UDK:535.525

Мохинур ЭЛБОЕВА,
Базовый докторант, Институт ионно-плазменных и лазерных технологий
Email: elboyevamoxinur1990@gmail.com,
Фархад АХМЕДЖАНОВ,
Заведующий лабораторией, Институт ионно-плазменных и лазерных технологий,– д.ф.-м.н.,доцент
Тел: +998-91-798-19-45

Рецензент: Институт химии и физики полимеров АНРУз., д.ф.-м.н. с.н.с., Н.Ш. Ашуров

ANISOTROPY OF ACOUSTO OPTICAL PROPERTIES IN $PbMoO_4$ CRYSTALS WITH NEODYMIUM ADMIXTURE

Annotation

The anisotropy of the efficiency of Bragg diffraction of light by longitudinal acoustic waves propagating along the [100] and [001] directions in pure and neodymium-doped lead molybdate crystals has been studied. The Nd impurity concentration was approximately 0.2 mol%. The Dixon method was used to determine the effective photoelasticity constants (p_{eff}) and the corresponding acousto-optical quality factors (M_2) for various directions of polarization of incident light. The velocity of acoustic waves was determined by measurement the angle of Bragg diffraction on these waves. It is shown that in pure and doped lead molybdate crystals there is a dependence of the p_{eff} and M_2on the direction of propagation of the acoustic wave and the polarization of the incident light.

Keywords: Bragg light diffraction, coefficient of acousto-optical quality, lead molybdate crystals, neodymium impurity, photoelastic constants.

АНИЗОТРОПИЯ АКУСТООПТИЧЕСКИХ СВОЙСТВ В КРИСТАЛЛАХ $PbMoO_4$ С ПРИМЕСЬЮ НЕОДИМА

Аннотация

Исследована анизотропия эффективности Брэгговской дифракции света на продольных акустических волнах, распространяющихся вдоль направлений [100] и [001], в чистых и легированных неодимом кристаллах молибдата свинца. Концентрация примеси Nd составляла примерно 0,2 мол %. Методом Диксона определены эффективные константы фотоупругости и соответствующие M_2для различных направлений поляризации падающего света. Скорость акустических волн определялась путем измерения угла Брэгговской дифракции на этих волнах. Показано, что в чистых и легированных кристаллах молибдата свинца существует зависимость $p_{эфф}$ и M_2 от направления распространения акустической волны и поляризации падающего света.

Ключевые слова: Брэгговская дифракция света, коэффициент акустооптического качества, кристаллы молибдата свинца, примесь неодима, фотоупругие константы.

NEODIMIY ARALASHMALI $PbMoO_4$ KRISTALLARIDA AKUSTO-OPTIK XUSUSIYATLARNING ANIZOTROPIYASI

Annotatsiya

Sof va neodimiy qo‘shilgan qo‘rg‘oshin molibdati kristallarida [100] va [001] yo‘nalishlar bo‘ylab tarqaladigan bo’ylama akustik to‘lqinlar orqali Bragg yorug‘lik difraksiyasi samaradorligining anizotropiyasi o‘rganildi. Nd konsentratsiyasi taxminan 0,2 mol% edi. Fotoelastiklikning doimiylari va tushayotgan yorug'lik qutblanishining turli yo'nalishlari uchun mos keladigan akusto-optik sifat koeffitsientini aniqlash uchun Dikson usuli ishlatilgan. Akustik to'lqinlarning tezligi ushbu to'lqinlardagi Bragg difraksiyasining burchagini o'lchash orqali aniqlandi. Sof va aralashmali qo'rg'oshin molibdat kristallarida p_{eff}va M_2ning akustik to'lqinning tarqalish yo'nalishiga va tushayotgan yorug'likning qutblanishiga bog'liqligi ko'rsatilgan.

Kalit so‘zlar: Bragg yorug'lik difraksiyasi, akusto-optik sifat koeffitsienti, qo'rg'oshin molibdat kristallari, neodimiy aralashma, fotoelastik konstantalar.

Introduction. The study of the photoelastic characteristics of crystals and the anisotropy of their acousto-optic properties, in addition to being of fundamental interest, is important for determining the most efficient crystal cuts used as working media and optimizing the parameters of acousto-optic devices. According to the generalized theory of the photoelastic effect [1, 2], the experimental determination of the values and signs of the components of the photoelastic tensor in gyrotropic crystals is a rather difficult task, since the contribution of the asymmetric part of the photoelastic tensor due to spatial dispersion can be significant.

As shown in [1, 2], even within the framework of the Pockels model, to find directions in a crystal that provide the maximum value of the p_{eff}, it is necessary to solve a system of 21 nonlinear equations of the fourth, third, and second order with high-rank tensors. In this regard, the photoelastic properties of crystals are usually considered for a specific geometry of the acousto-optic interaction and certain cross sections of crystals [3-7]. The symmetry of the crystal can simplify the problem. As found in [4], for cubic crystals the ant symmetric parts $p_{ij[kl]}$ of the photoelastic tensor are equal to zero and the expressions for the components of the photoelastic tensor are simplified.

To describe the photoelastic properties of materials in addition to the photoelastic coefficients p_{ijkl}, the coefficient of acousto-optical quality of the material M_2 introduced by Dixon [8] is used as a characteristic of the efficiency of Bragg diffraction by acoustic waves. This quality factor determines the intensity of diffracted light in a given material, regardless of the size of the piezoelectric transducer and acoustic power.

The expression for this quality coefficient in the case of an anisotropic medium can be written in the form [2, 4]:

$$M_2 = \frac{n_1^3 n_2^3 p_{eff}^2}{\rho V^3}, \qquad (1)$$

where n_1 and n_2 are the refractive indices of the incident and diffracted light, respectively, ρ is the density, V is the velocity of the acoustic wave, p_{eff} is the effective photoelastic constant, that is the convolution of the components of the photoelasticity tensor p_{ijkl} of the crystal under consideration by the normalized polarization vectors of the incident and diffracted light **α**, **β** and the propagation direction and polarization vector of the acoustic wave **κ** and **γ**, respectively [2, 5]:

$$p_{eff} = p_{ijkl}\alpha_i\beta_j\gamma_k\kappa_l \tag{2}$$

As can be seen from formulas (1) and (2), the coefficient M_2 depends on the chosen geometry of light diffraction on sound and allows a comparative assessment of the acousto-optic properties of different materials. In particular, by changing the direction of the polarization of the incident light relative to the wave vector and the polarization of the acoustic wave, one can influence the value of the effective photoelastic constant and, ultimately, control the efficiency of the Bragg light diffraction. Such experiments also make it possible to identify the most optimal geometries for obtaining the highest intensity of diffracted light with help of some crystals.

Using various geometries of the acousto-optic interaction, it is possible to obtain directly from the experiment a set of absolute values of p_{eff}, which, according to expression (2), will be equal to certain combinations of the components of the Pockels photoelastic tensor. With the help of several such combinations, one can also determine the independent components of the photoelastic tensor in the matrix notation $p_{\alpha\beta}$ [2, 5]. In this work, the photoelastic properties of pure and impurity $PbMoO_4$ crystals, which are widely used as a working active medium in acousto-optic devices [3–7] have been studied. In particular, the influence of the neodymium impurity in these crystals on the acousto-optic quality factor M_2 was studied.

Materials and Methods.

The experiments were carried out on pure and neodymium-doped $PbMoO_4$ samples. The Nd impurity concentration was approximately 0.2 mol%. The samples were oriented along the [100] and [001] crystallographic axes. The measurements were carried out by the Bragg light diffraction on longitudinal acoustic waves [9]. X-cut quartz piezoelectric transducers were used to excite the acoustic waves in frequency range from 0.4 up to 1.6 GHz. The light source was a helium-neon laser (λ_0=632.8 nm). The direction of polarization of the light beam incident on the sample relative to the wave vector and polarization of the acoustic wave was determined using a polarization analyzer [9].

Pulses of diffracted light were received using a photomultiplier, which reliably registers signals in the case of observation of light diffraction in samples having a sufficiently large length. This is due to the fact that in such samples the time interval between the received signals is quite large and the photomultiplier has time to recover to receive the next optical signal due to Bragg light diffraction. In this case, the relative intensities are determined, which is equivalent to measuring the amplitudes of electrical signals at the output of the photomultiplier, which are proportional to the intensity of the diffracted light at its input.

To determine the effective photoelastic constants, a modified Dixon-Cohen method was used, which consists in comparing the intensity of light diffracted by an acoustic wave in the sample under study and in the reference sample, the photoelastic constants of which are known [8]. The circuit is shown in Figure 1. In this method, piezoelectric transducers (3) are glued to both the reference sample (1) and the studied sample (2).

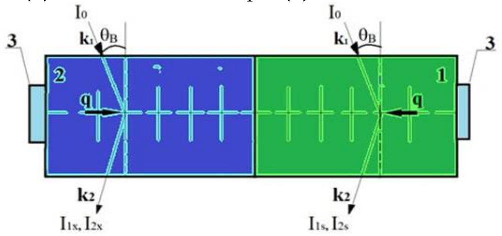

Figure 1. Scheme for determining photoelastic constants by modified Dixon method.

When acoustic waves were excited from the reference side, the values of the intensity of light diffracted in the reference I_{1S} and the studied sample I_{1X} were measured. Then, acoustic waves were excited from the side of the sample, and again the light intensities were measured in the sample, I_{2X}, and in the reference sample I_{2S}.A sample of fused quartz was used as a reference sample, for which the coefficient of acousto-optical quality M_2 upon light diffraction on a longitudinal acoustic wave was taken equal to $1.56\cdot10^{-15}$ s^3/kg [4]. Acoustic contact of the sample with the reference sample was carried out using epoxy resin.

The value of the effective photoelastic constant for each studied geometry of the Bragg light diffraction was determined from the relation [8]:

$$\left[\frac{p_{eff}^2 n^6}{\rho V^3}\frac{n^2}{(n+1)^4}\right]_X = \left[\frac{p_{eff}^2 n^6}{\rho V^3}\frac{n^2}{(n+1)^4}\right]_S \left(\frac{I_{1x}I_{2x}}{I_{1s}I_{2s}}\right)^{\frac{1}{2}}, \tag{3}$$

where ρ is the density of the crystal; n is the refractive index of light; V is the velocity of the acoustic wave, I_1x and I_1s are the intensities of light diffracted, respectively, in the studied sample and the standard reference sample, during the propagation of an acoustic wave from the reference to the studied sample; while I_2x and I_2s are the corresponding intensities of diffracted light during the propagation of an acoustic wave from the sample to the standard sample.

The Dixon method is a dynamic method for measuring photoelastic constants and, therefore, allows only the absolute value of these constants to be determined. However, if measurements are carried out for different directions of propagation of acoustic waves and for different polarizations of light, then in some cases it is possible to determine the relative sign of the photoelastic constants.

In equation (3) the designations "s" and "x" indicate, respectively, characteristics of the standard reference or studied samples. The accuracy of determining the effective photoelastic constants was approximately 20%. The values of density and refractive index required for the calculation for lead molybdate crystals were used from [6]. The accuracy of determining the value of M_2 with respect to the standard reference sample was approximately 20%. Note that in expressions (2) and (3), it is assumed that light propagates perpendicular to the wave vector of elastic waves, which is performed with sufficient accuracy in the case of Bragg light diffraction at not very high frequencies of acoustic waves (approximately no more than 1 GHz). For diffraction with rotation of the plane of polarization in optically anisotropic crystals, this condition, strictly speaking, is not satisfied.

The velocity of acoustic waves along the [100] and [001] crystallographic axes required for calculation was determined from the Bragg light diffraction angle on these waves [2, 8]:

$$\mathrm{V} = \frac{\lambda_0 \nu}{2\sin\,\theta_{\mathrm{B}}}, \tag{4}$$

where ν is the linear frequency of the acoustic wave, and θ_B is the outer angle of Bragg diffraction. The accuracy of determining the velocity of the acoustic wave depends on the accuracy of the angle measurement and was about 0.2%.

Results and discussion.

Based on the measured intensities of diffracted light in pure and neodymium-doped lead molybdate samples, the effective photoelastic constants peff and the acousto-optical quality factor M_2 were calculated for various directions and polarizations of light and acoustic waves. Calculations were carried out using experimentally obtained values of the velocity of longitudinal acoustic waves, relationships (1) and (3), as well as data on the density and refractive indices of lead molybdate from [5, 6]. Two geometries of Bragg light diffraction were considered. In the first case, the polarization of the light incident on the crystal was parallel to the wave vector of the acoustic wave, and in the second, it was perpendicular to it. The calculation results are presented in table. 1.

Table 1. Acousto-optic quality factor and photoelastic constants of pure and neodymium-doped $PbMoO_4$ crystals (λ_0=632.8 nm), k ‖ [010]

Crystal	q	γ	β	p_{eff}	M_2, 10^{-15} s^3/kg
$PbMoO_4$	[100]	[0.98 0.18 0]	[001]	0.18	9.5
	[100]	[0.98 0.18 0]	[100]	0.26	27.3
	[001]	[001]	[100]	0.27	38.8
	[001]	[001]	[001]	0.29	32.5
$PbMoO_4$: 0.2mol.Nd	[100]	[0.98 0.18 0]	[001]	0,12	4.4
	[100]	[0.98 0.18 0]	[100]	0,19	15.2
	[001]	[001]	[100]	0,21	22.9
	[001]	[001]	[001]	0.24	21.7

In the table1 the wave vectors q and k indicate the crystallographic direction of propagation of the acoustic and light waves, respectively, **γ** and **β** are the direction of polarization of the acoustic and incident light waves, respectively.From the table 1 it can be seen that in both pure and doped $PbMoO_4$ crystals there is a dependence of the effective photoelastic constant and acousto-optical quality factor on the direction of propagation of the acoustic wave and the polarization of the incident light. Moreover, for all considered geometries of Bragg light diffraction, the values of the acoustooptic characteristics in lead molybdate crystals with neodymium impurity are noticeably lower than in nominally pure crystals. In lead molybdate crystals doped with neodymium, the acousto-optical quality factor during light diffraction on longitudinal acoustic waves along the [001] axis becomes approximately five times greater than for the same waves along the [100] axis if the polarization of the incident light is perpendicular to the vector of the acoustic wave.

The observed difference is related to the difference in the polarization of the light interacting with the acoustic waves and, hence, to the difference in the effective photoelastic constants p_{eff}. The rest of the quantities included in relation (2) practically do not differ from each other in all crystals. In particular, doping of crystals practically does not change the propagation velocity of acoustic waves along the crystallographic axes. On Fig. 2 the dependence of the effective photoelastic constant on the direction of polarization of light incident on a $PbM0O_4$:0.2Nd sample along the crystallographic axis [010] is shown.

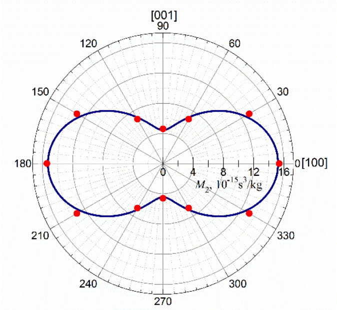

Figure.2.Dependence of the acousto-optical quality coefficient on the direction of light polarization in the (010) plane in the PbMoO4:0.2Nd crystal. The curved line is the calculation, the dots are the experiment.

It can be seen that the experimental values are in good agreement with the theoretical curve calculated from the expression:

$$p_{eff}^2 = p_{11}^2 \cos^2\psi + p_{31}^2 \sin^2\psi\,, \tag{5}$$

Whereψ is the angle between the light polarization vector and the [100] axis in the (010) plane.

As can be seen from Figure 2, by changing the direction of polarization of the incident light, it is can control the value of the acousto-optical quality coefficient and, accordingly, the efficiency of Bragg diffraction of light. In this case, the intensity of the diffracted light changes approximately four times.

Conclusions.

According to the results obtained, doping of lead molybdate crystals with neodymium impurity noticeably reduces the effective photoelastic constant p_{eff}, especially in the case of diffraction of light polarized along the [001] axis by longitudinal acoustic waves along the [100] axis. The results obtained can be explained if we assume that neodymium ions have a high mobility in the $PbMoO_4$ crystal lattice and their motion is quasi-one-dimensional predominantly along the [001] acoustic axis [10]. Such movement of neodymium ions can partially suppress the photoelastic effect during the interaction of acoustic waves with light polarized in the same direction.

For comparison, in crystals of paratellurite, which is most widely used in acousto-optics, the values of the acousto-optic Q-factor are almost the same as in lead molybdate, except for the anomalously large value of M_2 for a slow transverse wave along [110] direction [11, 12].

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