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Acousto-optic modulators based on a KYW crystal

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Abstract. **Two types of acousto-optic modulators based on new acousto-optic crystals $KY(WO_4)_2$ are developed and experimentally investigated. Their characteristics are compared with those of existing acousto-optic quartz modulators. It is shown that the new modulators provide an almost 10-fold efficiency gain, which eliminates the need for water cooling of such devices.**

Keywords: *acousto-optic modulation, high-power laser radiation, KYW.*

1. Introduction

Modulation of laser radiation is used in most laser applications: in signal transmission, detection, sounding and materials processing. In many cases, the most suitable means for modulation are acousto-optic (AO) modulators based on laser radiation diffraction on a bulk diffraction grating produced by an acoustic wave in a crystal [1]. The advantages of AO modulators are small switching times, simplicity and ease of use, relatively low cost and a great variety of modifications, which allows optimisation of the device for specific tasks, in particular to set a required wavelength or ensure a wide operating spectrum range. This diversity, however, does not pertain to the problems of generation and modulation of high-power laser radiation, in which the requirement of high radiation resistance is imposed on optical elements. Therefore, up to now, quartz (crystalline or fused) is the only material used for AO modulators of high-power laser radiation. And since this material is not notable for high AO quality, it is necessary to supply a high-frequency (HF) control signal of high power (up to 100 W) to the AO modulator. In turn, this leads to the need for water-cooling of the working crystals of AO modulators [2], which significantly complicates their use. In this regard, an urgent task is the development of efficient AO modulators of intense laser radiation, which do not require liquid cooling.

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Previously, we have shown that crystals of the families of double tungstates of potassium $KMe(WO_4)_2$, where Me is a metal (Gd, Y, Yb, Lu), which are used in laser technologies, are effective AO crystals [3], and, owing to their fairly high radiation resistance [4] and transparency for light in a wide spectral range (0.4 – 5 μm) [5], can serve as the basis for a number of AO devices designed for controlling high-power laser radiation. In the present work, we investigate the previously developed AO modulators based on $KY(WO_4)_2$ (KYW) [6] and show that they are much more efficient compared to classical modulators currently used.

2. Structure and features of AO modulators made of KYW

Potassium yttrium tungstate (KYW) crystals have an expressed anisotropy of properties, which is typical of monoclinic syngony. Therefore, in manufacturing AO modulators, correct orientation of a crystalline sample is of great importance. Mutual orientation of the axes of the coordinate systems used, including crystallographic, crystallophysical and crystallo-optical ones, is shown in the AO modulator scheme (Fig. 1).

As a result of the analysis of AO characteristics of the KYW crystal, we have found the possibility of designing an effective two-polarisation AO modulator [7] with a geometry

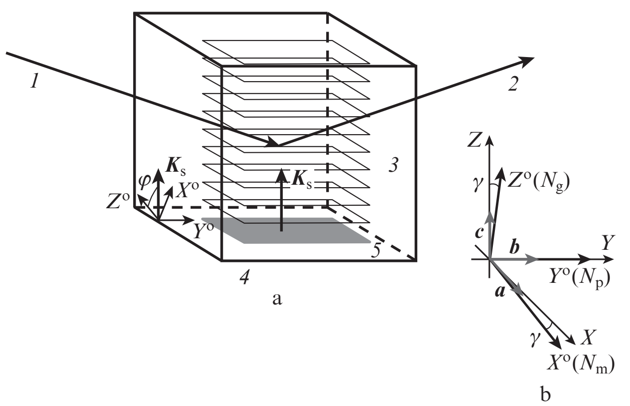

Figure 1. (a) Optical scheme of the AO modulator and (b) coordinate systems:
(*1*, *2*) incident and diffracted light beams; (*3*) acoustic wave forming a volume (Bragg) grating; (*4*) AO cell (light and sound conductor, working crystal); (*5*) piezotransducer; $\boldsymbol{K}_s$ is the wave vector of the acoustic wave; ***a***, ***b***, ***c*** are the basis vectors of the crystal lattice (crystallographic system); XYZ is the crystallophysical (orthonormal) system; $X^oY^oZ^o$ is the crystallo-optic system formed by the axes of the optical indicatrix N_m, N_p, N_g and obtained by rotating the system XYZ by the angle $\gamma \approx 17.5°$ around the Y axis [8].

in which a light wave that propagates in the direction close to the second-order symmetry axis Y of the crystal is diffracted on the longitudinal ultrasonic wave travelling in the direction of the Z^o axis (Fig. 2a). Next, it was shown in work [6] that the greatest value of the AO figure-of-merit M_2 in the case of diffraction on a longitudinal acoustic wave is reached in the course of its propagation in the plane $Z'Y$, which is obtained by the rotation of the plane Z^oY by the angle of –30° around the Y axis (Fig. 2b).

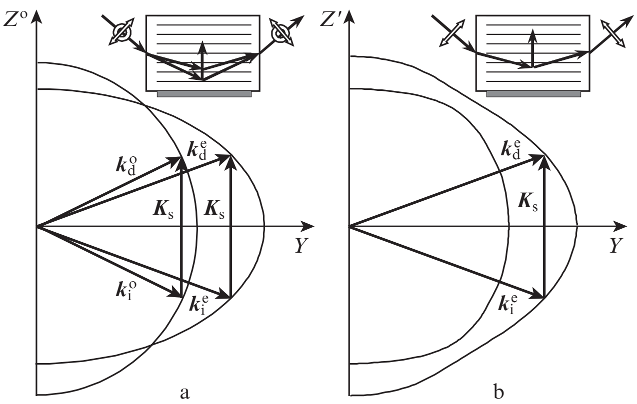

Figure 2. Vector diagrams of AO diffraction in the modulators designed (a) in 'two-polarisation' geometry and (b) in the most efficient geometry for linearly polarised radiation; $\boldsymbol{k}_{\rm i}^{\rm o,e}$ and $\boldsymbol{k}_{\rm d}^{\rm o,e}$ are the wave vectors of the incident and diffracted ordinary and extraordinary waves, respectively.

To develop experimental models of AO modulators for further investigations, the most promising geometries for AO interactions were analysed. To this end, the geometries were considered, in which light propagates in a direction close to the Y axis, as in Fig. 2, while the ultrasonic wave – in the orthogonal plane XZ. Figure 3 shows all basic physical parameters influencing the choice of the diffraction geometry as functions of the propagation direction of an ultrasonic wave ($\boldsymbol{K}_{\rm s}$): the AO figure-of-merit M_2, the velocity of acoustic waves and the deflection angle of the group velocity direction from the phase velocity direction (acoustic wave walk-off angle). The acoustic wave propagates in the X^oZ^o plane at an angle φ to the Z^o axis.

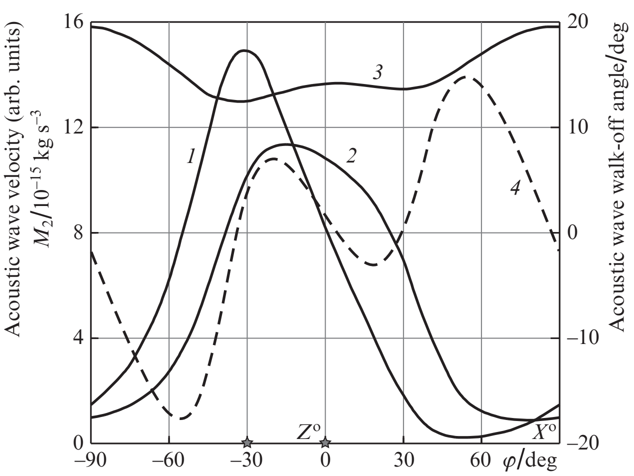

Figure 3. Calculated AO dependences and acoustic characteristics in the KYW crystals during the light propagation along the Y axis as functions of the propagation direction of ultrasound radiation (angle φ) in the plane containing the Y axis: the AO figure-of-merit M_2 for the light with polarisations along the (*1*) Z^o and (*2*) X^o axes, (*3*) acoustic wave velocities (the maximum value is equal to 5.55 km s^{-1} at $\varphi = \pm 90°$) and (*4*) acoustic wave walk-off angle. The asterisks indicate directions corresponding to the two selected geometries of the AO modulators.

As a result, two diffraction geometries were chosen for investigations: the most effective and two-polarisation ones. The first geometry (Fig. 2b), corresponding to the angle φ = –30°, provides the maximum value of the AO figure-of-merit M_2 – in this case light should be polarised along the Z^o axis. In the case of a two-polarisation AO modulator, for the sake of convenience, the angle $\varphi = 0$ was chosen to ensure close and sufficiently large M_2 values for light of both polarisations. In addition, in this geometry, the modulator base and the face on which the piezotransducer is applied are oriented normally to the optical axes, as is usually the case in laser optics. It can be seen that for the selected angles φ = –30° and 0, which are marked with an asterisk in Fig. 3, the acoustic wave walk-off angle is small: 3.4° and 1.6°, respectively. This is important in the development of AO modulators, because a large cell is required at a larger walk-off angle and additional difficulties may arise when adjusting the modulator. The velocities of acoustic waves at φ = –30° and 0 are equal to 4.56×10^5 and 4.79×10^5 cm s^{-1}, respectively.

For the chosen diffraction geometries, two AO modulators of different types were manufactured and investigated. Their AO cells are made in the form of prisms with optical faces perpendicular to the Y axis of the crystal. These faces have AR coatings for the light with a wavelength of 1.06 μm, so that the overall device transmittance (in the absence of ultrasound) constituted 99 %.

3. Investigating the characteristics of modulators

At the first stage, the diffraction efficiency of AO modulators was determined. In these studies, we used a 632.8-nm helium–neon laser with circular polarisation. Linear polarisation of the laser beam with an arbitrary direction of the polarisation vector was achieved using an additional crystalline polariser. Experimental results for different orientations of linear polarisation of the incident light (Fig. 4) generally correspond to the classical dependence of the diffraction coefficient T on the power P applied to the modulators: $T = \sin^2[(\pi/2)\sqrt{P/P_0}\,]$, where P_0 is the power providing the total diffraction of light. Calculations of the diffraction efficiency of AO modulators, defined as the steepness within the linear part of the dependence $w = T/P|_{T \ll 1} = \pi^2/(4P_0)$, have confirmed the results of the preliminary theoretical analysis based on the previously obtained data on the velocities and photoelastic coefficients: one of the modulators demonstrated the maximum efficiency (Fig. 4b), while the diffraction efficiencies in the other AO modulator were close for both polarisations (Fig. 4a).

For verification, the same measurements were repeated using the laser light with a wavelength of 1.06 μm, and the results were recalculated with allowance for the dependence of the diffraction efficiency on the optical radiation wavelength $w \propto n^6(\lambda)/\lambda^2$, which, among other factors, is conditioned by the dispersion of the refractive index $n(\lambda)$. The error in estimating the diffraction efficiency does not exceed 20 %, which corresponds to the determination accuracy of the elasto-optical characteristics [9].

At the second stage, using the same optical scheme with the aim of comparison with the existing analogues, we measured

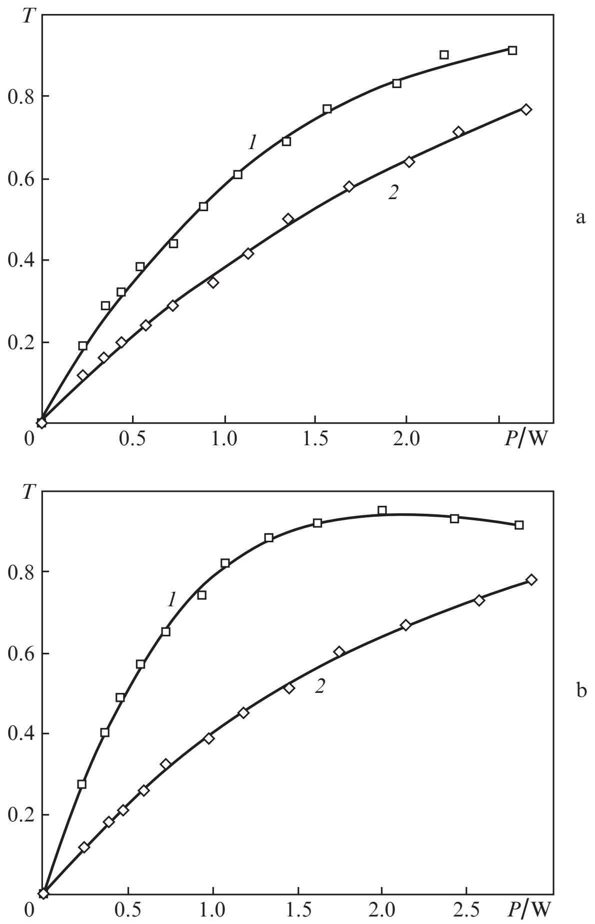

Figure 4. Dependences of the diffraction coefficient on the HF power supplied to the AO modulator made of KYW for two optical eigenmodes in the cases of (a) two-polarisation and (b) most effective geometries. Light is polarised along the Z^{o} and X^{o} axes. Points show experimental data, curves – approximations.

the diffraction efficiency of the commercially available MZ-321 AO modulator of nonpolarised light with crystalline quartz employed as a working medium (Fig. 5)

According to the results of measurements (Fig. 6), the efficiencies of two designed AO modulators made of the KYW crystal exceed the efficiency of the MZ-321 modulator by 3.7 and 6.6 times, respectively. It should be noted here that the MZ-321 modulator has a significantly longer ultrasonic converter than the AO modulators made of KYW (40 and 24 mm, respectively), which provides a much longer AO interaction length and makes the estimate obtained not completely correct. In addition, it should be taken into account that the ultrasonic converters of the compared AO modulators have different widths: 3 mm for MZ-321 and 2.5 mm for AO modulators made of KYW.

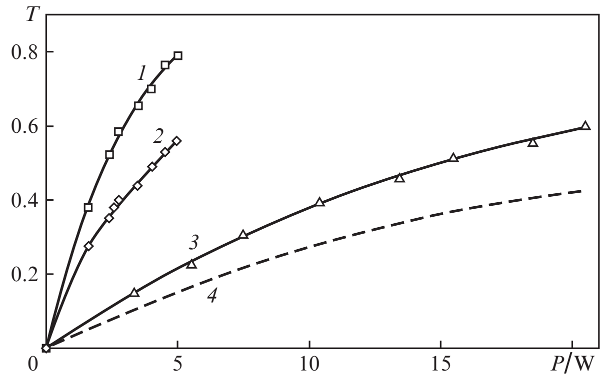

Figure 6. Dependences of the diffraction coefficient on the HF power supplied to two AO modulators based on KYW and a similar modulator made of SiO_2 in the case of (*1*) the most effective interaction geometry [curve (*1*) in Fig. 4b], (*2*) two-polarisation geometry [curve (*2*) in Fig. 4a] and (*3*) MZ-321 quartz modulator, as well as (*4*) dependence *3* recalculated for the size of the ultrasonic emitter of the modulators made of KYW, equal to the emitter size of the modulator based on SiO_2. Points show experimental data, curves – approximations.

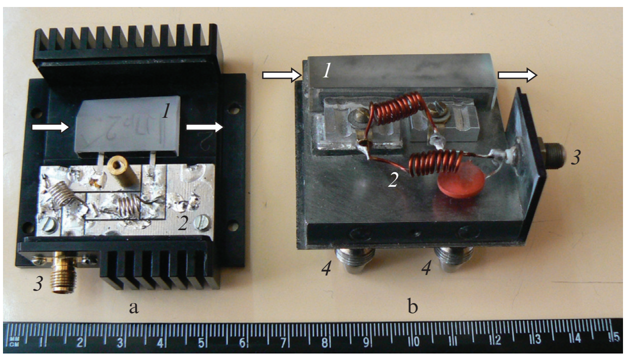

Figure 5. AO modulators for controlling high-power laser radiation – (a) modulator made of KYW that does not require cooling and (b) commercially available water-cooled MZ-321 quartz modulator:
(*1*) AO cell; (*2*) matching HF elements; (*3*) HF connector for the control signal; (*4*) water cooling system; white arrows indicate the direction of light propagation.

Accurate calculation taking all these factors into account [curve (*4*) in Fig. 6] has shown that, with other conditions being the same, the designed AO modulators made of KYW are more efficient compared to the MZ-321 AO modulator by 5.1 and 9.2 times, respectively. This comparison, based on the experimental results, completely corresponds to the estimates obtained from the data of the previous calculations of the photoelastic constants and AO figures-of-merits M_2 (the efficiencies differ by 6 and 10 times).

For correctness, it is necessary to compare the characteristics of the investigated modulators made of KYW with the AO modulators based on paratellurite (TeO_2), which is the most used and highly effective AO material. While the calculated efficiency of AO modulators based on the KYW crystal, depending on the diffraction geometry, is about by 2–3 times smaller than that of the modulators made of TeO_2, the radiation strength of the latter material is much lower. For paratellurite, the threshold of the laser-induced breakdown by short pulses is approximately 0.3 GW cm^{-2} [10] at a wavelength of 1 μm. The same value for the $KGd(WO_4)_2$ (KGW) crystal, belonging to the same family of potassium tungstates as $KY(WO_4)_2$, is no less than 50 GW cm^{-2} [4]. Investigations of the modulator made of KYW have shown its stability to pulsed laser radiation of 10 ns duration with an intensity of 0.85 GW cm^{-2}. Both the crystal itself and the antireflection coating have sustained this intensity. Thus, for high-power laser radiation, the characteristics of the modulators developed can be compared with the characteristics of a quartz modulator, whose radiation strength is comparable with the KGW crystal strength [10].

4. Conclusions

Experimental verification confirmed theoretical calculations demonstrating the unique properties of the AO modulators based on the KYW crystal. In particular, their efficiency in the geometry of Fig. 2b exceeds the efficiency of a typical AO quartz modulator by approximately 10 times. In another geometry (Fig. 2a), modulators made of KYW provide approximately equal diffraction efficiencies for both polarisation components of the light beam, which allows nonpolarised radiation to be modulated without significant losses. These modulators also outperform in efficiency quartz modulators by more than five times.

Both modulators developed do not require water cooling, since the control powers do not lead to overheating of the AO cell. They can be effectively used both for intracavity Q-switching and radiation modulation outside a resonator.

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