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Optimum configuration for acousto-optical modulator made of KGW

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Abstract

Acousto-optical figure-of merit has been investigated for $KGd(WO_4)_2$ crystal, which is applicable to control high intensity laser radiation. Using the data on acoustic velocities obtained earlier and the experimentally determined coefficients of light diffraction on acoustic waves, we have calculated for the first time 12 elements of the upper half of the elasto-optic matrix. This new data permitted to calculate angular dependence of acousto-optical figure-of-merit with respect to the light polarization for "isotropic" diffraction and to find the optimum geometry, which ensures maximum diffraction efficiency.

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1. Introduction

It was found earlier [1-3] that double-potassium tungstates $K\mathit{Me}(WO_4)_2$, where *Me* – luminescent metal ion, do not only represent promising laser crystals family [4], but demonstrate quite good acousto-optical properties. Acousto-optic (AO) figures-of-merit *M* of these crystals [5] yield only three times [1] to paratellurite values M_{TeO2} in modulator geometry and exceed other acousto-optical materials including quartz. And also AO modulators made of these materials provide some other advantages. First, due to radiation resistance [6] they can be used for control of high intensity laser beams. Second, as these tungstates were developed as laser active media, they can serve as a base

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for creation of hybrid elements providing both generation of light and its control. Therefore, their implementation in practice would be rather promising.

Previously we measured acousto-optic characteristics of four tungstates (Me = Y, Gd, Yb, Lu) for "isotropic" (polarization-preserving) AO diffraction [1]. Among 12 directions, which were investigated, those oriented along the dielectric axis N_g demonstrated the highest values of AO figures-of-merit (FOM). In practice, for acousto-optical devices development one needs to know the extreme value of AO FOM M_{max}. In the paper, we present (i) the procedure of finding the elasto-optic constants $P_{\alpha\beta}$ based on experimental data for $KGd(WO_4)_2$ crystals (abbreviated as KGW), (ii) the calculated angular dependence $M(\theta)$ in the most promising plane XZ (orthogonal to the symmetry axis Y), and an estimation of the optimum geometry modulator characteristics.

2. Basic data determination

The coefficient of light diffraction on an ultrasonic wave depends on the ultrasound intensity I_{ac}, the interaction length of light and sound L, and the optical wavelength λ, in following way

$$K_{dif} = \tfrac{\pi}{2} M\, I_{ac} L^2 / \lambda^2 . \tag{1}$$

The factor M is characterized by the properties of the crystal media and the diffraction geometry

$$M = \frac{n_i^3 n_d^3}{\rho V^3} P_{eff}^2 , \tag{2}$$

where n_i, n_d are refractive indices of input and diffracted light waves, V is the acoustic wave velocity, ρ is the crystal density, P_{eff} is an effective value of elasto-optic coefficient, which is defined by the combination of matrix elements $P_{\alpha\beta}$ ($\alpha, \beta = 1,\dots,6$).

In case of "isotropic" diffraction of the light beams propagating along the dielectric axes of optical indicatrix of the crystal (N_m, N_p, N_g) the only elements of the upper-half of the matrix have an effect ($\alpha = 1,\dots,3$). In this part of the matrix for KGW crystals possessing 2/m symmetry there are 12 non-zero elements ($P_{\alpha 4} = P_{\alpha 6} \equiv 0$), which must be determined. Three of them (P_{12}, P_{22}, P_{32}) can be calculated directly from the AO figure-of-merit values measured in the appropriate geometry. As the axis N_p coincides the crystal symmetry axis Y (see fig.1 below), each effective coefficient comprises the single element

$$M_{YY}^{\alpha} = \frac{(n_\alpha)^6}{\rho (V_{YY})^3} (P_{\alpha 2})^2 . \tag{3}$$

Here indices YY denote the longitudinal ultrasonic wave along axis Y, while α marks the light beam polarization, which was oriented along dielectric axes. It should be noted that calculated elements $P_{\alpha\beta}$ correspond to the matrix written in dielectric coordinate system, which axes are enumerated in following order: N_m, N_p, N_g (α=1,2,3).

The best way to determine other elements of the matrix $P_{\alpha\beta}$ is to investigate the diffraction on acoustic waves propagating in XZ plane normal to the symmetry axis. For any of these acoustic waves both the wave normal $\boldsymbol{k}$ and displacement $\boldsymbol{a}$ have zero projection on N_p axis and therefore effective value of elasto-optic coefficient P_{eff} is expressed as linear combination of 3 elements $P_{\alpha\beta}$

$$M_{AB}^{\alpha} = \frac{(n_\alpha)^6}{\rho (V_{AB})^3} \left[k_1 a_1 P_{11} + k_3 a_3 P_{13} + (k_1 a_3 + k_3 a_1) P_{15} \right]^2 . \tag{4}$$

Here indices *AB* denote the direction and polarization of ultrasonic wave. To find 3 different equations for determining 3 unknown elements we investigated diffraction on 3 different acoustic waves: quasi-longitudinal and 2 quasi-shear ones.

3. Calculation of elasto-optic coefficients

As each equation is quadratic the system has 2^3 variants of solutions. Only those were chosen, which satisfy physical requirements $P_{\alpha\beta} > 0$ ($\alpha, \beta = 1, 2, 3$). However, it was not enough for determination of the unambiguous solution. Therefore, we additionally measured AO FOM values in several other geometries: diffraction on quasi-longitudinal acoustic waves propagating in directions *X*, *Z*, [101], [10-1] and also diffraction on quasi-shear waves in directions N_g, *Z*, [101] with displacement ***a*** belonging to *XZ* plane. Then calculations of 3 unknown elements $P_{11,}$ P_{13}, P_{15} were repeated with new data and that solution was selected which was consistent with initial ones (within an experimental error).

Two other triads of elasto-optic coefficients $P_{21,}$ P_{23}, P_{25} and $P_{31,}$ P_{33}, P_{35} were determined in similar way using data obtained in diffraction experiments of light beams polarized along N_p and N_g correspondently (Table I). Totally, in experiments with 3 samples of KGW it was measured from 4 to 7 values of AO FOM for all the three directions of light polarization. With 20% measurement errors of *M* the net inaccuracy of $P_{\alpha\beta}$ is estimated as ±0.05.

Table 1. Elasto-optic coefficients of crystal $KGd(WO_4)_2$ in dielectric (optical indicatrix) coordinate system (N_m, N_p, N_g).

P_{11}	P_{12}	P_{13}	P_{21}	P_{22}	P_{23}	P_{31}	P_{32}	P_{33}	P_{15}	P_{25}	P_{35}
0.11	0.14	0.23	0.13	0.04	0.23	0.13	0.09	0.28	-0.05	-0.025	-0.13

4. Analysis of acousto-optical features

The determined 12 elasto-optic coefficients are sufficient for calculation of AO FOM angular dependence $M(\theta)$ in *XZ* plane most promising for AO modulator development (Fig. 1). The maximum value of AO figure-of-merit ($M_{max} \approx 29\cdot10^{-15}$ s^3/kg) corresponds to diffraction of N_g-polarized light beam on the acoustic quasi-shear wave propagating in +10°direction to N_m axis with displacements orthogonal to *Y* axis. This extreme value M_{max} is approximately 50% higher than the maximum value of experimentally measured.

Another important geometry corresponds to the diffraction on the quasi-longitudinal ultrasonic wave, which is easier to generate in the crystal and which is usual for Q-switch modulators. The optimum direction of acoustic wave is -30° to N_g axis, while light beam should be polarized along N_g. The extreme value ($17.7\cdot10^{-15}$ s^3/kg) also approximately 1.5 times exceeds earlier-known highest value. Thus, the driving acoustic power of AO modulator based can be two-time decreased by choosing an optimum geometry.

5. Conclusion

1. With experimentally determined coefficients of light diffraction on acoustic waves, we have calculated 12 elements of the upper half of the elasto-optic matrix $P_{\alpha\beta}$.
2. The angular dependence of acousto-optical figure-of-merit $M_2(\theta)$ was calculated for "isotropic" diffraction.
3. Two optimum geometries, 1st ensuring maximum diffraction efficiency, and 2nd providing polarization free modulation of high power laser beams, were determined.

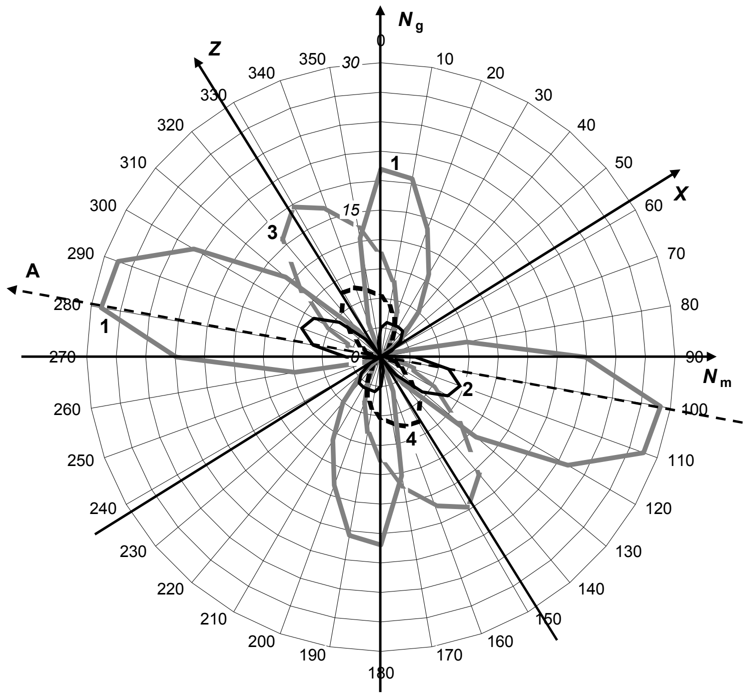

Fig. 1. Angular diagram of AO figure-of-merit for crystal $KGd(WO_4)_2$ depending on the ultrasonic wave propagation direction in *XZ* plane. Triangular and circles denotes experimental data. Calculated curves: 1 – diffraction of N_g-polarized light on quasi-shear acoustic wave (with displacement in *XZ* plane); 2 - the same for N_m-polarized light; 3 - diffraction of N_g-polarized light on quasi-longitudinal acoustic wave; 4 – diffraction of N_m-polarized light on quasi-longitudinal wave. *X*, *Z* – crystallo-physical axes; N_g, N_m – optical indicatrix axes tilted at 21.5° with respect to *X*, *Z*; axes *Y* and N_p are perpendicular to the picture plane.

A - maximum diffraction efficiency direction.

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