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PROPERTIES OF SOME ACOUSTO-OPTICAL MATERIALS

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The paper discusses the requirements to be met by the acousto-optical materials. Utilizing the scattering of laser light by acoustic wave, the measurements of the propagation velocity and absorption coefficients of acoustic waves and the photoelastic constants for $Bi_{12}GeO_{20}$, $Bi_{12}SiO_{20}$, TiO_2 crystals and for SF-14 flint glass were made. On the basis of the above measurements acousto-optical parameters of the examined crystals have been calculated and subsequently discussed.

1. Introduction

A rapid development of laser techniques and the possibility to generate acoustic waves over a wide frequency range have made the light—sound interaction the subject of significant practical importance. The experience acquired in this field has enabled the development of devices operating on the principles of this interaction, e.g. modulators and optical deflectors.

One of the basic problems in designing and developing the acousto-optical devices is the choice of suitable acousto-optical materials.

In this paper the requirements to be met by acousto-optical materials and the possibility to define their parameters on the basis of their physical and chemical properties will be discussed. Subsequently the results of measurements of acoustic and acousto-optical properties of some crystals available on the market, which may be applicable in acousto-optics, will be presented.

2. Parameters of acousto-optical materials

The materials used in acousto-optics should feature a high efficiency of light—sound interaction. This efficiency is described by the ratio of the intensity light diffracted by the acoustic wave to the intensity of incident light.

For the Bragg diffraction the ratio takes [5] the form

$$\eta = \frac{I}{I_0} = \frac{\pi^2}{2}\frac{n^6 p^2}{\varrho v^3}\frac{P_a L}{H\lambda_0^2 \cos^2\theta}, \tag{1}$$

where I_0 is the intensity of incident light, I — the intensity of diffracted light, n — the optical refraction index, p — the photoelastic constant, ϱ — the density of medium, θ — the angle of difraction of laser beam, v — the velocity of acoustic wave propagation, λ_0 — the wavelength of light in vacuum, P_a — the power of acoustic beam, L and H are the length of light path through acoustic beam and the height of acoustic beam, respectively.

The expression $n^6p^2/\varrho v^3$, appearing in (1), contains only material constants of the crystal. This expression will be denoted by M_2, as it is generally accepted in the literature [8].

Apart from high efficiency of light—sound interaction the acousto-optical materials should operate at a given angle of diffraction θ over as wide frequency range of acoustic waves as possible. This is made feasible by the use of an acoustic and laser beam with some divergence. It follows from theoretical calculations [2] that the best conditions of such an operation exist when divergencies of these beams are equal. It can be demonstrated that in this case the product of the efficiency of interaction η, the fundamental frequency f_0 and the band width Δf assumes the form

$$\eta f_0 \Delta f = \left(\frac{n^7p^2}{\varrho v}\right)\frac{\pi^2 P_a}{\lambda_0^3 H\cos\theta}, \tag{2}$$

where Δf is the frequency range of the acoustic wave in which the intensity of diffracted light is reduced by 3 dB, f_0 — the fundamental frequency at which the intensity of diffracted light attains its maximum.

The expression $n^7p^2/\varrho v$ is denoted by M_1 [3].

Frequently the third quantity

$$\eta f_0 = \pi^2\left(\frac{n^7p^2}{\varrho v^2}\right)\frac{P_a}{\lambda_0^3\cos\theta} \tag{3}$$

is introduced which, unlike expressions (1) and (2), does not vary with the size of the acoustic beam. Material constant $n^7p^2/\varrho v^2$ is denoted by M_3 [1].

It can be concluded that acousto-optical crystals should exhibit high values of the optical refraction index and photoelastic constants as well as a possibly low density and velocity of acoustic wave. It is also essential that the absorption of acoustic wave should be low. Furthermore, the crystals should meet several other requirements, the most important being:

1. high optical quality,
2. high chemical resistance and mechanical strength,
3. small temperature coefficients of physical constants.

3. Physico-chemical properties and acoustical parameters of crystals

Before the decision on growing a particular crystal can be made it is often desirable to gain some insight as regards the applicability of the crystals in acousto-optics, i.e. to be able to estimate the values of the velocity of acoustic wave, photoelastic constants and optical refraction index. In the sequel a brief description will be given of the relationship between the physico-chemical properties of crystals and the velocity of acoustic wave and photoelastic constants.

A. *Velocity of sound.* For estimating the velocity of sound [7] the empirical formula

$$\log \frac{v}{\varrho} = -b\bar{M} + d \tag{4}$$

is very often used, where b and d are constants for a given type of crystals, $\bar{M}$ is the mean atomic weight, ϱ – the density of crystal, v – the velocity of acoustic wave.

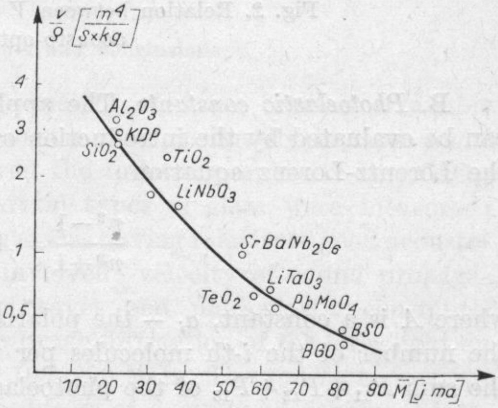

Fig. 1. Relation between V/ϱ and $\bar{M}$ for some acousto-optical crystals

Fig. 1 presents the dependence v/S on $\bar{M}$ for some substances. From this dependence it can be concluded that small velocities of sound can be anticipated for crystals with a high $\bar{M}$. The calculation of the velocity of sound – according to formula (4) – agrees within 25 % with the experimental values. In estimating the velocity of sound we also use [7, 9] formula

$$v = \sqrt{C \frac{T_t}{\bar{M}}}, \tag{5}$$

where T_t is the melting point, C – the constant for a given type of crystals, $\bar{M}$ – the mean atomic weight.

It seems that (5) is especially useful because it permits us to estimate the velocity of acoustic wave from conditions in which acousto-optical crystals are grown. Fig. 2 shows the dependence of v on T_t/M for some crystals. Similarly to the previous estimation, small velocities of acoustic wave can be anticipated for the crystals with high mean atomic weight and a low melting temperature at the same time.

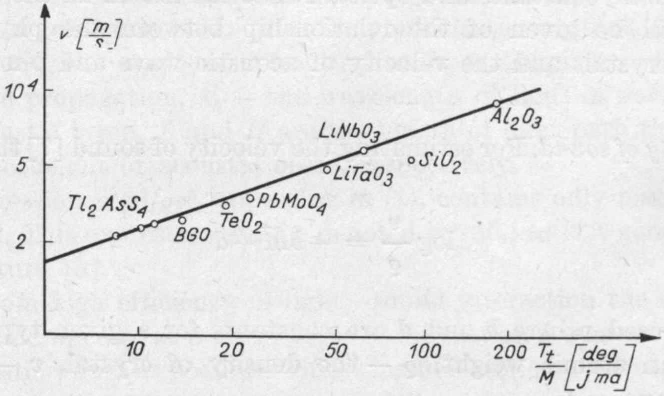

Fig. 2. Relation between V and the ratio T_t/M for some acousto-optical crystals

B. *Photoelastic constants.* The applicability of materials in acousto-optics can be evaluated by the introduction of the mean photoelastic constant. From the Lorentz-Lorenz equation

$$\frac{n^2-1}{n^2+1} = A\sum_i N_i a_i, \tag{6}$$

where A is a constant, a_i – the polarizability of the i-th molecule, and N_i – the number of the i-th molecules per unit volume, it is possible to calculate the sum $P_{11}+P_{12}+P_{13}$ of the photoelastic constants or the mean photoelastic constant

$$P_m = \frac{P_{11}+P_{12}+P_{13}}{3} = \frac{(n^2-1)(n^2+2)}{3n^4}(1-\Lambda_0), \tag{7}$$

where

$$\Lambda_0 = \frac{\varrho}{a}\frac{da}{d\varrho}.$$

For all materials of interest for acousto-optics $n > 1{,}5$ and thus, to a good approximation,

$$P_m = 0{,}35(1-\Lambda_0). \tag{8}$$

It follows that the value of photoelastic constants does not actually depend on the optical refraction index but is determined by the change in polarizability when the density of crystal is changed. These changes depend essentially on the type of crystal bonds. In crystals with an ionic bonding the polarizability increases with the increase of the atomic weight, since the outer electrons are less strongly bound to nuclei, the polarizability of the positive ions being smaller than that of the negative ones. If an ionic crystal is subjected to compression, the polarizability of the positive ion increases and that of the negative ion decreases. Hence $d\alpha/d\varrho < 0$, and $\Lambda_0 > 0$.

Experimental data indicate that $\Lambda_0 \cong 0.5$ for the ionic crystals. If the contribution of the covalent bonding in the crystal increases, then values of the photoelastic constants are dependent on two competing processes: the change of polarizability under pressure and the change of packing density. On the other hand, in crystals with a purely covalent bonding, there can be observed an intense decrease of the molecular polarizability due to the increased packing density. Consequently, crystals with a purely covalent bonding have a large Λ_0 and, therefore, exhibit weak acousto-optical properties.

Concluding, good acousto-optical properties should be expected for crystals with a very high mean atomic mass, low melting temperature and ionic or ionic-covalent bondings.

4. Results of experiments and conclusions

Measurement of acousto-optical parameters of some crystals available in the market, which can be used in acousto-optics, primarily in laser hight modulators, were made. The tests involved the following crystals: Bi_{12} GeO_{20} (BGO), Bi_{12} SiO_{20} (BSO), TiO_2. Also certain types of glass were measured; particular attention was devoted to the flint-glass having relatively good acousto-optical parameters. The measurements involved: velocity of sound propagation, absorption coefficients of acoustic waves and photoelastic constants. The measurements were made using the Bragg diffraction of the laser light on an acoustic wave over the frequency range 100 - 700 MHz. The source generating the longitudinal acoustic waves were transducers of quartz and lithium iodate, glued directly to the examined crystal or to the fused quartz, the latter being used as a reference substance.

The measuring system used is described in detail in [4].

The velocity of acoustic wave propagation was calculated from the measurement of Bragg angle according to the formula

$$v = \frac{\lambda_0 \nu}{2n \sin\theta}. \tag{9}$$

On the basis of the velocity of propagation, the elastic constants C_{ij} of the examined crystals were determined.

The elastic constants were determined by the measurement of the intensity of diffracted light in the examined crystal and in the reference substance (fused quartz) glued to the crystal.

It can be seen from relation (1) that the intensity of diffracted light is proportional to P^2 and it is easy to show that

$$P_x = P_0 \left(\frac{n_0}{n_x}\right)^3 \frac{\varrho_x v_x^3}{\varrho_0 v_0^3} \left(\frac{I_{1x} I_{2x}}{I_{10} I_{20}}\right)^{1/4} \frac{1-R_0}{1-R_x}, \tag{10}$$

where I_{1x}, I_{2x}, I_{10}, I_{20} are the intensities of light diffracted on the incident wave and refracted in the tested crystal and in the reference material. The subscript x refers to the tested substance, the subscript 0 – to the reference substance,

$$R_0 = \left(\frac{n_0-1}{n_0+1}\right)^2, \quad R_x = \left(\frac{n_x-1}{n_x+1}\right)^2.$$

For the fused quartz it was assumed that $P_{11} = 0.12$, $P_{12} = 0.27$. Table 1 summarizes the results of measurements. The accuracy of the velocity measurement is 0.2 % and that of photoelastic constants – 10 %.

Table 1. Velocity of the propagation of acoustic waves, elastic and photoelastic constants of the examined substances

Substance, crystallographic structure	n	ϱ 10^3 [kg/m^3]	Direction of the propagation of acoustic wave	v [m/s]	Elastic constants	Photoelastic constants
SF-14 Glass	1.76	4.54	–	3580	$C_{11} = 0.58$	$P_{11} = 0.14$ $P_{12} = 0.135$
BGO (cubic 23)	2.55	9.22	[100]	3740	$C_{11} = 1.29$	$P_{11} = 0.12$
			[110]	3398	$C_{12} = 0.30$	
			[111]	3276	$C_{44} = 0.26$	$P_{44} = 0.04$
BSO (cubic 23)	2.55	9.21	[100]	3727	$C_{11} = 1.28$	$P_{11} = 0.13$
			[110]	3350	$C_{12} = 0.27$	
			[111]	3217	$C_{44} = 0.25$	$P_{44} = 0.04$
TiO_2 (tetragonal 4/mmm)	2.58	4.23	[110]	7930	$C_{11} = 2.72$	$P_{11} = 0.01$
			[010]	7930	$C_{12} = 1.76$	$P_{13} = 0.16$
			[110]	9827	$C_{66} = 1.95$	$P_{31} = 0.10$

Also the measurements of the absorption coefficient of acoustic waves for the examined crystals were made, since it is known that this coefficient is essential in considering the application of a given material in acousto-opticla devices.

The measurements of the absorption coefficient were made using the method of stationary waves, and also by the measurement of intensity of diffracted light on the incident wave at different distances from the transducer.

In the former case, when the frequency of a continuous acoustic wave changes insignificantly, the intensity of diffracted light varies periodically between the maximum and the minimum values. The absorption coefficient was determined from the relation

$$a\left[\frac{\mathrm{dB}}{\mathrm{cm}}\right] = \frac{8.686}{L}\,\mathrm{ar\ tanh}\left(\frac{I_{\min}}{I_{\max}}\right)^{1/2}, \tag{11}$$

where L is the length of crystal, $I_{\min}$ and $I_{\max}$ – the intensities of light at the minimum and maximum, respectively.

In the latter case the absorption coefficient was calculated according to the formula

$$\alpha\left[\frac{\mathrm{dB}}{\mathrm{cm}}\right] = \frac{8.686}{2(x_2 - x_1)}\ln\frac{I(x_1)}{I(x_2)}, \tag{12}$$

where $I(x_1)$ and $I(x_2)$ are the intensities of diffracted light at distances x_1 and x_2 from the transducer, respectively.

The results of measurements obtained for the absorption coefficient are shown in Figs. 3-5. The accuracy of measurement of the absorption coefficient is about 10%.

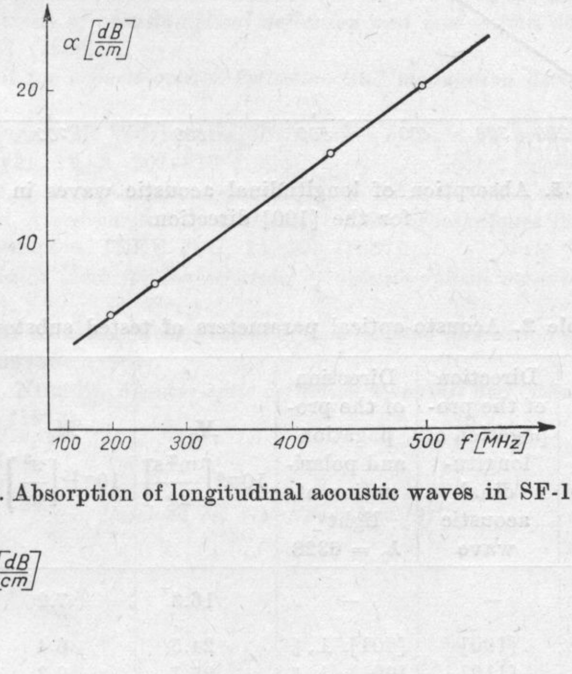

Fig. 3. Absorption of longitudinal acoustic waves in SF-14 glass

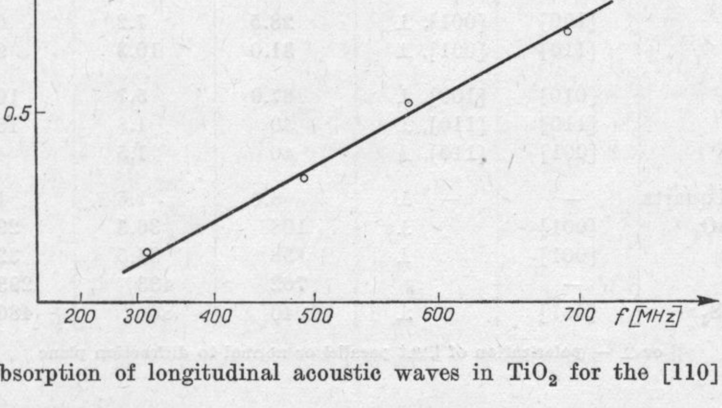

Fig. 4. Absorption of longitudinal acoustic waves in TiO_2 for the [110] direction

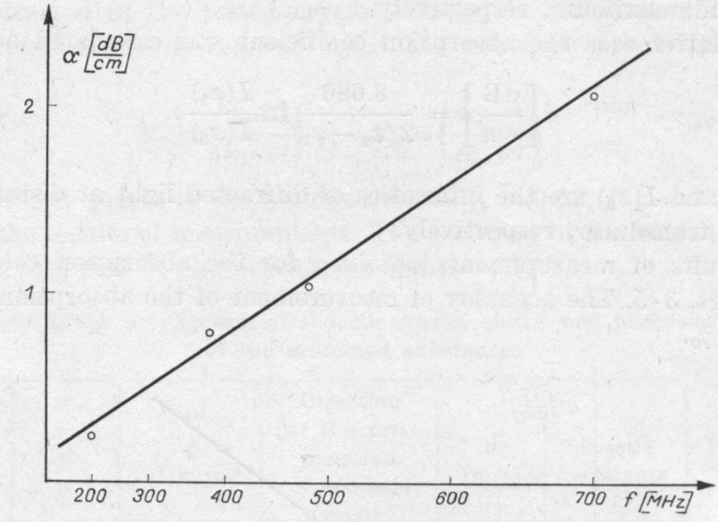

Fig. 5. Absorption of longitudinal acoustic waves in BGO for the [100] direction

Table 2. Acousto-optical parameters of tested substances

Substance	Direction of the propagation of longitudinal acoustic wave	Direction of the propagation and polarization of light $\lambda_0 = 6328$	M_1 $10^{-8}\left[\frac{m^2 s}{kg}\right]$	M_2 $10^{-15}\left[\frac{s^3}{kg}\right]$	M_3 $10^{-11}\left[\frac{ms^2}{kg}\right]$
SF-14	—	—	16.3	7.2	4.5
BGO	[100]	[001], ⊥, ‖	24.5	6.4	6.6
	[110]	[001], ⊥, ‖	27.1	9.3	8.0
BSO	[100]	[001], ⊥	28.5	7.2	6.3
	[110]	[001], ⊥	31.0	10.3	9.2
TiO_2	[010]	[100], ⊥	67.9	5.7	10.0
	[110]	[110], ⊥	30	1.8	18.4
	[001]	[110], ⊥	40	1.5	4.0
Fused quartz	—	— ⊥	8.0	1.6	1.3
$PbMoO_4$	[001]	⊥	108	36.3	29.8
TeO_2	[001]	⊥	138	34.5	32.8
As_2S_3	—	‖	762	433	293
Tl_3AsS_4	[001]	⊥	1040	800	480

‖ or ⊥ – polarization of light parallel or normal to diffraction plane

On the basis of these measurements the values of the parameters M_1, M_2 and M_3 (Table 2) for the examined crystals were calculated. For comparison the values of these parameters for the fused quartz, which is frequently used in acousto-optical measurements, are also enclosed. The data for these substances were taken from paper [9]. It results from the comparison that the examined crystals, especially BGO and BSO, exhibit quite good acousto-optical properties, but are inferior to such crystals as $PbMoO_4$ or TeO_2.

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