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An Acousto-Optic Modulator of Optical Radiation at the Double Acoustic Frequency

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Abstract—An acousto-optic (AO) modulator that converts a frequency shift of optical radiation into the amplitude modulation of light at the double acoustic frequency is proposed and described. A TeO_2 single-crystal modulator mockup that was developed and tested provides the amplitude modulation of linearly polarized optical radiation at a wavelength of 0.63 μm at the double acoustic frequency, which is equal to ~82 MHz.

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INTRODUCTION

One of the specific features of Bragg acousto-optic (AO) diffraction is a shift of the frequency of diffracted optical radiation by the sound frequency. This shift occurs due to the fact that light is reflected from a traveling acoustic lattice [1, 2]. This phenomenon has found its application in optical-heterodyning systems [3], laser Doppler anemometry systems [4], optical gyroscopes [5], etc. As will be shown below, the frequency shift can be also used for the amplitude modulation of optical signals. Such modulators are necessary, for example, for laser Doppler anemometers.

SCHEMATIC OF THE DEVICE

Figure 1a shows the optical diagram of the device that performs the function of converting a frequency shift into amplitude modulation, while Fig. 1b is a vector diagram of the AO interaction in the modulator crystal. The operating principle of the device is as follows. Linearly polarized radiation, I_0, is incident on the optical face of the modulator, *AOM*, at the angle Θ_1 to the wave front of an acoustic wave, whose wave vector is $\mathbf{q}$. The wave is generated by a piezoelectric transducer (*PET*), to which a high-frequency (HF) signal at the frequency f is fed.

The modulator is manufactured from a gyrotropic material. Optical radiation that is incident on such a material splits in it into two proper waves with right- and left-hand (RH and LH) circular polarizations. A wave of only one polarization participates in the AO diffraction. Suppose, for definitiveness, that only the left-hand circular wave (LCW) diffracts.

The conditions of the AO interaction are selected so that when an LCW diffracts into a right-hand circular wave (RCW) and vice versa, anisotropic diffraction occurs. As a result of the AO interaction, two beams form at the *AOM* output: the beam I_1 with the RH circular polarization that did not diffract and the diffracted beam I_2, whose polarization after the AO diffraction also became RH circular.

It should be added that during anisotropic AO diffraction, the angle of incidence Θ_1 does not generally coincide with the reflection angle Θ_2 [1, 2]. This is explained by the vector diagram that is shown in Fig. 1b. Here, the incident radiation that is represented by

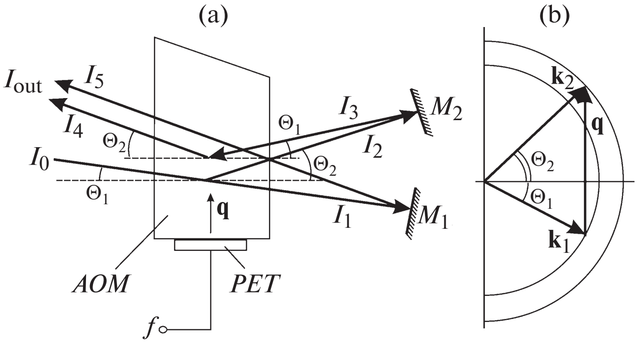

Fig. 1. The optical scheme of the device: (*AOM*) face of the acousto-optic modulator; (*PET*) piezoelectric transducer; and (M_1, M_2) reflecting mirrors.

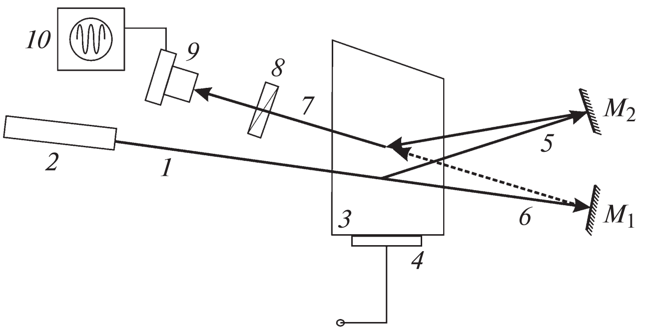

Fig. 2. The optical diagram of the experimental device: (*1*) incident radiation; (*2*) laser; (*3*) AO modulator; (*4*) PET; (*5*, *6*) diffracted and nondiffracted rays, respectively; (*7*) ray after the repeated diffraction; (*8*) polarizer; (*9*) photodetector; (*10*) oscilloscope; and (M_1, M_2) external mirrors.

the wave vector $\mathbf{k}_1$ interacts with the acoustic wave $\mathbf{q}$ and is reflected in the direction of the vector $\mathbf{k}_2$. The angles of incidence, Θ_1, and reflection, Θ_2, are not equal to each other. The inequality of the angles Θ_1 and Θ_2, for example, serves as the basis of cascade diffraction [6].

Reflecting mirrors M_1 and M_2 are installed on the paths of the rays I_1 and I_2 (Fig. 1a). After the reflections from the mirrors, the RH circular beams I_1 and I_2 become LH circular ones [7]. The mirror M_2 is oriented so as to direct the reflected ray I_3 at the angle Θ_1 to the AO modulator *AOM*.

The ray I_3 after the repeated diffraction in the *AOM* at the same acoustic wave propagates in the direction of the ray I_4. Because the repeated diffraction is also anisotropic, the ray I_4 polarization becomes RH circular. The mirror M_1 reflects the ray I_1 in the direction of the ray I_5, which is collinear to I_4.

Thus, the output radiation I_{out} consists of two rays, I_4 and I_5, with RH and LH circular polarizations, respectively. After such polarizations are added together, linearly polarized radiation is formed [8]. However, since the frequencies of the ray I_4 after the double AO diffraction and the ray I_5 are $\omega + 2\Omega$ and ω, respectively, where ω and Ω are the frequencies of light and sound, respectively, the linear-polarization vector of the ray I_{out} rotates at the difference frequency, which is equal to Ω [8, 9]. If a polarizer is installed on the path of the ray $I_{\text{out},}$ an amplitude-modulated ray at the modulation frequency Ω is formed after the polarizer. Thus, the radiation frequency shift is transformed into the amplitude modulation of light. The photodetector on which such radiation is incident generates an electric signal at the frequency 2Ω because it operates in a quadratic mode. Note that in any case, the characteristics of optical radiation are measured with photodetectors. As is known, the latter measures the light intensity but not its amplitude.

THE EXPERIMENT AND DISCUSSION OF THE RESULTS

The operation of the modulator was tested in an experiment. Its optical scheme is shown in Fig. 2. Linearly polarized radiation, *1,* with a wavelength of 0.63 μm, which is generated by a He–Ne laser, *2*, was directed to an AO modulator, *3.* The modulator is manufactured from a TeO_2 uniaxial gyrotropic crystal, which was cut orthogonally with respect to the [110], $[1\bar{1}0]$, [001] directions. The optical faces of the crystal are oriented orthogonally to its [001] optical axis.

The piezoelectric transducer, *4*, which is manufactured from *X*-cut crystal quartz, is pasted to the {110} face. The quartz-plate thickness is ~120 μm. The plate excited a transverse acoustic wave at a frequency of ~41 MHz (third harmonic of the PET). The velocity of sound in the TeO_2 crystal is 617 m/s. Strictly speaking, proper waves in TeO_2 are circular only when light propagates along the optical axis of the crystal. However, in our case, the angles Θ_1 and Θ_2 are small; inside the crystal, they are equal to 0.3° and 1.2°, respectively. Therefore, the ellipticity of proper waves is disregarded: they are assumed to be circularly polarized.

Two rays are formed at the crystal output: diffracted, *5,* and nondiffracted, *6,* rays. Both rays are again reflected by the external mirrors M_1 and M_2 into AO modulator, *3.* However, ray *5* undergoes a repeated diffraction, being transformed into ray *7,* while after being reflected, ray *6* propagates in the direction that coincides with ray *7.* Thus, the output beam is formed from two rays with different polarizations and frequencies. On the path of output radiation, a polarizer, *8,* is installed, after which radiation is detected with the photodetector, *9*, and the electric signal is guided to an oscilloscope, *10.* The maximum modulation depth is attained via selection of the acoustic power that is fed to the transducer, *4.*

Figure 3 shows a typical photograph of an alternating signal from the oscilloscope screen. It is seen that the modulation frequency on the screen is ~ 82 MHz, which corresponds to the double acoustic frequency. The time sweep of the oscilloscope in Fig. 3 is 5 ns/division, while the signal sensitivity is 20 mV/division.

CONCLUSIONS

On the basis of the above, the following conclusions can drawn

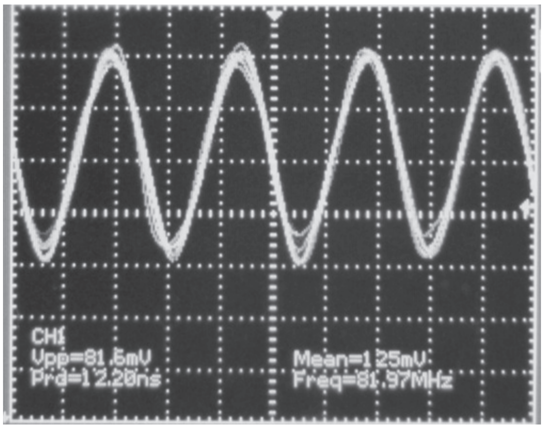

Fig. 3. A photograph of an electric signal on the oscilloscope screen. The time sweep is 5 ns/division, the signal level is 20 mV/division.

1. A quite simple scheme of an AO modulator is proposed. It allows the conversion of a radiation frequency shift, which is induced by the reflection of light from a traveling acoustic lattice, into an amplitude modulation of light at the acoustic frequency. The scheme is based on the use of a gyrotropic material as the AO medium and two reflecting mirrors.

2. An AO modulator prototype on the basis of a uniaxial gyrotropic TeO_2 crystal was developed. The photodetector that detects modulated radiation at a wavelength of 0.63 μm generates an electric signal at the double acoustic frequency equal to 82 MHz.

The described modulator can be used in various systems for controlling optical radiation, e.g., in laser Doppler anemometers.

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