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Acousto-Optics and Applications

Influence of Refractive Indices Dispersion on Parameters of Imaging AOTFs Operating with Non-Polarized Light

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The paper presents results on investigation of paratellurite based imaging tunable acousto-optic filters operating with arbitrary polarized light. We analyzed influence of dispersion of refractive indices in the crystal on a simultaneous satisfaction of the Bragg matching condition for ordinary and extraordinary polarized optical beams. The analysis was carried out at different optical wavelengths over the wide tuning range of the filters 400–1150 nm. Theoretical and experimental analysis of the problem proves that in a paratellurite tunable acousto-optic filter, the Bragg matching angle common for the two optical polarizations is varying in the limits up to 0.3°. This variation of the incidence angle may be as wide as a quarter of the filter angular aperture thus proving that the examined phenomenon should be considered in design of the imaging tunable acousto-optic filters.

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1. Introduction

During the last decades, acousto-optic devices have been widely used in modern optics, optoelectronics and laser technology for control of such parameters of electromagnetic radiation as intensity, phase, frequency, polarization direction, etc. [1].

One of the major modifications of the acousto-optic devices is represented by the tunable acousto-optic filters (AOTFs) [1, 2]. These filters can be divided into two classes: the collinear or quasi-collinear filters and the wide angle AOTFs. The collinear devices require collimated optical beams [2,3] while the wide angle imaging devices may operate with convergent and divergent beams. As known, the wide angle devices are capable of image processing [2, 4, 5]. In our days the AOTFs are becoming commercially available devices finding applications in spectroscopy, astronomy, space sciences and scientific investigations [6]. Moreover, analysis of scientific literature on the subject shows that the filters have also been used for solution of problems in medicine, ecology, agriculture, consumable and food industries, etc. [7]. One of the evident advantages of the imaging AOTFs is their ability to filter arbitrarily polarized radiation. Operation of the devices in case of non-polarized light provides not only spectral analysis of the arbitrarily polarized images but also control of state of the optic polarization. It is known that principle of operation of such filters is based on a simultaneous diffraction of light in ±1 Bragg diffraction orders at a single acoustic frequency. This operation mode is provided by a special adjustment of light incidence angle and a corresponding selection of acoustic frequency of the Bragg matching [8].

It should be noted that a few disadvantages of the imaging AOTFs were revealed during practical realization of the filters. One of the disadvantages is related to problems of precise satisfaction of the Bragg matching condition simultaneously for beams having two optical polarizations. This satisfaction becomes problematic at different optical wavelengths all over a tuning range of a filter. Our analysis proves that the problem of the Bragg matching originates from dispersion of refraction indices of birefringent crystalline materials used in the filters.

2. Acousto-optic interaction non-sensitive to polarization of incident light

Operation of an AOTF is based on the law of momentum conservation and can be illustrated by wave vector diagrams. In the vector diagram shown in Fig. 1, the AO interaction takes place in $\mathrm{TeO_2}$ crystal in the plane $(1\bar{1}0)$, when a slow shear acoustic wave propagates in the material and modulates its refractive index, n [1, 2]. A direction of the acoustic wave propagation in the $(1\bar{1}0)$ plane is described by the tilt angle α measured between the acoustic phase vector $\boldsymbol{K}$ and the axis [110] of the crystal. The diagram shows that there are two possibilities to realize the simultaneous diffraction of non-polarized light into ±1 diffracted orders at one and the same direction of acoustic propagation. The phase matching condition for the two interactions may be written as follows:

$$\boldsymbol{k}_{\mathrm{i}}^{\mathrm{e}}+\boldsymbol{K}=\boldsymbol{k}_{\mathrm{d}}^{\mathrm{o}},\quad \boldsymbol{k}_{\mathrm{i}}^{\mathrm{o}}+\boldsymbol{K}=\boldsymbol{k}_{\mathrm{d}}^{\mathrm{e}}, \tag{1}$$

where $k_{\mathrm{i}}^{\mathrm{e}}$ and $k_{\mathrm{i}}^{\mathrm{o}}$ are the wave vectors of incident light respectively for extraordinary and ordinary light, $k_{\mathrm{d}}^{\mathrm{o}}$ and $k_{\mathrm{d}}^{\mathrm{e}}$ are the corresponding wave vectors of diffracted light and $\boldsymbol{K}$ is the wave vector of ultrasound. It is possible to derive down an equation for the angular dependence of the acoustic frequency for extraordinary polarized light. We used for the purpose, sine and cosine projections of the wave vectors on the acoustic wave front and also on the direction of the acoustic wave vector $\boldsymbol{K}$:

$$f=(V/\lambda)\left(n_{\mathrm{i}}(\lambda)\sin\theta_{\mathrm{i}}^{\mathrm{e}}-\sqrt{n_{\mathrm{o}}^{2}-n_{\mathrm{i}}^{2}(\lambda)\cos^{2}\theta_{\mathrm{i}}^{\mathrm{e}}}\right). \tag{2}$$

We can also write down the relation between the angles

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*corresponding author; e-mail: yukhnevich@physics.msu.ru of the incident $\theta_{\rm i}^{\rm e}$ and the diffracted $\theta_{\rm d}^{0}$ beams

$$n_{\rm i}\cos\theta_{\rm i}^{\rm e} = n_{\rm o}\cos\theta_{\rm d}^{\rm o}. \qquad (3)$$

In the above expressions, V is the acoustic phase velocity, λ is the wavelength of light, $n_{\rm o}$ is the index of refraction of the ordinary polarized beams, $n_{\rm i}$ is the index of refraction of the extraordinary polarized radiation. This later depends on direction of optical propagation [5].

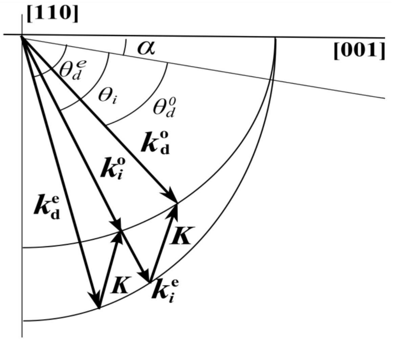

Fig. 1. Wave vector diagram illustrating simultaneous diffraction of non-polarized light into ±1 diffracted orders.

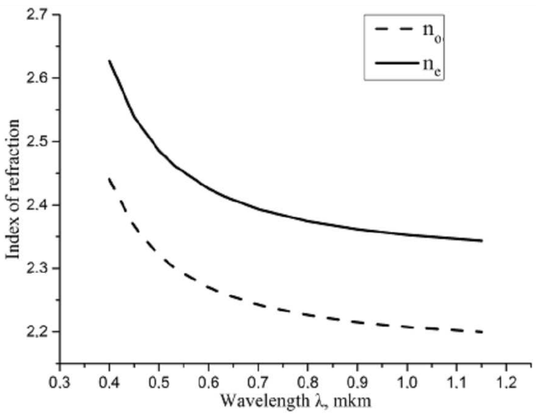

Fig. 2. Dispersion of the refractive indices in tellurium dioxide in the range of wavelengths 0.4–1.15 μm.

It is known that the indexes of refraction of paratellurite crystal depend on the optical wavelength. Data in Fig. 2 found in [9] present dispersion of the refractive indices in tellurium dioxide in the range of wavelengths 400–1150 nm. Our analysis proved that changing the wavelength of optical radiation one obtains shifts of the angular-frequency curve not only along the frequency axis f but also along the angle axis θ. That is why precise satisfaction of the Bragg matching condition simultaneously for both polarizations at different optical wavelengths over a wide tuning range of a filter is not possible. In other words, it is not unlikely to get equal intensities of light in ±1 diffraction orders all over the tuning range [10, 11]. We obtain strictly equal intensities only at a single optical wavelength.

3. Theoretical and experimental investigation

Using the presented equations, we calculated frequency dependence of the incidence angle for both polarizations of optical radiation. The calculation was carried out at different optical wavelengths for the acousto-optic imaging filter based on the tellurium dioxide crystal. Figure 3 shows the dependence of the Bragg angle $\theta_{\rm i}$ on the optical wavelength λ if light diffracts simultaneously into ±1orders with equal intensity. As mentioned the calculation was carried out at the cut angle of the crystal $\alpha = 10^\circ$ and the range of the wavelengths 400–1150 nm. The plots present angular shift 0.3° during tuning of the filter in the mentioned spectral range. It is known that an angular aperture of the imaging AOTFs operating with non-polarized light in air is usually equal to about $\Delta\theta \approx 1^\circ$[12]. It means that we have to take into account dispersion of the refractive indices in design of the filters intended to process arbitrary polarized imagines at different optical wavelengths. In a laboratory or outdoor experiment, it is necessary to carry out some kind of trade off in selection of the incidence angle to satisfy the matching condition in a wide spectral band.

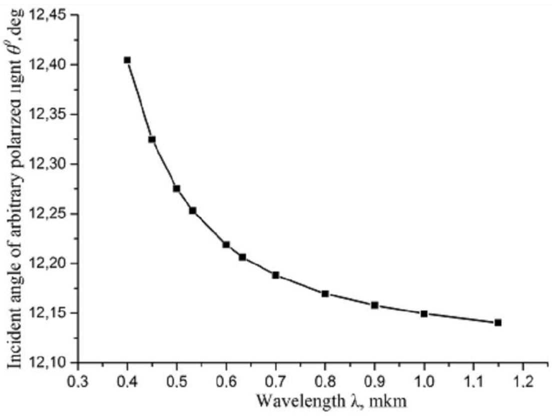

Fig. 3. Theoretical dependence of the Bragg angle $\theta_{\rm i}$ on the optical wavelength λ if light is difracted simultaneously into ±1 orders with equal intensity.

In the experimental part of the investigation, we used a wide angle acousto-optic $\mathrm{TeO_2}$ cell with the cut angle $\alpha = 10^\circ$ [8, 12, 13]. The measurements were performed using a He–Ne laser, at the wavelengths of light $\lambda = 1150$ and $\lambda = 633$ nm and YAG laser, at the wavelength $\lambda = 532$ nm. Slow shear acoustic waves were generated in the paratellurite sample by a piezoelectric transducer fabricated of X-cut lithium niobate crystal. Data in Fig. 4 present the experimentally measured dependences of the Bragg angle on the acoustic frequency $\theta_{\rm i}^{\rm e}(f)$ and $\theta_{\rm i}^{\rm o}(f)$ for the input extraordinary and ordinary polarized light. Analysis of these data confirms that the shift of the cross-section point of the two curves is $\delta\theta = 0.18^\circ$ when the optical wavelength changes from $\lambda = 532$ nm to $\lambda = 1150$ nm. Theoretical result predicts that the shifting is equal to $\delta\theta = 0.11^\circ$. The reason for

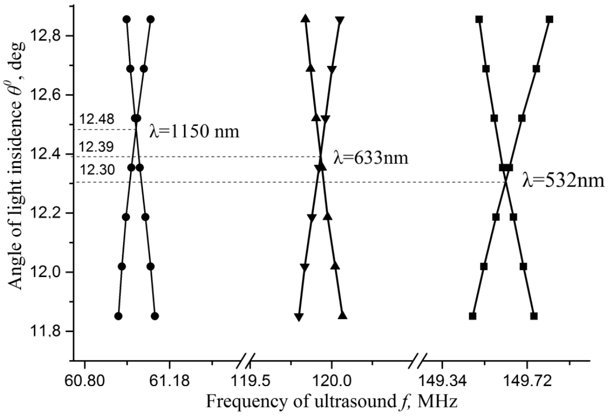

Fig. 4. Measured dependences of the Bragg angle on the acoustic frequency for the input extraordinary and ordinary polarized light.

the discrepancy is as follows. The examined filter was designed for operation with the ordinary polarized radiation for the case of the wide-angle diffraction. It means that the input optical facet of the crystal was cut orthogonally to the input ordinary polarized optical radiation. Therefore, the angle of inclination of the input facet for the extraordinary polarized radiation was not optimal. We had to send on the crystal the arbitrary polarized radiation at an angle with respect to the input facet. It means that the birefringence influenced on the process of the acousto-optic interaction.

4. Conclusion

Tunable acousto-optic filters capable of image processing are being used not only in science and technology related to physics, optic information processing, optical and electronic engineering, etc. but also in the fields related to everyday life such as ecology, medicine, food industry, and other human disciplines. Requirements on parameters of the acousto-optic filters are continuously growing because at present it is necessary to know not only general principles of the filter operation but many details determining precision and flexibility of measurements carried out by the filters. One of the factors strongly influencing on operation of the imaging filters is related to dispersion of refractive indexes of a crystal. As proved in the presentation, the optical dispersion in paratellurite crystal causes scene shifts of the order 0.3° which is about one third of the filter angular aperture. This drawback should be considered by specialists responsible for design and application of the imaging filters.

Acknowledgments

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