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Deflection of a monochromatic THz beam by acousto-optic methods

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Abstract. **The possibility of controlled deflection of an electromagnetic THz beam of a free-electron laser by acousto-optic (AO) methods has been demonstrated for the first time. The material of the AO deflector was chosen to be single-crystal germanium, which has a fairly large refractive index (n = 4.0) and a relatively low absorption coefficient for electromagnetic waves. The absorption coefficient α in germanium is 0.75 ± 0.02 cm^{-1} at a wavelength λ = 140 μm. The diffracted beam intensity is shown to be maximum at an effective AO interaction length $l = 1/\alpha$. A diffraction efficiency of 0.05 % at a travelling acoustic wave power of 1.0 W is experimentally obtained. It is established that a change in the ultrasonic frequency from 25 to 39 MHz leads to variation in the external Bragg angle in the range from 19.5° to 27.5°. At a fixed Bragg angle θ_B = 22.4° the frequency band of diffraction is 4.2 ± 0.1 MHz and the angular range of laser beam scanning reaches 2.5° ± 0.5°. The results obtained indicate that AO interaction can be used for controlled deflection of electromagnetic THz beams.**

Keywords: *acousto-optics, THz range, deflector, germanium, Bragg angle, free-electron laser.*

1. Introduction

In this paper, we report the results of analysing the control of parameters of electromagnetic THz radiation by acousto-optic (AO) methods. Similar studies were performed previously in [1, 2], where the modulation of THz radiation intensity with a depth of ~1 % and deflection of a THz beam by an angle of ~7° were implemented. Here, we experimentally demonstrate for the first time controlled deflection of a THz beam by large angles using AO interaction in the regime of a travelling acoustic wave, in contrast to [2], where a standing acoustic wave was used. It is also shown that an AO cell can operate as a deflector; the frequency and angular THz scan ranges and the maximum number of resolvable spots were calculated and measured for it. The dependence of the Bragg angle on the ultrasonic frequency at a level of diffracted radiation intensity of –3 dB was measured. It should be noted that the AO interaction was also investigated in [3, 4], where the diffraction was analysed using electron density waves in a piezoelectric material. Here, in contrast to [3, 4], the main mechanism providing formation of a diffraction grating is the photoelastic effect in crystalline germanium, which does not exhibit piezoelectric properties. The THz radiation source was a free-electron laser (FEL), generating monochromatic radiation at a wavelength λ = 140 μm and a power of several hundred watts [5].

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Acousto-optic interaction is known to be widely used to control a number of characteristics of electromagnetic radiation: propagation direction, intensity, polarisation, frequency, and phase. Due to the control simplicity, compactness, low power consumption, and high operating speed, AO devices are applied in spectroscopy, optical communication, image processing systems, laser technology, etc. for modulation, filtering, and controlled deflection of light beams [6–9].

According to the literature, AO devices operate at electromagnetic radiation wavelengths not longer than 10–20 μm [10, 11]. Unfortunately, the number of studies devoted to AO interactions in the far-IR range (and especially in the THz range) is very small, despite the great interest of researchers in these ranges of electromagnetic radiation [1–4]. It was proposed [3, 4] to use the mechanism of interaction of electromagnetic waves with electron density waves in piezoelectrics. However, many piezoelectrics are opaque in the THz range, and this circumstance impedes application of the aforementioned mechanism in the case of long wavelengths. Recently, devices based on tellurium single crystals, which operate at $\lambda \leqslant$ 23 μm (with an AO diffraction efficiency I_1/I_0 of several tens of percent at λ = 10.6 μm), have been actively developed [12]. The use of these devices in the far-IR range meets some difficulties, because the AO diffraction efficiency is inversely proportional to the squared electromagnetic radiation wavelength λ. In the linear regime, at a low AO diffraction efficiency and small Bragg angles in the crystal, the expressions for the transmitted and diffracted intensities can be written as [6]

$$\frac{I_1}{I_0^*} \approx \frac{\pi^2}{2\lambda^2}\frac{M_2 P_a}{d} l T, \qquad (1a)$$

$$I_0 \approx I_0^* T, \qquad (1b)$$

where I_0^* and I_0 are, respectively, the intensities of the incident radiation and the radiation transmitted through an AO cell in the absence of an acoustic wave; I_1 is the diffracted radiation intensity at the crystal output; T is the AO cell transmittance, determined by the Fresnel reflections; $M_2 = p^2 n^6/(\rho V^3)$ is the

AO figure of merit, which characterises the AO interaction efficiency; p is the effective photoelastic constant; n is the refractive index; ρ is the density; V is the acoustic-wave velocity; P_a is the acoustic-wave power; l is the effective AO interaction length; and d is the sound-beam size in the plane orthogonal to the AO interaction plane. It follows from expressions (1) that the AO diffraction efficiency in the THz range (at λ = 140 μm) is lower by a factor of about 170 than in the IR range (at λ = 10.6 μm) and several tens of thousand times lower than in the visible range (at λ = 0.6 μm). With allowance for the fact that the AO interaction efficiency is proportional to n^6, one should search for transparent materials with a large refractive index to provide an acceptable AO interaction efficiency at THz frequencies.

As was noted above, the possibility of AO diffraction of electromagnetic THz radiation was demonstrated in [1–4]. However, it is still unknown if AO devices for effective modulation and scanning of THz radiation can be designed. In recent years, the interest in such devices has increased in view of the active mastering of the far-IR, THz, and submillimetre ranges in modern physics and technology [13]. The purpose of our study was to develop an active element for controlling THz radiation parameters. In particular, we report the results of studying the first AO deflector based on a germanium single crystal and measuring its characteristics at a FEL-radiation wavelength λ = 140 μm.

2. Theoretical consideration of AO interaction in the THz range

With due regard to the values of the refractive index and absorption coefficient of the materials that can be used in an AO cell, we chose germanium, which has a fairly large real part of the refractive index and a relatively low absorption coefficient for THz radiation. According to the data in the literature, the real part of the refractive index n and the absorption coefficient α of crystalline germanium at λ = 140 μm are, respectively, 4.0 and 1.3 cm^{-1} [14]. Another factor in favour of germanium is that its characteristics at λ = 10.6 μm are well known [15]. Our experiment, which was performed at λ = 10.6 μm and control electric power of 2 W, provided an AO diffraction efficiency of ~15%. In further analysis, we took into account that the AO figure of merit of germanium (M_2) in the IR range is not 810×10^{-15} s^3 kg^{-1}, as was erroneously stated in [16], but smaller by a factor of about 4: $M_2 = 180\times10^{-15}$ s^3 kg^{-1} [15]. The Klein–Cook parameter Q at λ = 140 μm, ultrasonic frequency F = 30 MHz, l = 1 cm, n = 4.0, and $V = 5.6\times10^3$ m s^{-1} is ~60 ≫ 1, which corresponds to the Bragg diffraction conditions [6–9].

According to the data of [15], the effective photoelastic constant of germanium has a maximum value $p = (p_{11} + 2p_{12} + 4p_{44})/3$ upon interaction between a longitudinal acoustic wave propagating along the [111] crystal axis and an electromagnetic wave polarised along the same axis and incident orthogonally to the sound beam. To calculate the ultrasonic-wave velocity in germanium, we used the known values of elastic constants: $c_{11} = 1.30\times10^{12}$ dyn cm^{-2}, $c_{12} = 0.490\times10^{12}$ dyn cm^{-2} and $c_{44} = 0.670\times10^{12}$ dyn cm^{-2} [17]. With the known ultrasound velocity and photoelastic constants p_{11} = –0.154, p_{12} = –0.126, and p_{44} = –0.073 [17], which were assumed to be identical for the THz and IR ranges, we found the AO figure of merit of germanium crystal to be $M_2 = 240\times10^{-15}$ s^3 kg^{-1}. It turned out to be close to the coefficient $M_2 = 180\times10^{-15}$ s^3 kg^{-1}, a value reported in [15].

To take into account the absorption of electromagnetic radiation in the AO cell material in the calculation of the AO interaction efficiency, it is necessary to introduce a factor $\exp(-\alpha x)$, where x is the distance passed by light in a medium with an absorption coefficient α. Therefore, the intensity of the radiation transmitted through the AO cell, $I_0 = I_0^* T\exp(-\alpha l)$, and expression (1a) can be rewritten in the form

$$I_1 = \xi T I_0^* l = \xi T \int_0^l I_0^* \mathrm{d}x, \quad \xi = \frac{\pi^2}{2\lambda^2}\frac{M_2 P_a}{d}. \qquad (2)$$

As a result, taking into account the relation for I_0, we derive the expression from (2):

$$I_1 = \xi T \int_0^l [I_0^* \exp(-\alpha x)]\exp[-\alpha(l-x)]\mathrm{d}x = I_0^* \xi T l \exp(-\alpha l), \qquad (3)$$

where the factor $\exp[-\alpha(l-x)]$ takes into account the absorption of the waves deflected at a portion of length dx of the initial-beam path. The dependence I_1 on l was reported in [1] (but without derivation).

Based on expression (3), one can determine the optimal AO interaction length l_{opt}, at which the intensity I_1 reaches the maximum value I_1^{max}:

$$l_{opt} = \frac{1}{\alpha}, \; I_1^{max} = I_0^* T\left(\frac{\pi^2}{2\lambda^2}\frac{M_2 P_a}{d}\right)\frac{1}{\alpha e}. \qquad (4)$$

The l_{opt} value, calculated from formula (4) at λ = 140 μm, turned out to be ~1 cm. At α = 1.3 cm^{-1} and small Bragg angles in the crystal, the multipath interference can be neglected and the transmittance can be calculated from the formula $T = [1-(n-1)^2/(n+1)^2]^2$. In this case, at a characteristic transverse size of the piezoelectric transducer, d = 0.2 cm, and acoustic power P_a = 1.0 W, the AO diffraction efficiency I_1^{max}/I_0 = 0.02%, whereas the intensity ratio of the diffracted (I_1^{max}) and incident (I_0^*) beams reaches a maximum value of 0.004%.

In [1], the I_1/I_0^* ratio was found to be 0.07% at λ = 119 μm, control power of 150 W, absorption coefficient $\alpha \approx 1.5$ cm^{-1}, and piezoelectric transducer sizes l = 1.7 cm and d = 0.8 cm. A piezoelectric transducer with a resonant frequency of 1 MHz was used to excite an acoustic wave. At such a low frequency the angle between the diffracted and transmitted beams at the output of the germanium crystal was ~1°. The ratio I_1/I_0^* = 0.07%, experimentally found in [1], turned out to be somewhat smaller than the value given by formula (3): 0.08%. The diffraction efficiency I_1/I_0 = 2.3%, calculated based on experimental data, also differed only slightly from the value obtained from formula (4): 2.7%. Such large I_1/I_0^* and I_1/I_0 values are due to the high acoustic power.

In [2], the diffraction efficiency reached 1.5% at λ = 119 μm, while the beam separation angle was 7° for a germanium crystal with a length l = 2.9 cm, acoustic power density of about 1 W cm^{-2}, and frequency F = 5 MHz. The diffraction efficiency obtained in [2] greatly exceeded the value given by formula (4) (0.12%) due to the use of a standing longitudinal acoustic wave propagating along the [100] axis. In the regime of a standing ultrasonic wave, light is controlled only at several fixed frequencies F. However, the I_1/I_0^* ratio found from formula (3) at d = 0.2 cm, α = 1.3 cm^{-1}, and P_a = 1 W turned out to be 0.001%, which is smaller than the maximum attainable value because of the nonoptimal length of the crystal used. Note also that the propagation direction of acoustic waves in germanium (along the [100] axis) in [2] was not optimal.

Thus, the calculation results and analysis of the known data in the literature indicate that the I_1/I_0^* ratio in the THz range for crystalline germanium under low electric power (not larger than 1.0 W) is several tenths of percent.

3. Experimental study of AO deflector

We experimentally investigated the AO interaction using THz radiation of the FEL with $\lambda = 140$ μm [18]. In the preliminary stage we measured the absorption coefficient of electromagnetic radiation in two germanium samples with lengths of 4.5 and 1.5 cm. The laser beam had an aperture of 5 mm, and the detector was located directly behind the germanium crystal. The detector was a Golay cell, which calls for amplitude modulation of laser beam intensity with a frequency of 10 Hz. With allowance for the Fresnel loss, which amounts up to ~60 % under normal beam incidence ($n = 4.0$), the absorption coefficient α in germanium is 0.75 ± 0.02 cm^{-1}, a value smaller than that reported in [14] ($\alpha = 1.3$ cm^{-1}). A possible cause of this discrepancy is that we used a high-resistivity germanium crystal of good optical quality [19]. At such large α and n values, the multipath interference and beam divergence can be neglected.

A schematic of the experimental setup for studying the characteristics of the AO deflector is shown in Fig. 1. The beam intensity of the FEL (*1*) was controlled by a wire polariser (*2*) and an attenuator (*3*). The setup allows one to perform amplitude modulation of laser radiation intensity using a mechanical chopper (*4*). The polarisation of the output radiation was set along the [111] axis of the germanium crystal by a polariser (*5*), and the beam aperture was determined by a diaphragm (*6*). The AO cell of the deflector (*7*) was made of a germanium single crystal with a cut optimal for exciting a travelling longitudinal acoustic wave in the [111] direction. The radiation intensity transmitted through the deflector was measured by a Golay cell (*8*) (GC-1T) [20], which was installed at a distance of 15 cm from the AO cell. The setup included also a lock-in detector (*9*) (SR830), an rf generator (*10*), a pulsed generator (*11*), and a chopper control unit (*12*). The measurement results were processed with a personal computer (*13*).

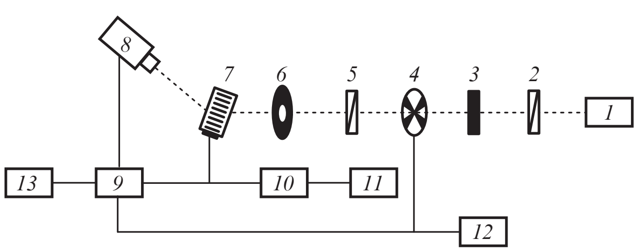

Figure 1. Schematic of the experimental setup:
(*1*) FEL; (*2*) wire polariser; (*3*) attenuator; (*4*) mechanical chopper; (*5*) polariser; (*6*) diaphragm; (*7*) deflector; (*8*) Golay cell; (*9*) lock-in detector; (*10*) high-frequency generator; (*11*) pulse generator; (*12*) chopper control unit; and (*13*) personal computer.

The size of the AO cell of the deflector along the light propagation direction was 4.5 cm, and the piezoelectric transducer length and width were, respectively, 2.0 and 0.2 cm. The transducer based on a lithium niobate crystal performed high-efficiency generation of longitudinal acoustic waves in the frequency range from 20 to 38 MHz. With these parameters, the intensity ratio for the diffracted and incident beams, calculated from formula (3), was $I_1/I_0^* \approx 0.001$ %. The diffraction efficiency was found to be $I_1/I_0 \approx 0.06$ %.

The AO diffraction efficiency was determined as follows. In the absence of the attenuator, the AO cell was rotated at a Bragg angle to the laser beam, which was limited by a diaphragm 2×10 mm in size. To prevent the Golay cell from recording the noise caused by scattering of THz radiation, the chopper was extracted from the setup. The amplitude modulation of only the THz beam deflected as a result of AO diffraction was performed using a pulse generator, which provided pulse modulation of the rf signal with an on–off time ratio of 2 and a duration of 0.1 s. The Golay cell was located at a constant distance of 15 cm and oriented at the Bragg angle with respect to the AO cell, which was rotated with respect to the initial laser beam with a step of 1°. At a specified angle of rotation of the AO cell, the rf generator frequency gradually changed, which made it possible to determine the band of AO interaction frequencies and the frequency dependence of the Bragg angle. To determine the intensity of the radiation incident on the AO cell, a calibrated attenuator and a chopper were additionally introduced into the THz beam, and the Golay cell measured the radiation intensity transmitted through the AO cell.

4. Experimental results and discussion

The AO diffraction efficiency in the deflector was measured to be ~0.05 % at supplied electric power of 1.0 W; this efficiency value coincides with that calculated from formula (3). In addition, we measured the dependence of the external Bragg angle θ_B on the ultrasound frequency in the range from 25 to 39 MHz. The acoustic diffraction frequency band at a constant angle of beam incidence ($\theta_B = 22.4°$) was also measured: $\Delta F = 4.2 \pm 0.1$ MHz. The scan frequency band was determined at the –3-dB level of diffraction efficiency. The experiment showed that the angular scanning range depended on the ultrasonic frequency F. In particular, at a fixed frequency $F = 27$ MHz, the THz-beam scanning range $\Delta\theta$ was $2.5° \pm 0.5°$, while at $F = 35$ MHz it was $3.0° \pm 0.5°$.

The measured dependences of the Bragg angle on the ultrasonic frequency are shown in Fig. 2. For clarity, the inset in Fig. 2 presents a dependence of the diffracted radiation intensity normalised to maximum, $I_1/I_1^{\max}$, on the ultrasonic frequency F at a fixed Bragg angle $\theta_B = 22.4°$. The experimental results coincide (within the error) with the theoretical dependence (dashed line), described by the well-known formula [6]:

$$\sin\theta_B = \frac{\lambda F}{2V}. \quad (5)$$

Approximation of the measurement results by the least-squares method (solid lines) yields the following value for the longitudinal acoustic wave velocity in germanium: $V = (5.48 \pm 0.09) \times 10^3$ m s^{-1}. It coincides (within the error) with that reported in [17]: 5.57×10^3 m s^{-1}, based on which the theoretical dependence of the Bragg angle on the ultrasonic frequency was constructed.

A calculation shows that at a light beam aperture $a = 1.0$ cm and acoustic-wave velocity $V = 5.48 \times 10^3$ m s^{-1} the quick-action of the AO cell is $\tau = a/V = 1.8$ μs. Then the maximum number of resolvable elements at the deflector output is $N = \Delta F \tau = 7.5$. This number can be increased (with a piezo-

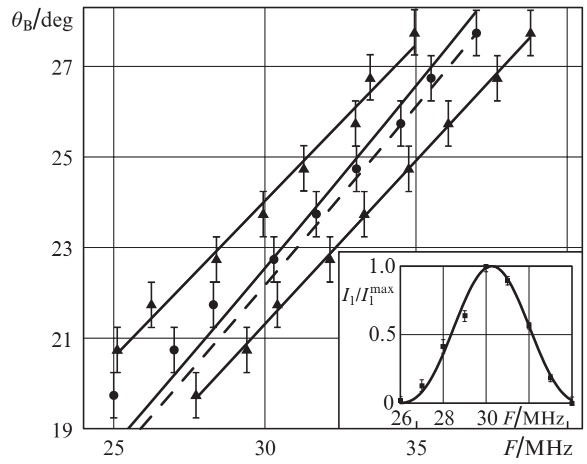

Figure 2. Dependence of the Bragg angle on ultrasonic frequency. The dashed line is the theoretical dependence [6]. Triangles correspond to the level of diffraction efficiency reduced by 3 dB, and circles correspond to the maximum AO diffraction efficiency. The inset shows the dependence of the diffracted radiation intensity (normalised to maximum) on the ultrasonic frequency at a fixed Bragg angle, $\theta_B = 22.4°$.

electric transducer of the same sizes) using a larger light beam aperture. Thus, this AO device based on a germanium crystal can be used as a terahertz wave deflector.

5. Conclusions

We derived a relation for the diffracted radiation intensity at a low AO interaction efficiency in a medium characterised by strong absorption of electromagnetic waves. The possibility of designing an AO deflector capable of deflecting THz FEL radiation by angles of several tens of degrees was experimentally confirmed for the first time. A specific feature of our study is the use of optimal AO interaction geometry in a germanium crystal at low powers of the travelling acoustic wave and relatively high ultrasonic frequencies.

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