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GENERAL EXPERIMENTAL TECHNIQUE

# Controlled Conversion of Rays with Different Wavelengths Using Acousto-optic Bragg Diffraction

**V. M. Kotov**[a]*

[a] *Kotelnikov Institute of Radio Engineering and Electronics, Russian Academy of Sciences, Fryazino, Moscow oblast, Russia 141195*

**e-mail: vmk277@ire216.msk.su*

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**Abstract**—A method is proposed for controlled convergence of beams with different wavelengths by means of acousto-optical (AO) Bragg diffraction. A method for calculating the parameters of the diffraction of two beams by one acoustic wave in a uniaxial crystal, which makes it possible to determine the condition for beam convergence, is presented. Calculations are demonstrated using the example of convergence of beams with wavelengths of 0.514 and 0.633 μm in a uniaxial paratellurite crystal by means of AO interaction with a "slow" acoustic wave. Experiments were carried out that confirmed the main theoretical conclusions.

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## INTRODUCTION

An acoustic wave, interacting with optical radiation in an elastic medium, makes it possible to control many parameters of light: its direction of propagation, amplitude, polarization, frequency, etc. [1–3]. Of particular interest is the mode of Bragg acousto-optic (AO) diffraction, when optical radiation is deflected by one order of magnitude with an efficiency close to 100% [1–3].

One of the promising applications of acousto-optics is the possibility of controlled combination of two beams to sum their optical powers. S.N. Antonov [4] demonstrated the summation of the powers of two semiconductor lasers of the same type with modulation of the received power by an acoustic wave. The method allows expanding the functionality of devices for laser cutting and processing materials, increasing the speed of applying images during the engraving process, etc.

This paper describes a method for combining beams with different wavelengths. This significantly expands the range of tasks that can be solved using this possibility. For example, converged beams, one of which is powerful and the other is weak probing, are extremely in demand in surgery, ophthalmology, etc. Two-color radiation, consisting of beams with the same power, is necessary for two-coordinate laser Doppler anemometry [5–7], in navigation systems [8], etc.

To solve the problem of efficient combining of beams with different wavelengths, it is necessary to find the frequency of sound and the angle of incidence of the beams on the crystal, at which both beams are in strict Bragg synchronism with one acoustic wave. These conditions change as the wavelengths of the optical rays change. In this paper, we describe a method for calculating the parameters of the AO interaction that ensures the convergence of two beams with arbitrary wavelengths and also present the experimental results of using the method using the example of the convergence of beams with wavelengths of 0.514 and 0.633 μm.

## THEORY

It is assumed that a crystal of paratellurite ($TeO_2$) will be used as AO-material because it is the most promising AO-material at the moment due to the anomalously high value of the AO-quality value $M_2$ [1–3]. This value, in fact, is the coefficient of proportionality between the efficiency of light diffraction and the power of sound. An analysis of the diffraction of two-color radiation by a single acoustic wave was carried out in sufficient detail in [9]. Many variants of such diffraction have been revealed, most of which occur when light propagates near the optical axis of the crystal. However, it must be kept in mind that $TeO_2$ is a uniaxial gyrotropic crystal. The eigenwaves of rays propagating near its optical axis are elliptically polarized, and the waves become linearly polarized only when the light is deflected by 4°–5° from the optical axis. Since most laser radiation sources generate beams with linear polarization, it is preferable to choose diffraction modes in a crystal when the crystal eigenwaves are also linearly polarized. When using $TeO_2$ this implies that the normals to the input and

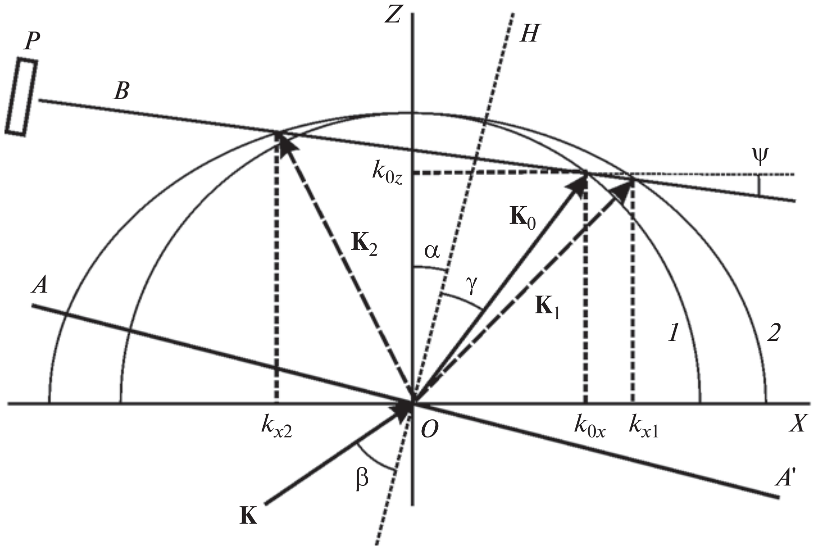


**Fig. 1.** Vector diagram of AO-diffraction in a uniaxial crystal: *AA'*—optical face of the crystal; **K**—wave vector of the wave incident on the crystal; $\mathbf{K}_0$—wave vector of the refracted wave; *H*—normal to the face *AA'*; β, γ—angles of incidence and refraction; α—angle between the normal *H* and optical axis *oz* crystal; *1, 2*—surfaces of wave vectors of the crystal; *B*—straight line describing the direction of sound wave propagation; *P*—sound emitter (piezo transducer); ψ—angle of inclination of the straight line *B* to the axis *OX*; $k_{0x}$, $k_{0z}$—projections $\mathbf{K}_0$ on axle *OX* and *oz*; $k_{x1}$, $k_{x2}$—projections of the points of intersection of the line *B* with surface *2* per axle *OX*; $\mathbf{K}_1$, $\mathbf{K}_2$—wave vectors of the diffracted rays.

output optical crystal faces must also be oriented at the same angles to the optical axis. This provides the best conditions for input and output of optical radiation from the crystal. In the present work, the slope of the acoustic facet is also assumed, which makes it possible to vary the frequency of the sound wave over a wide range.

The problem of combining two beams at the output of the AO cell will be solved based on the inverse problem, i.e., search for conditions for the splitting of two-color radiation into monochromatic components in the process of AO interaction, from which it is possible to determine all the parameters necessary for the effective convergence of two beams with different wavelengths into a single radiation.

We will consider the anisotropic diffraction of light by sound, accompanied by a change in the surfaces of wave vectors of the crystal [1–3]. Let us assume for definiteness that, in the process of diffraction, the "ordinary" beam diffracts into an "extraordinary" one. Figure 1 shows a vector diagram of such diffraction in a uniaxial positive crystal. The wave surfaces of the "ordinary" and "extraordinary" rays are denoted *1* and *2*, respectively; *oz* is the optical axis of the crystal. The optical facet on which the input radiation is incident is denoted as *AA'*. The normal to this face, denoted *H*, makes an angle α with the axis *oz*. Let the input optical radiation with wavelength λ and wave vector **K**, the value of which is equal to $K = 2\pi/\lambda$, falls to the edge *AA'* angle β. We believe that **K** is an "ordinary" ray. Inside the crystal, the beam is refracted at an angle γ related to β by the relation

$$\sin\gamma = \sin\beta\ /\ n_0, \tag{1}$$

where $n_0$ is refractive index of the "ordinary" beam.

Since the beam **K** is an "ordinary" ray, it belongs to the wave surface *1*. Inside the crystal, its wave vector is $\mathbf{K}_0$, its value $K_0 = 2\pi n_0/\lambda$. Surfaces *1* and *2* wave vectors in the crystallographic coordinate system are described by the following expressions:

$$k_x^2 + k_z^2 = K_0^2 - \text{"ordinary" beam}, \tag{2}$$

$$\frac{k_x^2}{K_e^2} + \frac{k_z^2}{K_0^2} = 1 - \text{"extraordinary" beam} \tag{3}$$

Here $k_x$ and $k_z$ are projections of the wave vector of light on the axis *OX* and *oz*, respectively; $K_0 = 2\pi n_0/\lambda$, $K_e = 2\pi n_e/\lambda$, where $n_0$ and $n_e$ are main refractive indices of the crystal.

Projections $K_0$ on axle *OX* and *oz* are equal:

$$k_{0x} = K_0\sin(\alpha+\gamma); \quad k_{0z} = K_0\cos(\alpha+\gamma). \tag{4}$$

Let the wave vector of the sound generated by the piezoelectric transducer *P*, directed along a straight line *B* passing through the point $(k_{0x}, k_{0z})$ and forming an angle ψ with the axis *OX*. In this case, straight *B* is given by the equation

$$k_z - k_{0z} = \mathrm{tg}\psi(k_x - k_{0x}). \tag{5}$$

Straight *B* crosses surfaces *1* and *2* at four points. We are only interested in the points of intersection of the line *B* with surface *2*. To find these points, it is necessary to solve equations (5) and (2) jointly with respect to the unknowns $k_x$ and $k_z$. Excluding $k_z$, we obtain a quadratic equation for $k_x$:

$$P_1 k_x^2 + 2R_1 k_x + Q_1 = 0. \quad (6)$$

Here

$$P_1 = \frac{1}{K_e^2} + \frac{\mathrm{tg}^2\psi}{K_0^2}, \quad R_1 = \mathrm{tg}\psi\frac{b_2}{K_0^2}, \quad Q_1 = \frac{b_2^2}{K_0^2} - 1, \quad (7)$$
$$\text{where} \quad b_2 = k_{0z} - \mathrm{tg}\psi k_{0x}.$$

Having defined $k_{x1}$ and $k_{x2}$ from formula (6) (we assume $k_{x1} > k_{x2}$), we find $k_{z1}$ and $k_{z2}$ from relation (5). Projections $k_{x1}$ and $k_{x2}$ are shown in Fig. 1. The sound frequencies at which anisotropic diffraction occurs are determined from the relationships:

$$f_1 = \frac{V}{2\pi}\sqrt{(k_{0x} - k_{x1})^2 + (k_{0z} - k_{z1})^2},$$
$$f_2 = \frac{V}{2\pi}\sqrt{(k_{0x} - k_{x2})^2 + (k_{0z} - k_{z2})^2}, \quad (8)$$

where $V$ is sound speed.

Note that the $TeO_2$ crystal has a strong acoustic anisotropy, so the speed of sound in it depends on the angle $\psi$. The speed is calculated based on the ratio [3]

$$V^2 = V_t^2\cos^2\psi + V_z^2\sin^2\psi, \quad (9)$$

where for $TeO_2$ $V_t = 0.617 \times 10^5$ cm/s, $V_z = 2.104 \times 10^5$ cm/s.

On Fig. 1 diffracted beams are $\mathbf{K}_1$ and $\mathbf{K}_2$. As can be seen from the figure, these rays are deflected on opposite sides of the incident radiation $\mathbf{K}_0$, and the beam diffracted at a frequency $f_1$ deviates from the transducer *P*, and that at the frequency $f_2$ is to the converter *P*.

The above technique makes it possible to find the optimal diffraction conditions based on the limiting parameters of any crystal. Let us demonstrate the technique for searching for parameters using the $TeO_2$ crystal as an example. The crystal has many advantages: a wide range of transparency (0.25–6 μm), high values of refractive indices and photoelastic constants, the presence of directions in which the sound wave propagates at an anomalously low speed ("slow" wave, $V = 617$ m/s) [10]. These characteristics provide a very high value for the AO-quality parameter $M_2$ material [1–3]. From a practical point of view, the formation of the total radiation with the smallest "spurious" illumination from spurious nondiffracted rays is realized at large deflection angles of the diffracted radiation, i.e., at high sound frequencies. However, a strong increase in the absorption of a "slow" sound wave with increasing frequency does not allow the use of $TeO_2$ at frequencies above 200 MHz [10]. In practice, most high-frequency modulators from $TeO_2$ operate at frequencies of 100–150 MHz. In this work, the diffraction parameters are chosen so that the "working" sound frequency is close to 130 MHz.

Figure 2 shows the dependences of the sound frequency, calculated on the basis of expressions (8) and (9), on the angle of incidence of light β on the crystal. Curves $f_1$ and $f_2$ are plotted for optical radiation with a wavelength of 0.63 μm and curves $F_1$ and $F_2$ for radiation with a wavelength of 0.514 μm. It was assumed in the calculations that diffraction occurs in the $TeO_2$ crystal whose refractive indices are $n_0 = 2.259$, $n_e = 2.41$ for radiation with a wavelength of 0.63 μm and $n_0 = 2.3115$, $n_e = 2.4735$ for radiation with a wavelength of 0.514 μm [10]. The speed of sound in the crystal was calculated according to formula (9) under the assumption that $\psi = 6.5°$. The slope angle α of the optical face was taken equal to 11°. For such values of ψ and α, the optical rays certainly propagate far from the optical axis of the crystal. Curves intersect each other in Fig. 2. Within the framework of the problem posed, the intersection of curves with different wavelengths is of greatest interest. There are two such intersections, the intersection points are marked *A* and *B*. At the point *A*, curves $f_2$ and $F_1$ intersect, while radiation with a wavelength of 0.63 μm is deflected towards the transducer, and radiation with a wavelength of 0.514 μm is deflected away from the transducer. At the point *B*, the reverse situation arises: the rays change places. The sound frequencies at which the curves intersect are approximately equal to each other and are approximately 130 MHz. Angles β for points *A* and *B* are different. This indicates two possibilities for convergence of rays with different wavelengths.

It is not difficult to determine the angles at which the diffracted rays exit the crystal. These angles, in fact, determine the condition of convergence of two rays by means of AO-diffraction. Note that the values of the wave vectors of the diffracted rays $K_1$ and $K_2$ are defined as

$$K_1 = \sqrt{k_{x1}^2 + k_{z1}^2}, \quad K_2 = \sqrt{k_{x2}^2 + k_{z2}^2}. \quad (10)$$

Hence the angles between the vectors $\mathbf{K}_1$ and $\mathbf{K}_2$ and optical axis *oz* are equal:

$$\tan\gamma_1 = \frac{k_{x1}}{k_{z1}}, \quad \tan\gamma_2 = \frac{k_{x2}}{k_{z2}}. \quad (11)$$

The angles of incidence of the diffracted rays on the inner output face of the crystal, oriented at the same angle α as the input face, will be equal to $(\gamma_1 - \alpha)$ and $(\gamma_2 - \alpha)$. Refraction angles $\eta_1$ and $\eta_2$ at the output of the crystal are determined from the relations:

$$\sin\eta_1 = \frac{K_1}{K}\sin(\gamma_1 - \alpha),$$
$$\sin\eta_2 = \frac{K_2}{K}\sin(\gamma_2 - \alpha). \quad (12)$$

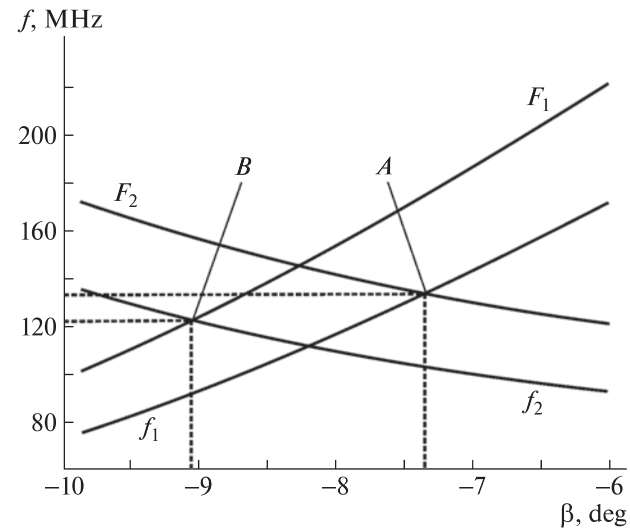


**Fig. 2.** Frequency dependencies $f$ Bragg diffraction from the angle of incidence $\beta$; $f_1$, $f_2$ —"branches" describing the diffraction of radiation with a wavelength of 0.633 μm; $F_1$, $F_2$—same for radiation with a wavelength of 0.514 μm; $A$, $B$—points of intersection of "branches" with different wavelengths.

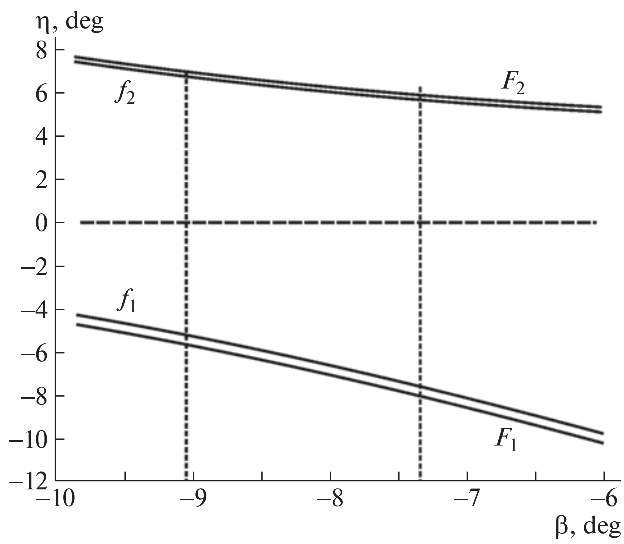


**Fig. 3.** Dependences of the angles of refraction η of the diffracted rays on the angle of incidence β of the rays on the crystal; $f_1$, $f_2$—branches of angles for radiation with a wavelength of 0.633 μm; $F_1$, $F_2$—same for radiation with a wavelength of 0.514 μm.

Figure 3 shows the dependences of the angles of refraction η at the output of the crystal of diffracted rays, counted from the angle β, depending on the angle of incidence β. Curves marked $f_1$ and $f_2$ correspond to the deflection angles of rays diffracted at frequencies $f_1$ and $f_2$ radiation with a wavelength of 0.63 μm. Similarly, curves $F_1$ and $F_2$ describe the deflection angles of rays with a wavelength of 0.514 μm. The vertical dotted lines mark the angles β at which the intersection points $A$ and $B$ are formed on Fig. 2. From comparison of Figs. 2 and 3, we can conclude that, at the point B, the angle of refraction $F_1$ is equal to minus 6° and the angle of refraction $f_2$ is approximately 7°. Similarly, at the point A, the angle of refraction of the diffracted beam $F_2$ is equal to 6° and the beam $f_1$ is minus 7°. The obtained angles determine the conditions under which it is necessary to direct beams with wavelengths of 0.63 μm and 0.514 μm to the AO cell in order to merge them. In practice, one can simply set the "desired" angle directly between the beams, and one can achieve their merging by orienting the AO cell.

## EXPERIMENTAL

To verify the obtained results, an AO cell was fabricated from $TeO_2$ with "oblique" cuts. A sketch of the drawing, according to which the crystal for the cell was made, is shown in Fig. 4. The crystal initially had the shape of a parallelepiped oriented along the crystallographic axes [110], [1$\bar{1}$0] and [001], where [001] is optical axis of the crystal. The dimensions of the parallelepiped along these axes were 13 × 10 × 15 mm. The (001) faces were then "bevelled" at an angle of 11°, forming optical faces $OO'$, and face (110) was "beveled" at an angle of 6.5°. This facet was the acoustic facet $A$. A piezoelectric transducer $P$ lithium niobate $X$-cut by cold welding was welded to this face [11]. Transducer size was 6 × 6 mm. As can be seen from the figure, the converter $P$ was offset from the center to the edge of the face. This is due to the strong acoustic anisotropy of the crystal, which leads to the "drift" of the acoustic wave. Transducer offset avoids unwanted sound reflections from the side edges. The transducer thickness was 90 μm. The sound was excited at the fifth harmonic, equal to approximately 131 MHz, in a frequency band of approximately 3 MHz at a level of 3 dB. Figure 5 shows a photograph of the fabricated AO cell. The size of the entire cell was 36 × 25 × 25 mm. This cell was used in subsequent experiments.

Figure 6 shows an optical scheme for bringing rays with different wavelengths into one beam. The sources of initial radiation were argon (Ar) and helium-neon (He-Ne) lasers generating beams with wavelengths of 0.514 and 0.633 μm, respectively. Since the Ar laser generates several lines in the blue-green region of the spectrum; an IF interference filter was used to separate radiation with a wavelength of 0.514 μm. After the filter, the radiation was directed directly to the AOM AO cell. The radiation of the He-Ne laser was reflected from the mirror M and directed to the input of the AOM cell at an angle φ to the radiation of the Ar laser. Before entering the cell, both beams were passed through a polarizer P to form linear polarizations of the beams corresponding to the polarizations of "extraordinary" beams in the crystal. In our case, the polarizations of the rays should be parallel to the

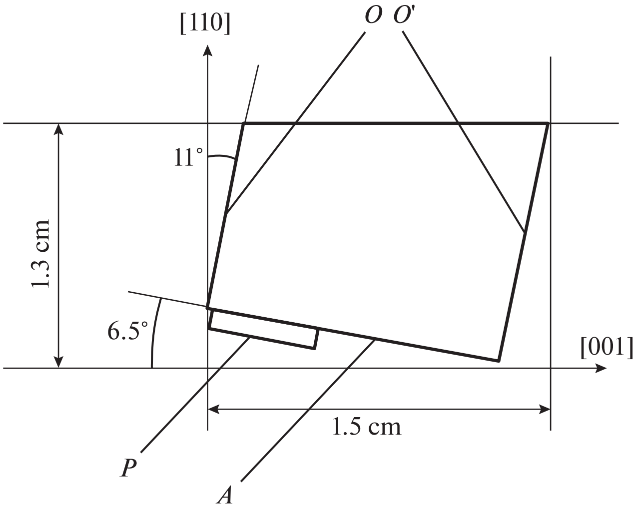


**Fig. 4.** Sketch for making an AO-crystal from $TeO_2$: [110], [001]—directions of crystallographic axes; [001]—optical axis of the crystal; *OO*—optical faces of the crystal; *A*—acoustic edge; *P*—piezoelectric transducer.

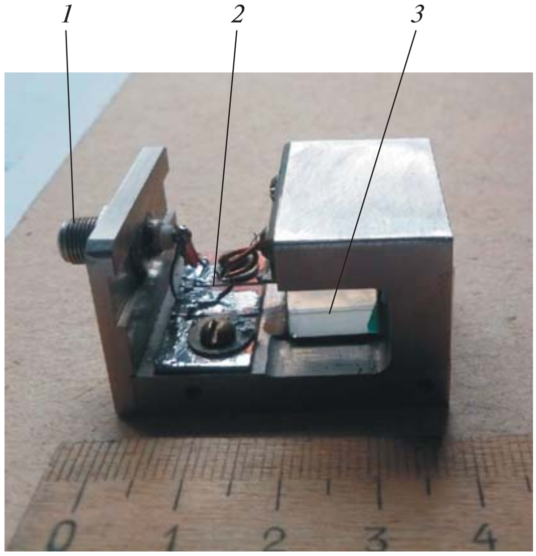


**Fig. 5.** Photograph of the fabricated AO cell. *1*—Connector for electrical signal input; *2*—elements of coordination; *3*—AO-crystal.

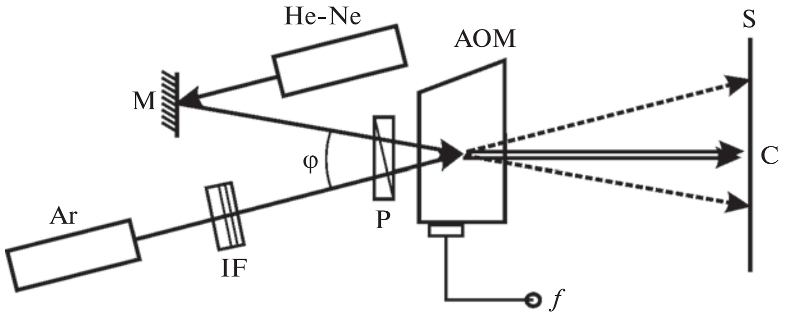


**Fig. 6.** Optical layout of the experiment. Ar and He-Ne—argon and helium-neon lasers; IF—interference filter; M—reflecting mirror; P—polarizer; AOM—a.a. cell; *f*—signal applied to the cell; φ—angle between the input beams; S—screen; C—point of convergence of two rays.

direction of sound propagation. An electrical signal with a frequency of 130 MHz was applied to the AOM AO cell. By the angular adjustment of the AO cell, we reached a situation where both diffracted beams "merged" into one spot C on the screen S. We managed to achieve "merging" of the beams at an angle φ between the initial beams equal to 12°. This angle is slightly different from the calculated value of 13°, which may be due to inaccurate orientation of the crystal relative to the crystallographic axes as well as with the inaccuracy of the "beveled" crystal faces. The diffraction efficiency of each beam was approximately 70%. By varying the sound power, one can increase the diffraction efficiency of one beam at the expense of the other. At the same time, it is impossible to obtain a high efficiency of both beams close to 100%. This is due to the rather high selectivity of diffraction to the wavelength of light. From works [1–3], it is known that the Bragg diffraction efficiency μ is determined by the expression

$$\mu = \frac{I_1}{I_0} = \sin^2\left(\frac{\pi}{\lambda\cos\theta_b}\sqrt{\frac{P_a L}{2H_a}M_2}\right), \tag{13}$$

where $I_0$ and $I_1$ are the intensities of the incident and diffracted beams, respectively; λ is the wavelength of light; $\theta_b$ is Bragg angle (because $\theta_b \ll 1$, can be accepted $\cos\theta_b \approx 1$); $P_a$ is acoustic power; $L$ is the length of the AO interaction; $H_a$ is the height of the acoustic "column"; and $M_2$ is the AO quality coefficient of the material.

It follows from formula (13) that it is impossible to provide simultaneous 100% diffraction efficiency for two different wavelengths λ. It was shown in [9] that the wavelength selectivity decreases significantly (the wavelength band covers almost the entire visible range) if we restrict ourselves to a diffraction efficiency of 90%. In addition, there are a number of works (for example, [12–14]), in which methods are proposed for significantly reducing the selectivity of diffraction to the wavelength of light, for example, by eliminating the effect of overmodulation. In other words, if there is a need for a significant decrease in the diffraction selectivity, then one can use the techniques developed in [9, 12–14].

## CONCLUSIONS

1. A technique has been developed for determining the parameters of the Bragg diffraction of two beams with different wavelengths on the same acoustic wave occurring in a uniaxial crystal. The technique takes into account the refraction of radiation on arbitrarily oriented optical faces and also assumes an arbitrary orientation of the acoustic facet relative to the crystallographic axes. This makes it possible to determine the best conditions for convergence of two beams depending on the limiting parameters of the crystal.

2. According to the method, the optimal parameters of the Bragg diffraction in the $TeO_2$ crystal are determined to bring together two beams with wavelengths of 0.514 and 0.633 μm, interacting with a "slow" sound wave. The optimal mode is achieved when the optical facet is tilted by an angle of approximately 11° relative to the optical [001] axis and the acoustic facet is tilted by an angle of approximately 6.5° relative to the [110] axis. The sound frequency is 130 MHz.

3. Experiments performed using the $TeO_2$ AO cell, made in accordance with the above parameters, made it possible to combine two beams with wavelengths of 0.514 and 0.633 μm generated by Ar- and He-Ne lasers into a single beam. The diffraction efficiency of each radiation was approximately 70%.

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