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Estimating the Parameters of Monocrystal-Based Acousto-Optic Devices for Terahertz Radiation Control

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Abstract—The acoustic and optical properties of a number of monocrystals transparent in the terahertz range are systematized. Acousto-optic (AO) figure of merit is calculated for the quasi-orthogonal and collinear geometries of AO interaction. The parameters of AO deflectors and filters of THz radiation are determined.

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INTRODUCTION

Acousto-optic (AO) devices are widely used to control electromagnetic radiation in the visible, infrared, and ultraviolet ranges [1]. The terahertz (THz) range, which corresponds to radiation with wavelengths from 30 to 300 μm, has been is intensively utilized in recent years. Stationary metallic and silicon diffraction units are normally used to control powerful laser THz radiation [2], so the AO effect can be used in developing high-speed data processing devices that operate in the THz range. The aim of this work was to identify the monocrystals best suited for developing AO devices that operate with THz radiation.

ANALYTICAL APPROACH

The factors governing the selection of a material for an OA cell are transparency and acousto-optic figure of merit M_2. The materials used for a particular spectral range are listed below:

(1) ultraviolet: SiO_2, MgF_2, KDP, TeO_2;

(2) visible: $CaMoO_4$, $LiNbO_3$, TeO_2;

(3) near infrared (IR): TeO_2;

(4) middle IR: Ge, Hg_2Cl_2, Hg_2Br_2, Tl_3AsSe_3, Te.

It is known that many substances have strong absorption lines in the THz range [3]. At the same time, the length of AO interaction must be around 1 cm in order to obtain acceptable values of the efficiency of diffraction. It is therefore advantageous to use only relatively transparent media with radiation absorption coefficient $\alpha = 4\pi k/\lambda$ of no more than 5 cm^{-1}, where k is the imaginary part of the refraction index. The dependences of n and k on wavelength λ for a wide range of monocrystals were systematized by Palik in [4]. From this range, we selected monocrystals with $\alpha < 5$ cm^{-1}. It was established that birefringent and piezoelectric crystals do not satisfy this transparency criterion. It is therefore impossible to process AO images in the THz range, or to implement spatial scanning with a laser beam characterized by a large number of resolved elements. In addition, AO devices for THz radiation control must be equipped with a sound emitter, while the generation of a bulk ultrasonic wave from the surface of a piezoelectric $LiNbO_3$ crystal is used in AO devices for the visible range.

The acoustic, photoelastic, and optical properties of monocrystals in the THz range are systemized for the first time in Table 1: (1) real n and imaginary k parts of the index of refraction at $\lambda = 100$ μm; (2) density ρ; (3) elastic constants c_{11}, c_{12}, and c_{44}; and (4) photoelastic constants p_{11}, p_{12}, and p_{44} for the IR range. It was assumed that intensity I of an electromagnetic wave and power P_a of an acoustic wave decay exponentially with distance l traveled in a medium:

$$I \propto \exp(-\alpha l); \quad P_a \propto \exp(-\alpha_s l). \tag{1}$$

It is known that the highest values of AO figure of merit $M_2 = p_{eff}^2 n^6 / \rho V^3$ correspond to longitudinal acoustic waves propagating along crystal axes [111] and [100]. This is due to the proportionality of AO figure of merit to the square of effective photoelastic constant p_{eff}, the maximum value of which corresponds to the given directions of ultrasonic wave propagation:

$$M_2 = \frac{p_{eff}^2 n^6}{\rho V^3}. \tag{2}$$

Velocities $V_{L[111]}$ and $V_{L[100]}$ of longitudinal ultrasonic waves propagating along crystal axes [111] and

Table 1. Optical, photoelastic, and acoustic parameters of monocrystals

Crystal	n	k, 10^{-3}	α, cm^{-1}	p_{11} p_{12} p_{44}	ρ, g/cm^3	c_{11}, c_{12}, c_{44}, 10^{11} N/m^2	$V_{L[111]}$, km/s	$V_{L[100]}$, km/s
GaSb	3.997 [4]	0.720 [4]	0.9	0.434 [6] 0.467 [6] –0.062 [6]	5.614 [8]	0.884 [8] 0.404 [8] 0.435 [8]	4.51	3.97
AlSb	3.370 [4]	2.000 [4]	2.5	0.300 [6] 0.400 [6] –0.067 [6]	4.360 [7]	0.883 [7] 0.402 [7] 0.432 [7]	5.11	4.50
Ge	4.007 [4]	–	2.3 [5]	–0.151 [7] –0.128 [7] –0.072 [7]	5.313 [7]	1.284 [7] 0.482 [7] 0.667 [7]	5.55	4.92
GaAs	3.650 [4]	3.600 [4]	4.5	–0.160 [8] –0.130 [8] –0.050 [8]	5.317 [8]	1.181 [8] 0.536 [8] 0.594 [8]	5.39	4.71
Si	3.419 [4]	0.290 [4]	0.36	–0.094 [8] 0.017 [8] –0.151 [8]	2.329 [8]	1.652 [8] 0.631 [8] 0.792 [8]	9.33	8.42
GaP	3.365 [4]	3.364 [4]	4.2	–0.151 [7] –0.082 [7] –0.074 [7]	4.130 [7]	1.412 [7] 0.625 [7] 0.705 [7]	6.65	5.85

[100], respectively (see [9]), were thus added to the acoustic properties of monocrystals:

$$V_{L[100]} = \sqrt{\frac{c_{11}}{\rho}};\ \ V_{L[111]} = \sqrt{\frac{c_{11} + 2c_{12} + 4c_{44}}{3\rho}}. \qquad (3)$$

The considered crystals have an ultrasonic velocity of about 5 km/s and density of about 5 g/cm^3. The refraction index of crystals in the THz range is $n = 3$–4, and the ones most transparent are silicon (Si) and gallium antimonide (GaSb). The low values of radiation absorption index α for GaSb were obtained as a result of measurements at cryogenic temperature, while those of α for other crystals were determined at room temperature. It should be noted that a drop in temperature normally results in semiconducting crystals becoming more transparent. It is therefore technically impossible to compare the AO properties of GaSb to those of other crystals. This crystal is nevertheless worthy of attention because of its extremely high AO figure of merit M_2, which is comparable to that of paratellurite (TeO_2).

There are two basic modes of AO device operation: (1) the quasi-orthogonal geometry of AO interaction, where the angle of deflection of diffracted radiation is small and the wave vectors of the zero and first diffraction orders are considered to be virtually orthogonal to the wave vector of sound; (2) collinear geometry, for which the wave vectors of interacting waves are parallel. Since the considered crystals are optically isotropic, the wave vector of sound in collinear geometry should be twice that of electromagnetic radiation. Diffracted radiation in this case propagates toward radiation incident at the AO cell. The term backward collinear diffraction is used to describe this phenomenon.

Since efficiency I_1/I_0 of AO diffraction is inversely proportional to squared wavelength λ of radiation, the typical values of I_1/I_0 in the THz range are fractions of one percent. This allows us to employ the analytical dependences obtained in [10, 11] using the assumed field approximation to calculate optimum length L_{opt} of AO interaction, efficiency of diffraction I_1/I_0, and band ΔK of AO interaction for the ultrasonic wave number:

(1) For quasi-orthogonal geometry,

$$L = L_{opt} = \frac{1}{\alpha};\ \ \frac{I_1}{I_0} = \frac{\pi^2}{2\lambda^2}\frac{M_2 P_a}{d} L \exp(-\alpha L); \qquad (4)$$

(2) For collinear geometry,

$$L_{opt} = \frac{1}{\alpha + \alpha_s/2}\ln\left(\frac{2\alpha}{\alpha_s} + 2\right); \qquad (5)$$

$$\frac{I_{-1}(0)}{I_0(0)} = \frac{\pi^2}{2\lambda^2}\frac{M_2 P_a}{S}\left(\alpha + \frac{\alpha_s}{2}\right)^{-2} \qquad (6)$$
$$\times \left\{1 + \exp\left[-2\left(\alpha + \alpha_s/2\right)L\right] - 2\exp\left[-\left(\alpha + \alpha_s/2\right)L\right]\right\}$$
$$\times \exp\left(-\alpha_s L\right).$$

Table 2. Parameters of monocrystal-based AO deflectors

Crystal	L_{opt}, cm	F, MHz	M_2, 10^{-15} s^3/kg	I_1/I_0, 10^{-4}	N
GaSb	1.11	9.0	1950	8	30
AlSb	0.40	10.2	430	0.6	80
Ge	0.44	11.1	240	0.4	80
GaAs	0.22	10.8	120	0.10	150
Si	2.74	18.7	6.5	0.07	11
GaP	0.24	13.3	50	0.04	130

For the quasi-orthogonal geometry of AO interaction, the angle of deflection of diffracted radiation is equal to double the Bragg angle,

$$\theta_B = \frac{\lambda F}{2V}, \tag{7}$$

and is proportional to ultrasonic frequency F. This allows us to use this mode in developing AO deflectors.

To be precise, we assumed that $\theta_B = 0.1$ and $F = 0.2V/\lambda$. The maximum value of AO figure of merit M_2 for this mode corresponds to a longitudinal ultrasonic wave propagating along axis [111] with velocity $V_{L[111]}$. Only the maximum value of M_2 is shown In Table 2. Note that the effective photoelastic constant depends on the polarization of radiation:

(1) when the vector of electromagnetic wave is parallel to crystal axis [111]:

$$p_{eff}^{\parallel} = \frac{p_{11} + 2p_{12} + 4p_{44}}{3}; \tag{8}$$

(2) when the vector of polarization of an electromagnetic wave is normal to a given direction:

$$p_{eff}^{\perp} = \frac{p_{11} + 2p_{12} - 2p_{44}}{3}. \tag{9}$$

Number N of resolved elements was determined using the relation

$$N = \frac{\Delta\theta}{\Delta\varphi}, \tag{10}$$

where $\Delta\theta$ is the bandwidth of angles of deflection of radiation diffracted in a medium by varying the ultrasonic frequency and wavenumber by ΔF and ΔK, respectively:

$$\Delta\theta = \frac{\Delta K}{k} = \frac{\lambda\Delta F}{nV}, \tag{11}$$

and $\delta\varphi$ is the width of the angular spectrum of a diffracted beam with aperture d_i in the plane of AO interaction:

$$\delta\varphi = \frac{\lambda}{nd_i}. \tag{12}$$

The following expression for ultrasonic frequency band ΔF, in which there is effective AO interaction in quasi-orthogonal geometry, was derived in [12]:

$$\Delta F = \frac{1.8nV^2}{\lambda FL}. \tag{13}$$

Number N of resolved elements is therefore

$$N = \frac{1.8nVd_i}{\lambda FL}, \tag{14}$$

where d and $L = L_{opt} = 1/\alpha$ are the dimensions of the ultrasonic transducer. The transverse sizes of the beam of THz radiation incident on the ultrasound column were assumed to be $d = 5$ mm and $d_i = 10$ mm.

At the collinear geometry of AO interaction, the beam of radiation crosses a considerably larger number of the phase grating grooves induced by an acoustic wave in a medium. The selectivity of AO interaction toward the wavelength of radiation grows, allowing us to use this mode of operation to develop AO filters. The maximum value of AO figure of merit M_2 for this mode corresponds to a longitudinal ultrasonic wave propagating along axis [100] with velocity $V_{L[100]}$, and to effective photoelastic constant $p_{eff} = p_{11}$. The required ultrasonic frequency can be calculated as

$$F = \frac{2nV}{\lambda}. \tag{15}$$

Using a vector diagram, we can show that the band of effective AO interaction via backward collinear diffraction is 50% lower over the light wave number than over the ultrasonic wave number: $\Delta k = \Delta K/2$. Spectral resolution $R = \lambda/\Delta\lambda$ of an AO filter of THz radiation was therefore calculated as

$$R = \frac{2\pi n}{\lambda}\frac{1}{\sqrt[4]{(\alpha + \alpha_s/2)^4 + (0.89\pi/L)^4}}. \tag{16}$$

The results from calculating maximum number N of the resolved elements and diffraction efficiency I_1/I_0 of AO deflectors operating in the mode of quasi-orthogonal geometry are shown in Table 2. It was established that AO deflectors with higher efficiencies of diffraction are characterized by a lower ultimate number of resolved elements, since the efficiency of diffraction is proportional to length L of AO interaction, while the number of resolved elements is inversely proportional to L. The isopleths obtained for this material by varying length L of AO interaction will therefore be parallel to curves $NI_1/I_0 = \text{const}$ on this diagram.

Similar calculations were performed for the AO filters. It can be seen from Table 3 that resolution R of the AO filters based on various crystals does not correlate with maximum achieved efficiency of diffraction I_{-1}/I_0, since the considered crystals have considerably different M_2 values.

Table 3. Parameters of monocrystal-based AO filters

Crystal	F, MHz	α_s, cm^{-1}	M_2, 10^{-15} s^3/kg	L_{opt}, cm	I_{-1}/I_0, 10^{-4}	R, 10^3
GaSb	317.2	1.2 [13]	2535	0.85	4.3	0.8
AlSb	303.4	1.0	589	0.65	0.5	0.5
Ge	393.9	0.8 [14]	107	0.75	0.12	0.6
GaAs	344.0	0.6 [14]	72	0.59	0.04	0.4
Si	575.8	0.6 [14]	0.3	1.81	0.003	1.4
GaP	393.5	0.5 [15]	12	0.68	0.008	0.4

If this were not so, raising I_{-1}/I_0 by two orders of magnitude would increase R by an order of magnitude, since the efficiency of diffraction is inversely proportional to the square of the combined $(\alpha + \alpha_s/2)$ coefficients of ultrasonic attenuation and light absorption, while resolution is inversely proportional to the first degree of this combination.

CONCLUSIONS

The characteristics of monocrystals, systematized here for the first time, allowed us to estimate the parameters of AO defectors and filters of THz radiation. The plotted diagrams showed that the most promising material for an AO cell is gallium antimonide, cooled to cryogenic temperature. At room temperature, it is advantageous to use aluminum antimonide, which allows us to raise the efficiency of AO diffraction by as much as 500%, compared to germanium.

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