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DIFFRACTION OF LIGHT

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Diffraction of three-colour radiation on an acoustic wave

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Abstract. **We study acousto-optic Bragg diffraction of three-colour radiation having wavelengths of 488, 514 and 633 nm on a single acoustic wave propagating in a TeO_2 crystal. A technique is developed that allows one to find diffraction regimes with a proportional change in the intensity of all radiations by varying the acoustic power. According to the technique, radiation with a maximum wavelength has to be in strict Bragg synchronism with the acoustic wave, while other radiations diffract during the synchronism detuning. The results obtained using this technique are experimentally confirmed.**

Keywords: *acousto-optic diffraction, Bragg regime, three-colour laser radiation.*

1. Introduction

Acousto-optic (AO) diffraction is effectively used to control two-colour optical radiation [1–3], as well as multicolour radiation, all lines of which lie in a relatively narrow wavelength band [4, 5]. However, for a number of tasks, such as designing triaxial anemometers [6], colour television systems [7, 8], etc., it is necessary to control three optical radiations with arbitrary wavelengths. The most interesting scenario in this case is to control three-colour radiation by means of AO diffraction on a single acoustic wave. This scheme allows one to eliminate intermodulation effects; to reduce the electrical power input, size of the modulator, its cost; to increase reliability; etc.

In this paper we study diffraction of three-colour radiation with wavelengths significantly spaced apart. The radiation is made up of two lines of an Ar laser (λ_1 = 488 nm, λ_2 = 514 nm) and a line of a He–Ne laser (λ_3 = 633 nm). These lasers are widely used in practice. We consider diffraction in a TeO_2 single crystal on a 'slow' acoustic wave travelling at a velocity of 0.617×10^5 cm s^{-1}. Looking ahead, note that it is impossible to ensure strict Bragg synchronism of these lines with a single acoustic wave propagating in TeO_2. However, as will be shown below, the synchronism detuning can be used to provide a proportional change in the intensity of diffracted radiations of different wavelengths when changing the acoustic power. This effect allows the construction of multi-colour light modulators with a proportional change in the intensity of radiations.

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2. Theory

Consider the features of AO diffraction in the case of synchronism detuning. The diffraction efficiency to the first order is given by [9, 10]

$$\eta = \frac{I_1}{I_{\rm inc}} = \frac{(0.5v)^2}{(0.5\Delta kL)^2 + (0.5v)^2}\sin^2\left[\sqrt{(0.5\Delta kL)^2 + (0.5v)^2}\right], \quad (1)$$

where I_1 is the intensity of a beam diffracted in the first order; $I_{\rm inc}$ is the intensity of radiation incident on the crystal;

$$v \approx \frac{2\pi}{\lambda}\sqrt{\frac{M_2 L}{2H}P_{\rm ac}}$$

is the Raman–Nath parameter; M_2 is the quality factor of the AO material; L is the length of AO interaction; H is the height of the acoustic column; $P_{\rm ac}$ is the acoustic power; and Δk is the synchronism detuning. At small values of $P_{\rm ac}$ the diffraction efficiency varies linearly with $P_{\rm ac}$. The slope η depends essentially on the value of ΔkL. The slope angle η in the dependence $\eta(P_{\rm ac})$ is defined by the derivative

$$\frac{\partial\eta}{\partial P_{\rm ac}} = \left(\frac{2\pi}{\lambda}\right)^2\frac{M_2 L}{2H}\frac{\sin^2(0.5\Delta kL)}{(0.5\Delta kL)^2} \quad (2)$$

at $P_{\rm ac} \to 0$. From (2), we see, in particular, that the maximum slope angle is reached at $\Delta k = 0$.

Equation (2) allows one to 'equalise' the slopes η for different wavelengths. The condition of equality $\partial\eta/\partial P_{\rm ac}$ for wavelengths λ_1 and λ_2 leads to the relation

$$\frac{\lambda_2}{\sqrt{M_2(\lambda_2)}}\frac{\sin(0.5\Delta k_1 L)}{0.5\Delta k_1 L} = \frac{\lambda_1}{\sqrt{M_2(\lambda_1)}}\frac{\sin(0.5\Delta k_2 L)}{0.5\Delta k_2 L}, \quad (3)$$

where $M_2(\lambda_1)$, $M_2(\lambda_2)$ are the M_2 coefficients; and Δk_1 and Δk_2 are the Bragg synchronism detunings for radiations with λ_1 and λ_2, respectively. Assuming that M_2 is independent of λ, provided that $\Delta k_1 = 0$, we obtain from (3)

$$\lambda_1 - \lambda_2 = \lambda_1\left[1 - \frac{\sin(0.5\Delta k_2 L)}{0.5\Delta k_2 L}\right]. \quad (4)$$

Consider a change in $0.5\Delta k_2 L$ in the interval $[0, \pi]$. Then, one can easily see from (4) that $\lambda_2 \leqslant \lambda_1$. Only in this way one can ensure a 'proportionality' of changes in the intensity of diffracted radiations with λ_1 and λ_2 when the acoustic power changes. In other words, the detuning should decrease with increasing wavelength of light. This means that from the three laser radiations used by us, the radiation with a maximum wavelength must have a minimum detuning Δk. For this radiation we set $\Delta k = 0$. Other radiations with shorter wavelengths will diffract during synchronism detuning.

Figure 1 shows the dependence of ΔkL on λ, built on the basis of (4) under the assumption that $\Delta k = 0$ for $\lambda = 633$ nm. It is seen that

$$\Delta kL = 2.4 \text{ for } \lambda_1 = 488 \text{ nm}, \Delta kL = 2.2 \text{ for } \lambda_2 = 514 \text{ nm}. \quad (5)$$

In practice, as a rule, the length L is the same for all the radiations and so ΔkL can be changed only by changing the factor Δk for each radiation separately.

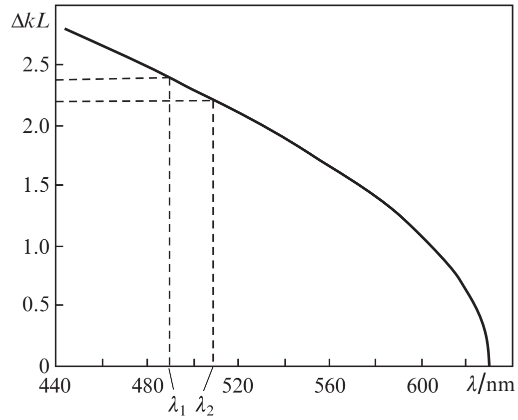

Figure 1. Dependence of ΔkL on λ.

We will define Δk on the basis of an analysis of the vector diagram given in Fig. 2. Figure 2 shows the diffraction of radiations with λ_1, λ_2 and λ_3 in the TeO_2 crystal. The radiation with a maximum wavelength (λ_3) is in strict synchronism with the acoustic wave, while other two radiations diffract during the synchronism detunings Δk_1 and Δk_2, respectively. Three-colour radiation T is incident at angle α to an optical face of crystal P, oriented orthogonally to the optical axis z of the crystal. Inside the crystal the radiation is split into monochromatic components with wave vectors $\boldsymbol{K}_1$, $\boldsymbol{K}_2$ and $\boldsymbol{K}_3$, the wavelengths of which are λ_1, λ_2 and λ_3, respectively. Each radiation diffracts on the acoustic wave, and the acoustic wave vector $\boldsymbol{q}$ is directed orthogonally to z. As an example we consider the scenario, when all three vectors ($\boldsymbol{K}_1$, $\boldsymbol{K}_2$, $\boldsymbol{K}_3$) belong to the inner surface of the wave. There occurs anisotropic diffraction of light by sound. The vectors $\boldsymbol{K}_{1\text{d}}$, $\boldsymbol{K}_{2\text{d}}$ and $\boldsymbol{K}_{3\text{d}}$ show diffracted radiations. For the optimal scenario we will search for the domains in which Δk_1 and Δk_2 are minimal and $\Delta k_3 = 0$.

The surfaces of the wave vectors of a uniaxial gyrotropic crystal in the Cartesian coordinate system have the form

$$k_z^4\left(\frac{1}{n_\text{o}^4} - G_{33}^2\right) + (k_x^2 + k_y^2)\left(\frac{1}{n_\text{o}^2} + \frac{1}{n_\text{e}^2}\right)\left[\frac{k_z^2}{n_\text{o}^2} - \left(\frac{2\pi}{\lambda}\right)^2\right]$$

$$+ \frac{(k_x^2 + k_y^2)^2}{n_\text{o}^2 n_\text{e}^2} - \left(\frac{2\pi}{\lambda}\right)^2 \frac{2k_z^2}{n_\text{o}^2} + \left(\frac{2\pi}{\lambda}\right)^4 = 0, \quad (6)$$

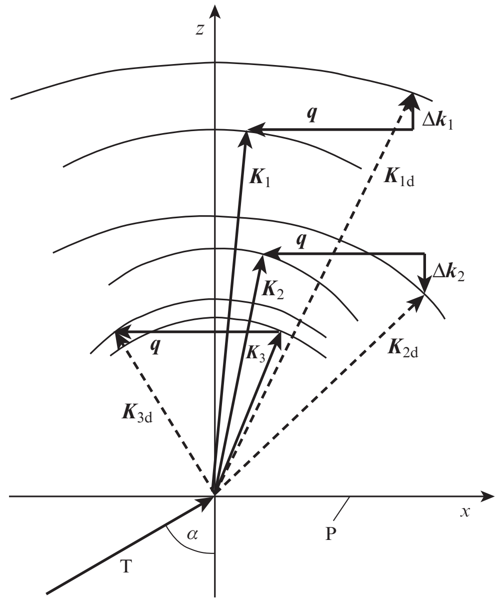

Figure 2. Vector diagram of AO diffraction of three-colour optical radiation.

where k_x, k_y, k_z are the projections of the wave vector in the orthogonal coordinate system xyz (the direction of z coincides with the optical axis of the crystal); and n_o, n_e, G_{33} are the principal refractive indices of the crystal and the component of the pseudo-tensor of gyration for radiation with a wavelength of light λ. Let the diffraction plane be the plane xz, coinciding with the plane [110] [001] of the TeO_2 crystal. Then, assuming $k_y = 0$ in (6) and $k_x = (2\pi/\lambda)\sin\alpha$, arising from the condition of the refraction of light at the interface with the crystal, we obtain a biquadratic equation with respect to k_z:

$$Ak_z^4 + 2Bk_z^2 + C = 0, \quad (7)$$

where

$$A = \left(\frac{1}{n_\text{o}^4} - G_{33}^2\right); \quad B = \frac{k_x^2}{2n_\text{o}^2}\left(\frac{1}{n_\text{o}^2} + \frac{1}{n_\text{e}^2}\right) - \left(\frac{2\pi}{\lambda}\right)^2 \frac{1}{n_\text{o}^2};$$

$$C = \left(\frac{2\pi}{\lambda}\right)^4 - k_x^2\left(\frac{1}{n_\text{o}^2} + \frac{1}{n_\text{e}^2}\right)\left(\frac{2\pi}{\lambda}\right)^2 + \frac{k_x^4}{n_\text{o}^2 n_\text{e}^2}. \quad (8)$$

Equation (7) has two positive roots, the largest of which describes the outer surface of the wave, and the smallest – the inner surface. The modulus of the acoustic wave vector is given by the relation $q = 2\pi f V^{-1}$, where f and V are the frequency and speed of the acoustic wave. The method for calculating Δk for a given wave surface is well known (see, for example, [11]). Figure 3 shows the dependences of Δk_1, Δk_2, Δk_3 on the angle of incidence α. The dependences of n_o, n_e, G_{33} on λ are taken from [12]; $V = 0.617 \times 10^5$ cm s^{-1}. The dependences are plotted for $f = 48.65$ MHz. One can see that the dependences are almost linear, straight lines Δk_1 and Δk_2 being parallel and intersecting the straight line Δk_3. When $\alpha = 0.58°$, Δk_1 and Δk_2 are arranged symmetrically with respect to $\Delta k_3 = 0$ and equal to 5 and -5 cm^{-1}, respectively. If we take the length of AO interaction equal to 0.45 cm, by slightly varying α we can change Δk_1 and Δk_2, thus providing a maximum approximation to their values given in (5). In this case, the value of Δk_3 changes insignificantly. The found domain is,

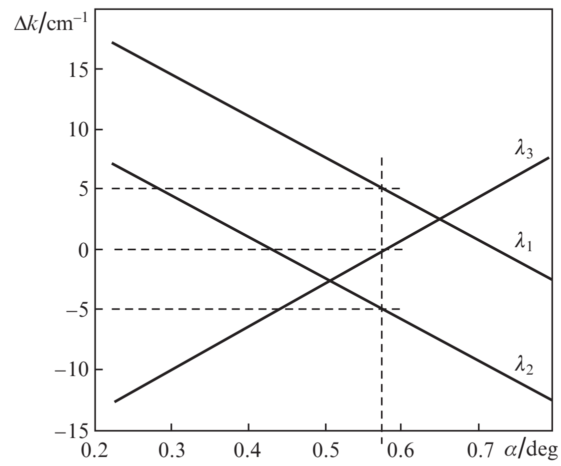

Figure 3. Detuning as a function of the angle of incidence of radiation on the crystal.

in our opinion, optimal for linear modulation of the three above-mentioned radiations.

Figure 4 shows the dependences of the diffraction efficiency of radiation on the acoustic power, calculated on the basis of (1) with (5) taken into account. The radiations with λ_1 = 488 nm, λ_2 = 514 nm and λ_3 = 633 nm propagated in TeO_2. In the calculations we used the following parameters: L = 0.45 cm, H = 0.5 cm and M_2 =1200 × 10^{-18}. For comparison, we present the curve λ_1^0 of the dependence η for radiation at λ_1 under the condition $\Delta k_1 = 0$. It can be seen that curves λ_1, λ_2, λ_3 virtually merge at small values of P_{ac}, but λ_1^0 sharply deviates from them.

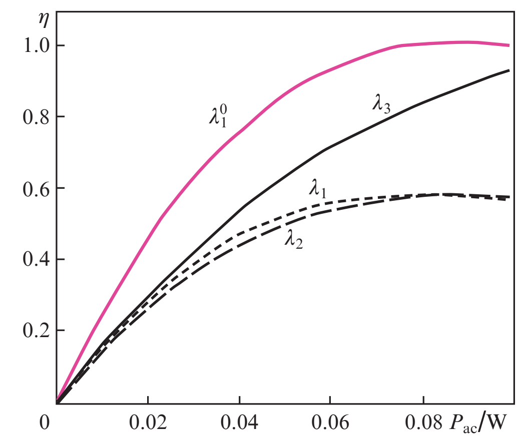

Figure 4. Diffraction efficiency of three wavelengths as a function of the acoustic power.

Thus, these calculations indicate the possibility of a proportional change in the diffraction intensity of three laser radiations when the power of the acoustic wave changes.

3. Experiment and discussion of the experimental results

Figure 5 shows the optical scheme of the experiment. The Ar laser (*1*) generates radiation with two bright lines (λ_1 = 488 nm and λ_2 = 514 nm). The laser radiation is directed to an attenuator (*2*), passes it and falls on a glass plate (*3*), both surfaces of which are AR-coated for Ar-laser radiation. Radiation of the He–Ne laser (*4*) with λ_3 = 633 nm is directed to the same plate. About 80% of radiation with λ_3 is reflected from plate *3* in the direction collinear with the propagation of radiation with λ_1 and λ_2. All the three radiations pass a polariser (*5*) and a mechanical modulator (*6*), and then are directed to an AO cell (*7*). The cell is made of a TeO_2 single crystal whose faces are oriented perpendicularly to the crystallographic directions [110], [110] and [001]. Diffraction of radiation occurs on a 'slow' acoustic wave propagating in TeO_2 along [110] at 0.617 × 10^5 cm s^{-1}. At the crystal output the diffracted radiations are formed, wherein radiations with λ_1 and λ_2 propagate on one side of the input radiation, and the radiation with λ_3 – on the other. The experiment ensures strict Bragg synchronism of radiation with λ_3, whereas radiations with λ_1 and λ_2 diffract during the phase mismatch. The measured intensities of radiations with λ_1, λ_2 and λ_3, incident on the crystal, are equal to 1.0, 1.5 and 0.7 mW. Diffracted radiations are measured one by one by a photodetector (*8*). For a separate measurement of radiations with λ_1 and λ_2, use is made of polarising filters (*9*).

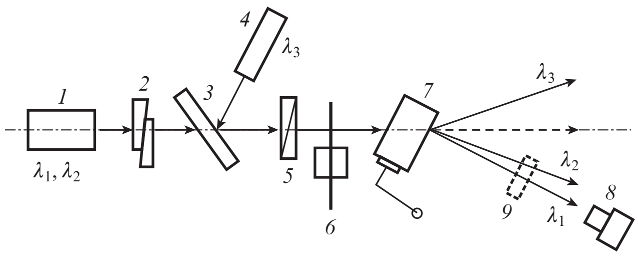

Figure 5. Optical scheme of the experiment.

By changing the acoustic frequency and orientation of the AO cell, we achieved a situation when the relative changes in the intensity of the diffracted radiations were the same in the process of changing the acoustic power. We observed this situation at an acoustic frequency of ~45 MHz. A proportional change in the intensities (with an accuracy up to 5%) was observed when changing the acoustic power up to a level that ensures the diffraction efficiency of ~15%. In other words, a good agreement between experimental and theoretical data was obtained. The discrepancy may be due to the divergence of light and acoustic waves, inhomogeneity of the crystal, inaccuracy of the model used, etc.

If it is necessary to obtain a high diffraction efficiency of multi-colour radiation, it is possible to use, for example, diffraction regimes without overmodulation [13, 14] observed in strongly inhomogeneous acoustic fields. Then the intensity of all the components of a multi-colour radiation, after reaching an efficiency maximum, will not decrease with increasing acoustic power. We plan to study this effect, as applied to the multi-colour radiation, in the future.

4. Conclusions

1. We have considered AO diffraction of three-colour optical radiation with wavelengths of 488, 514 and 633 nm on a 'slow' acoustic wave propagating in TeO_2.

2. It is found that the simultaneous implementation of strict Bragg synchronism of the three mentioned radiations with one acoustic wave in TeO_2 is impossible.

3. We have developed a technique for finding the optimal domain of diffraction of three-colour radiation on a single acoustic wave. Using this technique we have proposed a regime under which the radiation with a maximum wavelength diffracts without phase-matching detuning, and the values of the synchronism detuning of two other radiations are selected in such a way as to ensure a proportional change in the intensity of all the radiations with a change in the acoustic power.

4. The experiments performed using TeO_2 AO cells have confirmed the principal conclusions of the theory.

These results can be applied in practice to develop AO modulators of multicolour radiation with a proportional change in the intensity of its components.

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