Dependence of the characteristics of acousto-optic modulators and filters based on single-crystal media on the radiation wavelength in the infrared and terahertz ranges

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Abstract.
A theoretical study of the dependence of the spectral resolution of acousto-optic filters and the maximum number of resolved elements of acousto-optic deflectors on the radiation wavelength in the range $40 - 100 \, \mu m$ was carried out. Semiconductor single crystals with a cubic crystal lattice, which are transparent in the considered range, were chosen as the material of acousto-optic devices. It is shown that with increasing wavelength from 40 to 100 $\mu m$, the spectral resolution of the filters increases from $10$ to $10^3$, and the maximum number of resolved elements of the deflectors decreases from $10^4$ to $10^2$.

1. Introduction
When solving the problems of non-destructive testing of various technical objects, one of the most effective methods are optical methods for obtaining information. The capabilities of these methods can be expanded through the use of acousto-optic (AO) diffraction. This phenomenon consists in the diffraction of electromagnetic radiation by a phase diffraction grating induced by an ultrasonic wave in a medium [1]. By changing the electrical drive signal, it is possible to influence in real time the amplitude and phase structure of the diffracted radiation beam. The phenomenon of AO diffraction is widely used to control the parameters of electromagnetic radiation in the ultraviolet, visible and near infrared ranges. The use of this effect in the far infrared range is hindered by the low AO diffraction efficiency $\xi$, which is inversely proportional to the square of the radiation wavelength $\lambda$. Therefore, in the far infrared and terahertz (THz) ranges it is advisable to use the AO effect only in cases where the low intensity of diffracted radiation is not critical, but it is important to obtain one or another desired effect (filtering, edge enhancement, etc.). In [2] the acoustic, photo-elastic and optical properties of single crystals in the THz range are systematized, which made it possible to evaluate the parameters of AO devices for working with radiation with a wavelength of 130 $\mu m$. The aim of this work is to determine the dependence of the characteristics of AO devices based on single crystals on the radiation wavelength in the range $40 - 100 \, \mu m$. 

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2. Objects and methods

One of the main criteria for choosing the AO interaction medium is the value of the AO diffraction efficiency $\xi$. The value of $\xi$ is equal to the ratio of the diffracted radiation intensity to the intensity of the radiation incident on the AO cell. At low diffraction efficiency ($\xi \ll 1$), the intensity of the diffracted radiation is proportional to the AO figure of merit $M_2$, which is a combination of the elastic and photo-elastic properties of the medium [3]. In addition, the AO devices based on birefringent crystals are characterized by a wider range of possibilities. However, a review of the literature showed that in the spectral range under consideration only cubic single crystals (which are optically isotropic) are transparent [2,4,5].

In the work, only the basic geometries of the AO interaction were considered: quasi-orthogonal and collinear (see figure 1). The numbers in the figure correspond to the diffraction order number. In the calculations, it was assumed that the sound beam is characterized by power $P_a = 1$ W and has cross-sectional dimensions $(d,L)$ under quasi-orthogonal geometry and $(d,d)$ under collinear geometry, whereas light beam has cross-sectional dimensions $(d,d_1)$ under quasi-orthogonal geometry and $(d,d)$ collinear geometry, where $d = 5$ mm and $d_1 = 10$ mm.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{The main modes of the AO diffraction: (a) quasi-orthogonal and (b) collinear geometries of the AO interaction.}
\end{figure}

In quasi-orthogonal geometry, ultrasound with a low frequency is used so that the wave number of the sound wave is much less than the radiation wave number. In this mode, the deflection angle is proportional to the ultrasound frequency, which allows the implementation of AO THz radiation deflector [6]. At a high frequency of ultrasound, the wave number of a sound wave can be 2 times greater than the wave number of radiation. In this case, diffracted radiation propagates toward the incident radiation, and the spectral bandwidth is several orders of magnitude smaller than under quasi-orthogonal geometry. Therefore, the collinear AO interaction mode is used in AO filters [7].

When changing the wavelength of radiation $\lambda$, it is necessary to take into account the dispersion of the refractive index $n$ and radiation absorption coefficient $\alpha$. Dependencies of $n(\lambda)$ and $\alpha(\lambda)$ were taken from the handbook [4,5] and are shown in figure 2.

For each radiation wavelength $\lambda$, the ultrasound frequency $F$ corresponding to the Bragg condition and the attenuation coefficient of the ultrasonic wave $\alpha_s$ were calculated. In the quasi-orthogonal geometry of the AO interaction, it was assumed that the external Bragg angle is 0.1. The dependences of the diffraction efficiency $\xi$, the maximum number of resolvable elements $N$ and the spectral resolution $R$ on the radiation wavelength $\lambda$ were obtained using the relations given in [2] and taking into account the Fresnel losses $T$ [8]:
Using relations (1) and (3), the diffraction efficiency \( \xi \) was calculated for crystals with an optimal length \( L_{\text{opt}} \), at which \( \xi \) is maximum. As can be seen, the optimal length is determined only by the absorption coefficient of radiation \( \alpha \) and the attenuation coefficient of ultrasound \( \alpha_s \), which is proportional to the square of the ultrasound frequency \( F \).

As shown by preliminary studies using the THz radiation of the Novosibirsk free electron laser (FEL), using the Golay cell and lock-in amplification, one can confidently detect diffracted radiation only at \( \xi > 10^{-5} \). Therefore, among the single-crystal media, only crystals that were relatively transparent for THz radiation and were characterized by a diffraction efficiency of \( \xi > 10^{-6} \) per 1 W of controlling electric power were chosen, namely, aluminum antimonide (AlSb), germanium (Ge), arsenide, gallium (GaAs), silicon (Si) and gallium phosphide (GaP).
3. Results and discussion

Using reference data on the dependence of the absorption coefficient of radiation $\alpha$ and the calculated dependences of the attenuation coefficient of ultrasound $\alpha_s$ on the radiation wavelength $\lambda$, the dependences of the optimal length $L_{opt}$ on $\lambda$ were plotted. As can be seen from figure 3, the optimal AO interaction length increases with the wavelength and its value varies from several millimeters to tenths of a millimeter.

![Figure 3](image)

**Figure 3.** Dispersion dependences of the optimal AO interaction length on the radiation wavelength for a number of single crystals: (a) quasi-orthogonal geometry; (b) collinear geometry.

It was found that under quasi-orthogonal geometry, the diffraction efficiency $\xi$ for a Si crystal is an order of magnitude greater than for other crystals (see figure 4). This is due to its high transparency for THz radiation. Therefore, the optimal length of a Si crystal should be about ten centimeters, while for other crystals it should be a few centimeters or less. It follows that under real conditions ($L \approx 1$ cm), AO Si-based modulators and deflectors will be characterized by an order of magnitude lower diffraction efficiency than the analogue ones based on other crystals (with the same maximum number of resolved elements $N$). Among the crystals that can be used in the manufacture of AO devices based on quasi-orthogonal geometry, AlSb and Ge can be distinguished. It has been shown that at $\lambda$ from 40 to 70 $\mu$m devices based on germanium are characterized by the highest diffraction efficiency, and at $\lambda > 70 \mu$m – ones based on aluminum antimonide: $\xi_{Ge} \approx 10\xi_{AlSb}$ at $\lambda = 40 \mu$m; $\xi_{Ge} \approx \xi_{AlSb}$ at $\lambda = 70 \mu$m; $\xi_{Ge} \approx \xi_{AlSb}/3$ at $\lambda = 100 \mu$m. The relation between the maximum numbers of resolved elements $N$ for devices based on these crystals is as follows: $N_{Ge} \approx N_{AlSb}/20$ at $\lambda = 40 \mu$m; $N_{Ge} \approx N_{AlSb}$ at $\lambda = 85 \mu$m; $N_{Ge} \approx 2N_{AlSb}$ at $\lambda = 100 \mu$m. Thus, the choice of the AO interaction medium between AlSb and Ge is determined by the more important factor: the efficiency of AO diffraction or the maximum number of resolved elements.

Under the collinear geometry of AO interaction, the radiation interacts with an order of magnitude greater number of periods of the phase diffraction grating induced by ultrasound in the medium. Therefore, AO diffraction in this mode is more resonant and can be used in the AO filters. From figure 5 it follows that the highest diffraction efficiency can be achieved using AlSb, Ge and Si. In the wavelength range from 80 to 100 $\mu$m, the diffraction efficiency and spectral resolution of AO filters based on these crystals are approximately the same. In the range from
40 to 80 μm, the diffraction efficiency ξ, as well as the spectral resolution of R, AO filters based on AlSb, GaAs and GaP with decreasing wavelength decrease by an order of magnitude. At the same time, for AO filters based on Ge and Si there is practically no dispersion of the parameters ξ and R in the range from 40 to 100 μm.

We offer the following interpretation of the results. As is known, the increment in the intensity of diffracted radiation on an infinitesimal length is proportional to the product of the length, the radiation intensity of zero diffraction order in the same region and sound power. At the same
time, this increasing function multiplies the exponential factor associated with the absorption of radiation in the medium. Therefore, there is an optimal length of the AO interaction region \( L_{\text{opt}} \propto 1/\alpha \). As follows from figure 2, the transparency of the considered single crystals increases with the wavelength \( \lambda \). In addition, the equations (1) and (2) show that with an increase in the radiation wavelength, the ultrasound frequency decreases \( F \propto 1/\lambda \). Therefore, the longer radiation wavelength the weaker attenuation of ultrasound \( \alpha_s \propto F^2 \propto 1/\lambda^2 \). It follows that the optimal length \( L_{\text{opt}} \) increases with increasing \( \lambda \). It can be seen from the germanium crystal example (see figure 4 and figure 5) that, in the absence of dispersion of the absorption coefficient \( \alpha \), the diffraction efficiency \( \xi \) decreases with the wavelength for the quasi-orthogonal geometry of the AO interaction and remains practically constant for the collinear geometry. This fact, in our opinion, is due to the relation \( \xi \propto L/\lambda^2 \). If the optimal length increases with the wavelength, then the dependence \( \xi(\lambda) \) becomes increasing. From the expression for the maximum number of resolvable elements \( N \) for the AO deflector (see the equation (1) it follows that an increase in \( L \) and \( \lambda \) leads to a decrease in \( N \). This confirms the results in figure 4. From figure 5 it can be seen that the spectral resolution \( R \) of the AO filter increases with the wavelength. Therefore, it follows from (2) that the factor \( (\alpha + \alpha_s) \) decreases faster than the function \( 1/\lambda \). This conclusion agrees well with the Lorentz oscillator model, according to which \( \alpha \propto 1/\lambda^2 \) [9].

4. Conclusion

Using the results obtained, it is possible to choose the optimal single crystal medium for creating AO devices operating in the infrared and THz ranges. So, AO deflectors for radiation with a wavelength of 40 to 100 \( \mu \)m, as well as AO filters for radiation with a wavelength of 40 to 80 \( \mu \)m, should be based on germanium. It is advisable to use silicon for spectral filtering of longer wavelength radiation. It is shown that in the THz range it is necessary to use crystals with an optimal length of about 1 cm, while in the infrared range it is on the order of several millimeters. It was found that when using crystals with an optimal length, the maximum number of resolved elements decreases with the radiation wavelength, whereas the spectral resolution increases. From the obtained dependences it follows that for reliable detection of diffracted radiation, an acoustic power of at least 10 W is required.

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