ISSN 1064-2269, Journal of Communications Technology and Electronics, 2023, Vol. 68, No. 3, pp. 373–377. © Pleiades Publishing, Inc., 2023.
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Amplitude Modulation of Two-Color Radiation at Double Sound Frequency

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Received August 2, 2022; revised August 14, 2022; accepted November 21, 2022

Abstract—For amplitude modulation of two-color optical radiation at a double sound frequency, it is proposed to use a device consisting of two identical acousto-optic (AO) cells operating at the same sound frequency and providing Bragg matching of two optical beams with one acoustic wave. As an AO medium, it is proposed to use a gyrotropic crystal whose eigenwaves are circularly polarized. The modulation is caused by the interference of waves with circular polarizations. The amplitude modulation of two-color Ar laser radiation (λ_1 = 0.488 μm and λ_2 = 0.514 μm) at a frequency of 236 MHz was experimentally obtained using two paratellurite AO cells.

Keywords: acousto-optic diffraction, two-color radiation, Bragg regime, frequency shift, amplitude modulation

DOI: 10.1134/S1064226923030105

INTRODUCTION

Acousto-optic (AO) amplitude modulators are the most widespread among all AO devices [1–3]. Traditionally used modulators are based on the AO interaction of light with sound wave pulses propagating in an AO crystal. In this case, the pulse duration is significantly less than the carrier frequency of audio signal *f* [12]. One of the most effective ways to significantly increase the modulation frequency is to use the interference of two waves with different frequencies [4, 5], while the frequency difference of the interfering waves is set by the frequency of the sound wave. The modulation frequency in this case may exceed sound frequency *f* several times. For example, in [5], the modulation of light at a frequency of 4*f*. However, in all the above studies, only monochromatic radiation was modulated. In this paper, we propose a method for obtaining amplitude modulation of two-color optical radiation at a double sound frequency.

Two-color modulated optical signals are needed, for example, for the development of spectral-type processors [6], in two-coordinate laser Doppler anemometry (LDA) [7, 8], for the development of two-frequency gyroscopes [9], etc.

1. OPTICAL LAYOUT OF THE DEVICE

To modulate two-color radiation, we use diffraction modes that ensure the implementation of strict Bragg synchronism of two different optical beams with one acoustic wave. Such regimes were studied in [10]. The optical scheme of the proposed device is shown in Fig. 1. Here is two-color radiation I_0, consisting of two monochromatic beams with wavelengths λ_1 and λ_2 ($\lambda_1 < \lambda_2$), is sent to the AO cell *AO-1.* At the output of the cell, part of the radiation is not diffracted in the crystal; it passes in the form of two-color radiation *1*,

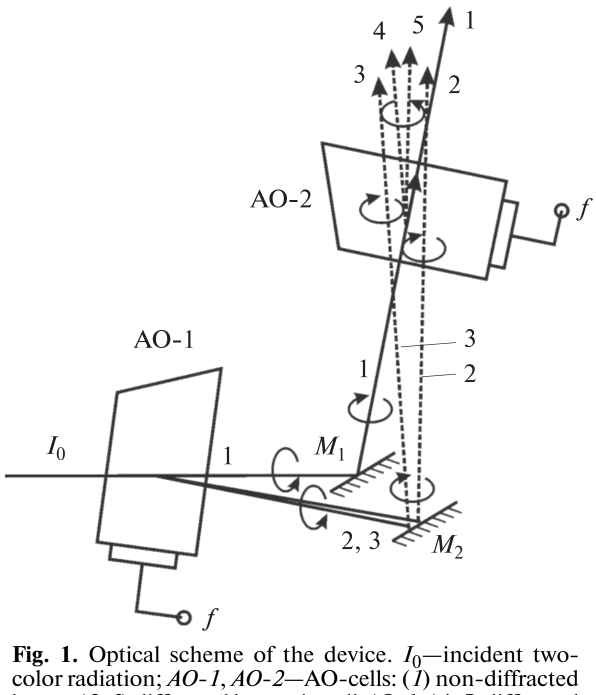

Fig. 1. Optical scheme of the device. I_0—incident two-color radiation; *AO-1*, *AO-2*—AO-cells: (*1*) non-diffracted beam; (*2, 3*) diffracted beams in cell *AO-1*; (*4, 5*) diffracted beams in the cell *AO-2*; M_1, M_2—reflective mirrors; *f* is the signal applied to the cells.

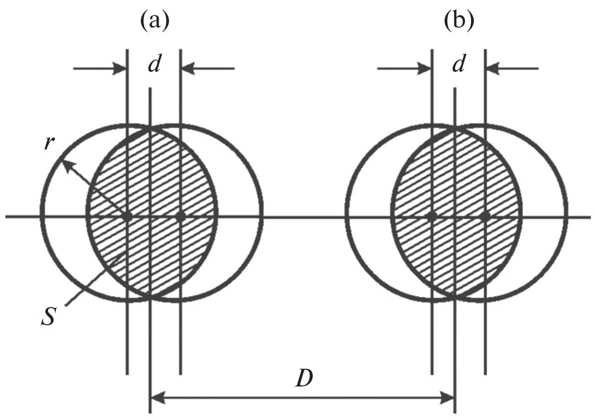

Fig. 2. Superposition of interfering beams: (a) beams with a wavelength λ_1; (b) beams with a wavelength λ_2; d is the distance between the centers of the beams; r is the beam radius; S is the area of intersection of the beams; D is the distance between the centers of pairs of beams.

and the other part to minus first diffracted order, deviating in the direction of beams *2* and *3* with wavelengths λ_1 and λ_2.

We assume that the AO cell is made of a gyrotropic crystal. The eigenwaves of such a crystal have right-handed and left-handed circular polarizations (R and L polarization). We assume that anisotropic diffraction of light by sound occurs, i.e., R-polarized beams are diffracted into L-polarized and vice versa L-beams are diffracted into R-beams. Note that these two types of diffraction occur at different Bragg angles, so in practice either one type of diffraction or the other is chosen. Let the mode be chosen when R-beams are diffracted into L-beams. Then, R-polarized radiation components I_0 diffract into beams *2* and *3*, which are L-polarized, non-diffracted beams *1* are also L-polarized. Beam *1* reflected by mirror M_1 in the direction of AO-cell *AO-2*, is identical to cell *AO-1*. The signals to both cells come from the same electrical signal generator. Beams *2* and *3* reflected in mirror M_2 in the direction of the same cell *AO-2*. It is known [11] that after reflection from a mirror, circularly polarized beams change their polarizations to mutually orthogonal ones, i.e., L-polarized beams *1*, *2* and *3* after reflection from mirrors M_1 and M_2 will be R-polarized. The diffraction conditions in the *AO-2* are chosen in such a way that R-polarized beam *1* diffracts on an acoustic wave in the directions of L-polarized beams *4* and *5*, R-polarized beams *2* and *3* pass through the cell *AO-2* without diffraction. Mirror M_2 reflects beams *2* and *3* so that the beam *2* propagates parallel to the beam *5*, and beam *3*, parallel to the beam *4*. Note that the wavelength of beams *2* and *5* is equal to λ_1, and beams *3* and *4*, to λ_2. To obtain the modulation effect, it is necessary that parallel propagating beams interfere with each other, while the frequencies of the beams must be different. To obtain different frequencies of interfering beams, the property of AO-diffraction is used to shift the frequency of light of the diffracted radiation relative to the frequency of the incident. The shift frequency is equal to the frequency of the sound wave. Based on this, cells *AO-1* and *AO-2* are oriented in such a way that the diffraction of beams in the first cell is carried out in the minus first order, and in the second, in the first order. In other words, the frequencies of beams *2* and *3* diffracted in cell *AO-1* are $(\omega_1 - \Omega)$ and $(\omega_2 - \Omega)$, respectively, and the frequencies of beams *5* and *4*, formed as a result of diffraction in *AO-2*, are equal to $(\omega_1 + \Omega)$ and $(\omega_2 + \Omega)$. Here, ω_1 and ω_2 are the cyclic frequencies of beams with wavelengths λ_1 and λ_2; Ω is the cyclic frequency of the acoustic wave. It is related to frequency f and ratio $f = \Omega/2\pi$. Thus, beams *2* and *5,* propagating in parallel, have frequencies $(\omega_1 - \Omega)$ and $(\omega_1 + \Omega)$, their addition will lead to the formation of linearly polarized radiation with frequency ω_1, whose polarization vector rotates with frequency Ω [12]. Similarly, the addition of two beams *3* and *4* will lead to the formation of a linearly polarized wave with frequency ω_1, whose polarization vector rotates with frequency Ω. This will lead to the fact that at the output of the device two linearly polarized beams are formed with wavelengths λ_1 and λ_2. The polarization vectors of both beams rotate with the same frequency, Ω. If a polarizer is placed after the cell *AO-2*, then at the output of the device we will obtain two beams with wavelengths λ_1 and λ_2, modulated at frequency $2f$.

2. THE DEGREE OF OVERLAP OF OPTICAL BEAMS

As is clear from Fig. 1, the parallel beams do not completely overlap each other. Only the overlapping part of the beams is, in fact, a modulated signal. Let us estimate the degree of overlap of two beams depending on the distance between the centers of the beams. Figure 2 shows a cross section of two pairs of intersecting beams with wavelengths λ_1 (a) and λ_2 (b). We assume that the cross sections of all beams are circles with the same radius r. Circles overlap each other and the distance between the centers of the circles is d. The distance between the centers of pairs of beams is D. The total area of the circles (the area of intersection) is indicated as S.

It is easy to show that area S is calculated according to expression

$$S = 2r\left(r\varphi - 0.5d\sin\varphi\right), \quad (1)$$

where $\varphi = \arccos(0.5d/r)$. The degree of overlap of two circles μ is the ratio of area S to the area of the circle, i.e.

$$\mu = S/\pi r^2. \quad (2)$$

Let us perform numerical estimates as applied to the experimental conditions. All calculations will be done using the example of two-color radiation generated by an Ar laser at wavelengths $\lambda_1 = 0.488$ μm and $\lambda_2 = 0.514$ μm. Since TeO_2 is not only a gyrotropic, but also a uniaxial crystal, the polarizations of its own waves, strictly speaking, are elliptical. Refractive indices of TeO_2 are defined by expressions [10]

$$n_{1,2}^2 = \frac{1 + \tan^2\varphi}{\frac{1}{n_0^2} + \frac{\tan^2\varphi}{2}\left(\frac{1}{n_0^2} + \frac{1}{n_e^2}\right) \pm \frac{1}{2}\sqrt{\tan^4\varphi\left(\frac{1}{n_0^2} - \frac{1}{n_e^2}\right)^2 + 4G_{33}^2}}, \quad (3)$$

and the ellipticities of the crystal eigenwaves are calculated as

$$\rho = \frac{1}{2G_{33}}\left[\sqrt{\tan^4\varphi\left(\frac{1}{n_0^2} - \frac{1}{n_e^2}\right)^2 + 4G_{33}^2} - \tan^2\varphi\left(\frac{1}{n_0^2} - \frac{1}{n_e^2}\right)\right]. \quad (4)$$

Here n_0 and n_e are the principal refractive indices of the crystal; φ is the angle between optical axis [001] of the crystal and the wave vector of the light wave; G_{33} is the component of the gyration pseudotensor. Based on tabular values [13, 14] for TeO_2 we have:

$$\lambda_1 = 0.488\ \mu\text{m};\quad n_0 = 2.3303;$$
$$n_e = 2.494;\quad G_{33} = 3.93 \times 10^{-5};$$
$$\lambda_2 = 0.5145\ \mu\text{m};\quad n_0 = 2.3115;$$
$$n_e = 2.4735;\quad G_{33} = 3.69 \times 10^{-5}.$$

It was assumed in the calculations that two-color radiation propagates near the optical axis of the crystal [001], diffraction occurs on a “slow” sound wave propagating along the [110] direction of the crystal, with a velocity equal to $V = 0.617 \times 10^5$ cm/s. Calculations show that the best conditions for phase matching of two-color Ar laser radiation with one acoustic wave in TeO_2 achieved in the frequency band of 102–120 MHz at a level of 3 dB.

3. EXPERIMENT AND DISCUSSION OF EXPERIMENTAL RESULTS

The experimental setup fully corresponded to the optical scheme shown in Fig. 1. For experiments, we chose a frequency of 118 MHz. At this frequency, the angle of incidence of light on the crystal, according to calculations, is 3.3°. Angle between beam *1* and beams *2* and *3* equals ~5°, the angle between beams *2* and *3* is ~0.2°. The angle is the same between beams *4* and *5*. The ellipticity of beams with wavelengths λ_1 and λ_2 equal $\rho_1 = 0.82$ and $\rho_2 = 0.84$, respectively. As can be seen, the ellipticities of the beams are close to unity, which ensures efficient conversion of the polarizations of the beams when they are reflected from the mirrors.

In the experimental setup, optical radiation passed between cells *AO-1* and *AO-2* with a length of ~8 cm. In this case, the centers of diffracted beams *2* and *3* diverged by 0.14 mm. Radii *r* of optical beams according to our measurements were equal to ~0.5 mm. The degree of beam overlap of *2* and *5*, as well as beams *3* and *4*, according to calculations based on expressions (1) and (2), is equal to $\mu = 0.867$. In other words, monochromatic pairs overlap on ~87%. On a screen at a distance of ~1 m from cell *AO-2*, two diffraction spots were clearly observed, corresponding to beams with wavelengths λ_1 and λ_2, spot sizes were ~1 mm. The distance between the spots was ~3.5 mm. If necessary, diffraction spots can be reduced to a single beam. We did this by using a TeO_2 prism with apex angle ~11° located immediately after cell *AO-2*. To observe the modulation of each monochromatic component of the output diffracted radiation, a polarizer was installed after cell *AO-2*, and a photodetector was located at a distance of 1 m along the propagation of the beams, with which the amplitude modulation of each beam was measured in turn. Figure 3 shows a typical signal from a beam with wavelength λ_1 (curve *1*) taken from the photodetector and observed on the

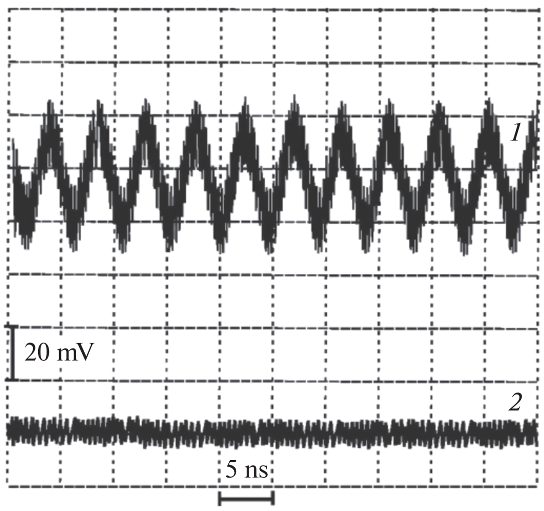

Fig. 3. The modulated signal observed on the oscilloscope screen: (*1*) is a modulated beam signal with a wavelength λ_1; (*2*) is the signal in the absence of optical radiation.

oscilloscope screen. Beam signal λ_2 is similar to beam signal λ_1 and is not shown here. Here, the zero signal (*2*) is recorded in the absence of optical radiation.

Signal frequency *1* corresponds to twice the frequency of the signal applied to the cells, which was verified by frequency measurements using a frequency meter.

The signal modulation depth was ~20–25% depending on polarizer orientation. This effect can be explained by the presence of ellipticity of the interfering beams. The relatively small depth of the observed signal in Fig. 3 can be explained by several reasons. First of all, the real waves we use in our experiments are not plane waves. They have a Gaussian distribution. In addition to the incomplete superposition of waves considered in this article, the interference depth is affected by such factors as the distortion of laser beams during AO interaction. It was shown in [15] that the distortion of the diffracted field depends on the geometry of the light and acoustic beams and on the magnitude of the acoustic power. In particular, the light field narrows along the direction of sound wave propagation by $\sqrt{1-\xi/4}$, where ξ is a dimensionless parameter equal to the ratio of the acoustic power emitted by the transducer to the power at which the diffraction efficiency is 100%. In our case, $\xi \approx 1$. Thus, the beam narrows to ~15%. The narrowing effect, on the other hand, leads to an increase in the intensity of the central part of the beam due to redistribution of its power, which leads to a distortion of the beam profile. This, according to our estimates, also reduces the interference depth by ~15%. The profile of the optical field is also affected by the inhomogeneity of the sound wave [16]. According to our estimates, sound inhomogeneity leads to a decrease in the interference depth by 5–7%. In addition, parasitic light scattering in AO cells, incomplete identity of AO cells, etc., can affect the final result. It is also important that in experiments the situation was achieved when the depth of modulation of beams with wavelengths λ_1 and λ_2 was the same, which is fundamentally important for the practical use of the device, for example, in LDA systems. Note that by more careful angular adjustment and selection of the input power, it was possible to increase (by 7–10%) the modulation depth of one of the beams to the detriment of the modulation depth of the other beam. However, we preferred to choose a mode that ensures the equality of the modulation depths of both beams.

Note that the result is in no way inferior to the characteristics of optical radiation used in LDA differential circuits [17]. There, the radiation is formed as a result of the interference of two beams, which is then used to measure the speed of the flows.

The results can be used in devices designed to control two-color laser radiation.

CONCLUSIONS

Based on the material presented, the following conclusions can be drawn.

(1) For amplitude modulation of two-color optical radiation with a controlled frequency, it is proposed to use a device consisting of two identical AO cells operating at the same sound frequency and providing Bragg synchronism of two optical beams with one acoustic wave. As an AO medium, it is proposed to use a gyrotropic crystal whose eigenwaves are circularly polarized. The modulation is caused by the interference of waves with circular polarizations.

(2) To ensure different frequencies of interfering beams, it is proposed to use AO diffraction modes, in which diffraction in one cell occurs with an increase in the frequency of the beams diffracted in the crystal, and in another cell with a decrease in frequency.

(3) The scheme was tested on a device consisting of two paratellurite AO cells operating at an audio frequency of 118 MHz. An Ar laser was used as a source of two-color radiation, generating the two brightest lines with wavelengths of 0.488 μm and 0.514 μm. The modulation of monochromatic components at a frequency of 236 MHz has been obtained.

FUNDING

The study was carried out within a state task of the Institute of Radioengineering and Electronics, Russian Academy of Sciences.

CONFLICT OF INTEREST

The authors declare that they do not have a conflict of interest.

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