficiency, as in the case where one uses polarisation-insensitive AO elements in combination with an external mirror [13–15]. As shown in Ref. [15], an elliptically polarised wave reflected from a mirror is decomposed in a gyrotropic medium into two natural waves with intensities

$$I_1 = \frac{I_0(1 \pm \rho\xi)^2}{(1+\xi^2)(1+\rho^2)}, \qquad I_2 = \frac{I_0(\rho \mp \xi)^2}{(1+\xi^2)(1+\rho^2)}, \qquad (3)$$

where I_0 is the total light intensity; ξ is the ellipticity of the incident wave, and ρ is the ellipticity of the natural modes of the TeO_2 crystal. For the acoustic frequency $f = 80$ MHz (the frequency used in the experiment described below), the optical wavelength $\lambda = 0.633$ μm, $n_o = 2.259$, $n_e = 2.41$, $G_{33} = 2.62 \times 10^{-5}$, and $\Theta \approx 1°$, one obtains from Eqn (2) $\rho \approx 0.97$. For $\rho \approx \xi$ from Eqns (3) it follows that $I_1 = 10^{-3} I_0$ and $I_2 = 0.999 I_0$; i.e., the reflected wave is almost completely transformed into the radiation with intensity I_2.

As noted above, the realisation of the method proposed here requires that the angles Θ_i and Θ_d are sufficiently different from one another. Fig. 3 presents the calculated dependences of Θ_i and Θ_d on f for diffraction of optical radiation of a He–Ne laser in a TeO_2 crystal for the parameters specified above. The calculations were based on the vector diagram shown in Fig. 1. The acoustic velocity in TeO_2 was assumed to

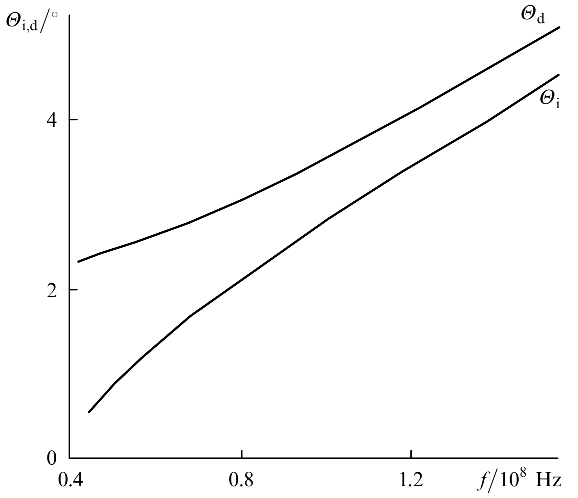

Figure 3. Dependences of the frequencies Θ_i and Θ_d on the acoustic frequency f.

be $V = 0.617 \times 10^5 \text{cm s}^{-1}$. The refractive indices for natural modes of the crystals were calculated by the formula [14]

$$n_{1,2}^2 = 1+\tan^2\Theta\left\{\frac{1}{n_o^2}+\frac{\tan^2\Theta}{2}\left(\frac{1}{n_o^2}+\frac{1}{n_e^2}\right)\pm\frac{1}{2}\left[\frac{\tan^4\Theta}{2}\left(\frac{1}{n_o^2}-\frac{1}{n_e^2}\right)^2+4G_{33}^2\right]^{1/2}\right\}^{-1}. \quad (4)$$

The angles $\Theta_{i,d}$ presented in Fig. 3 correspond to the propagation of radiation outside the crystal (in air). One can see that these angles are substantially different. For $f = 80$ MHz we have $\Theta_i = 2.1°$ and $\Theta_d = 3°$; i.e., for the optical radiation with divergence of $\sim 0.05°$, the angles Θ_i and Θ_d are well separated.

The experiments were performed with an extensively used TeO_2 single crystal whose dimensions along the [110], $[1\bar{1}0]$, and [001] axes were 6, 6, and 14 mm, respectively. A $LiNbO_3$ transducer cemented onto the {110} face generated an acoustic wave, with shear directed along the $[1\bar{1}0]$ axis. The AO interaction length was 6 mm, and the acoustic frequency was 80 MHz.

The schematic diagram of the experimental setup is presented in Fig. 4. The optical radiation of a He – Ne laser (1) passed through a Babinet compensator (2), which produced polarisation with the desired ellipticity. The resulting radiation passed through a slit in a screen (3) and entered an AO cell (4) at the Bragg angle to the direction of the acoustic wave. The diffracted beams were reflected from mirrors 5 and 6 according to the diagram presented in Fig. 2. Screen 3 was used to align mirror 5 and to measure angles Θ_i and Θ_d. Mirror 6 was aligned by using another screen (not shown in Fig. 4), which partially blocked the mirror 5. Upon alignment of the optical system we observed five cascades of diffraction. Mirrors 5 and 6 were found at a distance of 100 mm from the optical faces of the AO cell, the spacing between the optical beams on the mirrors was about 3 mm, and the number of cascades of diffraction was limited by the crystal length (14 mm). This number can be increased, in particular, by decreasing the distance between the mirrors and the AO cell, but this makes the alignment of the system more difficult. The efficiency of one-cascade diffraction η for an input electric power of 0.2 W was found to be 72%. Output beam 7 had an intensity of 8% with respect to the input beam intensity. The frequency shift of the output optical beam was 400 MHz. In the experiment, the purely Bragg diffraction was used. The Klein – Cook parameter [16] was equal to 186.

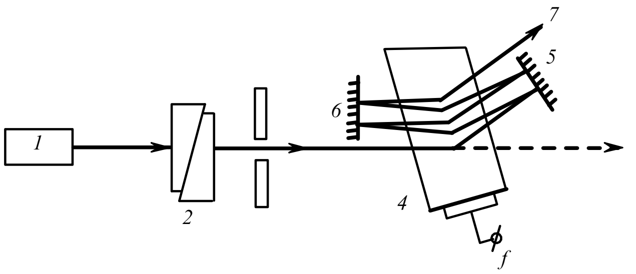

Figure 4. Schematic optical diagram of the experimental setup: (1) He – Ne laser, (2) Babinet compensator, (3) screen with a slit, (4) AO cell, (5, 6) mirrors, (7) output beam.

One can substantially improve the parameters of cascade diffraction. In particular, the resulting efficiency of five-cascade AO diffraction can reach 77%, provided the efficiency of one-cascade diffraction is increased by up to 95%. Moreover, the number of cascades can also be increased (for the given experimental setup, by up to 30). We did not seek to obtain the limiting frequency shift. The aim of the work was to verify the feasibility of realising the method by using an industrial AO cell and a standard set of optical units.

Thus we have proposed a method for multiplication of the frequency shift of optical radiation by using cascade diffraction of radiation by the same acoustic wave. The method is based on the difference of the angles of incidence and scattering in anisotropic media and on the use of optical properties of a gyrotropic crystal and two reflecting surfaces. The method was realised experimentally by using an AO cell made of a TeO_2 crystal. Five-cascade Bragg diffraction with an efficiency of 8% was obtained. It was shown that the method is promising for obtaining the frequency shift of optical radiation that exceeds the acoustic wave frequency by more than an order of magnitude.

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