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Frequency and angular bandwidth of acousto-optic deflectors with ultrasonic walk-off

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ABSTRACT

In the paper, bandwidth parameters of acousto-optical deflectors (AODs) are analyzed from the point of view of acoustical anisotropy. Equations for bandwidth and central frequency of AOD are derived for arbitrary propagation direction of ultrasound in optically uniaxial crystals. The phenomenon of bandwidth shift due to phase mismatch at the central frequency is studied theoretically and verified experimentally.

1. Introduction

Acousto-optical deflectors (AODs) is a class of all-solid-state photonic devices that are used for continuous scanning of laser light beams [1]. The deflector is characterized by a wide bandwidth of diffraction, and deflection angle of light is proportional to the frequency of driving ultrasound. Broadband ultrasonic deflection of light is applied in RF spectrum analyzers [2], multichannel WDM commutators [3–5], optical tweezers for particle trapping [6–8], image scanners [9–11], fringe projectors [12–14], and frequency shifters [15,16]. Flat frequency response and precise knowledge of AOD bandwidth is required for most applications.

Anisotropic acousto-optical diffraction in crystals was proposed for deflection of laser beams independently by Dixon [17] and by Lean et al. [18]. Later, Warner et al. introduced axial AOD in paratellurite that used optical activity of the crystal [19]. An important feature of that device was midband degeneracy caused by double Bragg scattering. Application of that effect for increasing bandwidth of deflection was demonstrated by Voloshinov et al. [20] and by Chang and Hecht [21]. Meanwhile, Yano et al. developed an off-axial AOD that was free of midband degeneracy [22]. That device featured strong acoustical energy walk-off that is due to extremely high elastic anisotropy of slow shear acoustic wave in paratellurite [23]. The walk-off angle in $(1\bar{1}0)$ plane of paratellurite quickly grows when the acoustical wave vector is tilted from $[110]$-axis and reaches the maximum of 54° [24–26]. Theoretical and experimental analysis of two-coordinate AOD was performed by Maák et al. [27]. Several recent works were also devoted to the problem of thermal impact on performance of AOD [28,29].

Bragg phase matching in AOD is realized in tangential geometry, and phase mismatch magnitude is approximately proportional to the square of ultrasonic frequency deviation, providing zero derivative at the central frequency [20]. The tangential phase matching can be obtained only when the slow optical eigenwave is incident, and the fast eigenwave is diffracted [1].

Extensive development of laser technologies establishes a challenge for searching new materials that can be applied in acousto-optics. Crystals with stronger optical anisotropy, including biaxial ones, are being studied. The aim of this work is to generalize methods for calculation of basic parameters of AOD in crystals with optical and acoustical anisotropy. Special attention is paid to the shift of AOD bandwidth when the device operates under phase mismatch condition relatively to the central frequency of tangential phase matching. This phenomenon was observed for AOD on the base of paratellurite (TeO_2) crystals.

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2. Theoretical analysis

2.1. Coupling of modes: plane waves approximation

We consider plane wave approximation of anisotropic Bragg diffraction in a crystal with strong elastic anisotropy. The piezotransducer with the length l along x-axis launches in the crystal an ultrasonic wave that has a walk-off angle of energy flow ψ, i.e. the angle between the phase velocity **V** and the group velocity **U**. As a result, the cross-section of acoustical beam in the crystal along ξ-axis has a length $L = l\cos\psi$ that is referred as the length of acousto-optical interaction. Schematic design of AOD is shown in Fig. 1. Typical regime of deflector operation is characterized by approximate phase matching, when a finite mismatch $H \neq 0$ is present. Diffraction efficiency in Bragg regime can be described in terms of coupled modes theory. The transmission coefficient T is defined as ratio of diffracted light intensity to the incident light intensity. The following transmission function can be obtained for Bragg diffraction [30]:

$$T(P,h) \propto \frac{\sin^2\left(\frac{\pi}{2}\sqrt{P/P_0 + (hl/\pi)^2}\right)}{P/P_0 + (hl/\pi)^2}, \qquad (1)$$

where $h = H\cos\psi$ is the x-component of the mismatch, P is the ultrasonic power, and P_0 is the characteristic ultrasonic power for 100% diffraction efficiency. Eq. (1) determines admissible mismatch magnitudes $|hl| = \phi_{max}$ for different relative levels of driving ultrasonic power (P/P_0) and different criteria of bandwidth ripples. For a conventional -3 dB criterion at $P/P_0 = 1$, the maximum normalized mismatch is $\phi_{max}/\pi = 0.8$. For some applications, better uniformity of transmission function is required. For example, 10% of intensity nonuniformity that corresponds to -0.5 dB reduction of diffraction efficiency restricts maximum mismatch as $\phi_{max}/\pi = 0.34$.

2.2. Wave vector diagrams for phase mismatch

In the following analysis we use the method of wave vector diagrams. The wave vector of incident light $\mathbf{k}_i$ is coupled with the wave vector of diffracted light $\mathbf{k}_d$ via the wave vector of ultrasound **K** and the phase mismatch vector **H**:

$$\mathbf{k}_i + \mathbf{K} + \mathbf{H} = \mathbf{k}_d. \qquad (2)$$

It is important to note that coupled modes theory of acousto-optic diffraction justifies that method in the plane-waves approximation [31–33]. The phase mismatch magnitude is determined as projection of wave vectors difference to the ξ-axis, *i.e.* orthogonally to acoustical energy flow [34,35]:

$$H = k_{d,\xi} - k_{i,\xi} - K_\xi. \qquad (3)$$

Thus, the phase mismatch vector is orthogonal to the acoustical group velocity vector **U**. In the chosen axes {x,y}, the components of mismatch vector are equal to $\mathbf{H} = \{-h, -h\tan\psi\}$ (according to the accepted choice of signs, the magnitude of ψ hereinafter is negative).

For further analysis, we use a general representation of optical normal surface sections as two ellipses. This approach covers most practical cases of crystals with optical anisotropy that are recently used in acousto-optics: uniaxial crystals with arbitrary orientation of ultrasonic wave vector, and also biaxial crystals in (001) and (100) planes. However, we will use notation that is typical for a positive uniaxial crystal, *i.e.* n_o and n_e for refractive indices of ordinary and extraordinary waves that propagate orthogonally to the optical axis; n_f and n_s are used for the fast and slow waves correspondingly that propagate in the principal optical plane of the crystal. Wave vector diagram of Bragg phase matching with both high-frequency and low-frequency diffraction in AOD is shown in Fig. 2. Tilt angle of the acoustical wave vector **K** relatively [110]-axis is designated as α.

Consider the case when exact phase matching ($H = 0$) takes place. For the low-frequency branch of diffraction $\mathbf{K}_c = \mathbf{K}_l$ and $\mathbf{k}_i = \mathbf{k}_l$, while for the high-frequency branch $\mathbf{K}_c = \mathbf{K}_h$ and $\mathbf{k}_i = \mathbf{k}_h$ correspondingly. Ultrasonic frequency $f_c = |K_c|V/(2\pi)$ is the central frequency of AOD bandwidth. Correspondent wave vector of diffracted light equals to $\mathbf{k}_c = \mathbf{k}_i + \mathbf{K}_c$. If the frequency of ultrasound is varied, *i.e.* $K = K_c + \Delta K$, the phase mismatch appears:

$$\mathbf{k}_c + \Delta\mathbf{K} + \mathbf{H} = \mathbf{k}_d. \qquad (4)$$

The wave vector of diffracted light $\mathbf{k}_d$ corresponds to the deflected light beam.

Under perfect phase matching, the diffracted wave vector $\mathrm{k}_c = \{x_c, y_c\}$ is determined by the following components:

$$x_c = \frac{\omega}{c}\sqrt{n_f^2\cos^2\alpha + n_o^2\sin^2\alpha}; \qquad (5)$$

$$y_c = -\frac{\omega}{c}\frac{(n_o^2 - n_f^2)\cos\alpha\sin\alpha}{\sqrt{n_f^2\cos^2\alpha + n_o^2\sin^2\alpha}}. \qquad (6)$$

The tilt angle of diffracted wave vector relatively to x-axis equals to

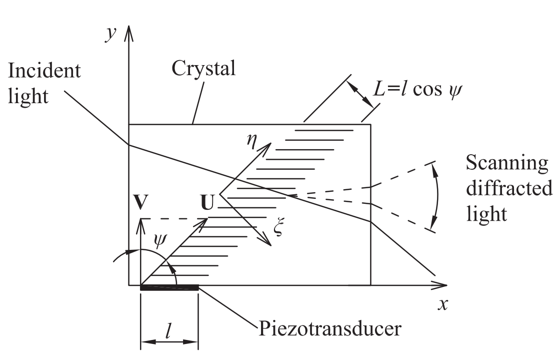

Fig. 1. Schematic layout representing off-axial AOD unit.

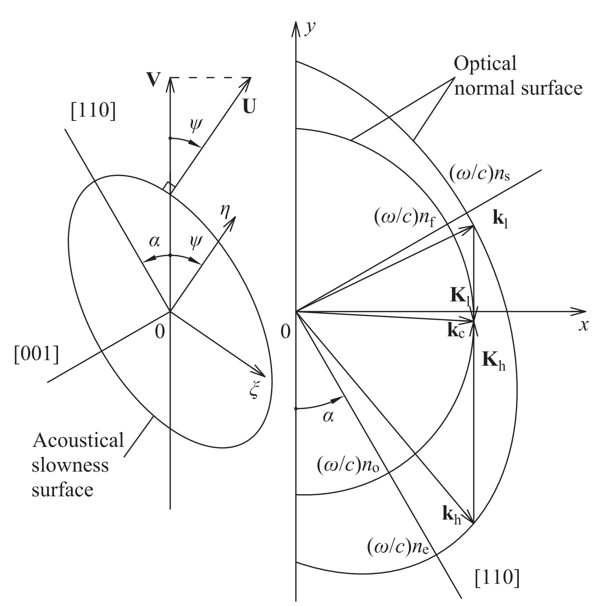

Fig. 2. Wave vector diagram of tangential phase matching.