Research on the broadband operating mode of anisotropic acousto-optic deflector using tellurium dioxide crystal

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Keywords: acousto-optic effect, geometrical relationships, acousto-optic deflector, broadband, tellurium dioxide

Abstract. Theoretical studies on the broadband operating mode of anisotropic acousto-optic deflector (AOD) using tellurium dioxide crystal are carried out, the operating properties of the bandwidth and the central frequency of the AOD are systematically studied by solving the Dixon equation that characterizes the geometrical relationships of the acousto-optic interaction. The calculation results show that the bandwidth and the central frequency of the AOD are highly depended on the off-axis angle of the ultrasonic vector, which shows linear properties in the operating bandwidth both for the +1 order and -1 order diffractions.

Introduction

Acousto-optic deflector is usually used for continuous scanning of laser beam, the basic principle of the acousto-optic effect is that the light beam can be diffracted by the periodic distribution of the refractive index due to the propagation of the ultrasonic waves in the acousto-optic crystal. The acousto-optic effect is firstly proposed by Brillouin in 1922 [1] and experimentally demonstrated by Lucas and Biquard [2] in France, and Debye and Sears [3] in U.S. Much research work has been reported on the applications of AOD on frequency shifters [4], laser beam steering[5], imaging spectrometer[6], laser beam shaping [7], fringe projectors [8], multichannel communications[9] and optical tweezers [10]. The bandwidth and central frequency are the two most important design parameters of acousto-optic deflector, thus the comprehensive studies on the wideband operating mode are highly required for most applications. In this paper the broadband operation mode are studied by solving the Dixon equation of the anonymous acousto-optic interaction of tellurium dioxide crystal. The separation of the index ellipsoid in the direction of the optical axis enables the broadband design of tellurium dioxide, where the polarization of the incident light is set parallel to the operation plane and the polarization of the diffractive light is vertical to the operation plane to satisfy the momentum match condition. Based on the theoretical calculation of the acoustic properties of tellurium dioxide crystal under different off-axis angle, the relationships of the central frequency and the bandwidth in respect to the operating frequency in the TOZ plane are systematically analyzed both for the +1 order diffraction and -1 order diffraction, respectively.

Geometrical relationships of anisotropic acousto-optic interaction of tellurium dioxide crystal

Anisotropic acousto-optic interaction can be described by the momentum match condition

$$\vec{k}_d = \vec{k}_i \pm \vec{K} \tag{1}$$

Where $\vec{k}_d$, $\vec{k}_i$ and $\vec{K}$ are the wave vectors of the incident light, the diffraction light and the acoustic wave, the expressions of $\vec{k}_d$, $\vec{k}_i$ and $\vec{K}$ can be written as:

$$k_i = \frac{2\pi n_i}{\lambda},\ k_d = \frac{2\pi n_d}{\lambda},\ k = \frac{2\pi}{\Lambda} = \frac{2\pi f}{v} \tag{2}$$

Where n_d is the refractive index of the diffractive light; n_i is the refractive index of the incident light, v is the velocity of the ultrasonic wave and f is the frequency of the ultrasonic wave, λ is the wavelength of the light wave. The geometrical relationships of tellurium dioxide anisotropic acousto-optic interaction in the TOZ plane are illustrated in Fig.1.

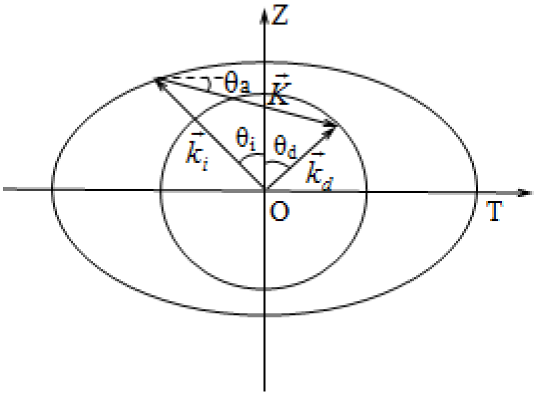


Fig.1 Schematic diagram of the anisotropic acousto-optic interaction of tellurium dioxide

It is noted that the T axis is along the direction of the angular bisector of XOY plane, θ_a is the angle between the vector of the ultrasonic wave and the T axis, θ_i is the angle between the vector of the incident light and Z axis and θ_d is the angle between the vector of the diffractive light and Z axis. From Fig.1 it can be observed that the index ellipsoids of the incident light and the diffractive light are separated due to the optical rotation of tellurium dioxide, it enables the broadband design of the AOD under the operating mode of $e \rightarrow o$, where the incident light is polarized parallel to the TOZ plane as well as the polarization of the diffractive light is perpendicular to the TOZ plane. Based on the anisotropic acousto-optic diffraction theory proposed by Dixon [11] and by Lean et al. [12], the geometrical relationships illustrated in Fig.1 can be derived as:

$$\sin[\pm(\theta_d - \theta_a)] = \frac{\lambda}{2n_o V(\theta_a)}[f - \frac{n_o^2 V^2}{f\lambda^2}(4\delta + \frac{n_e^2 - n_o^2}{n_e^2}\sin^2\theta_i)] \tag{3}$$

$$\sin\pm[(\theta_a - \theta_i)] = \frac{\lambda}{2n_o V(\theta_a)}[f + \frac{n_o^2 V^2}{f\lambda^2}(4\delta + \frac{n_e^2 - n_o^2}{n_e^2}\sin^2\theta_i)] \tag{4}$$

Where the "±" means the +1 order diffraction and -1 order diffraction, respectively.

The acoustic properties of tellurium dioxide crystal in the TOZ plane

From formulas of (3) - (4) it can be found that the velocity of the ultrasonic wave is related to the off-axis angle, the acoustic properties of tellurium dioxide in the TOZ plane can be calculated by the Christoffel equation

$$\left(\Gamma_{ij} - \rho v^2 \delta_{ij}\right)\cdot u_j = 0 \tag{5}$$

Where $\Gamma_{ij} = L_{iJ} c_{JI} L_{Ij}$, ρ is the density of the crystal and v is the velocity of the ultrasonic, and the expressions of δ_{ij}, L_{iJ} and C_{JI} are given as (8)-(10).

$$\delta_{ij} = \begin{cases} 0 & i = j \\ 1 & i \neq j \end{cases} \tag{6}$$

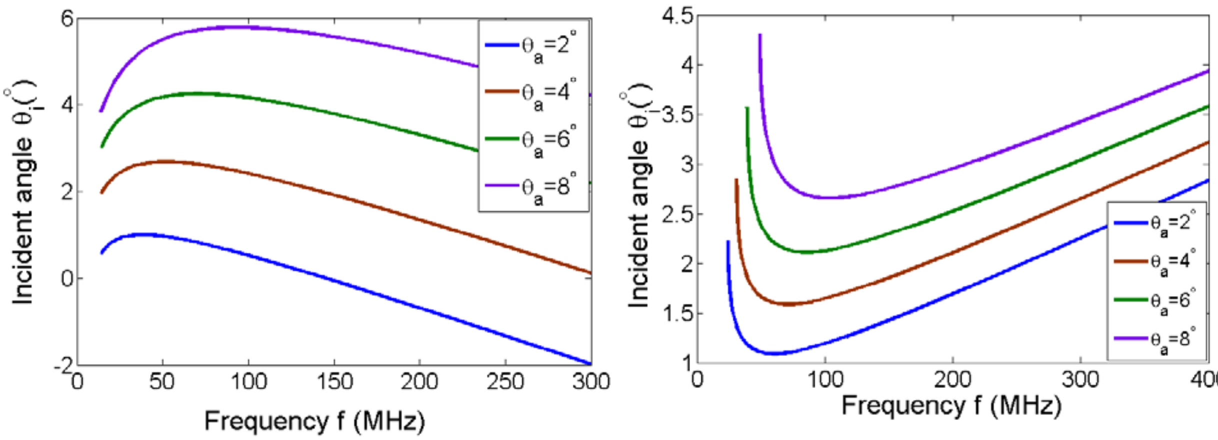
$$L_{iJ} = \begin{pmatrix} l_x & 0 & 0 & 0 & l_z & l_y \\ 0 & l_y & 0 & l_z & 0 & l_x \\ 0 & 0 & l_z & l_y & l_x & 0 \end{pmatrix} \tag{7}$$

$$c_{JI} = \begin{pmatrix} c_{11} & c_{12} & c_{13} & 0 & 0 & 0 \\ c_{12} & c_{11} & c_{13} & 0 & 0 & 0 \\ c_{13} & c_{13} & c_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & c_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & c_{44} & 0 \\ 0 & 0 & 0 & 0 & 0 & c_{66} \end{pmatrix} \quad (8)$$

Where l_x, l_y, l_z is the direction cosine of the vector of ultrasonic wave, the values of the parameters is set as: $c_{44} = 2.65$, $c_{33} = 10.58$, $c_{13} = 2.18$, $c_{12} = 5.12$, $c_{11} = 5.57$, $c_{66} = 6.59$.

The operation properties of anisotropic AOD under the broadband design

The broadband design of the anisotropic AOD is based on the separation of the index ellipsoids of tellurium dioxide, which enables the non-monotonicity condition of the $\theta_i(f)$ curves with respect to the operating frequency in the operating bandwidth. The $\theta_i(f)$ curves under different off-axis angle θ_a are shown in Fig.2 (a)-(b).

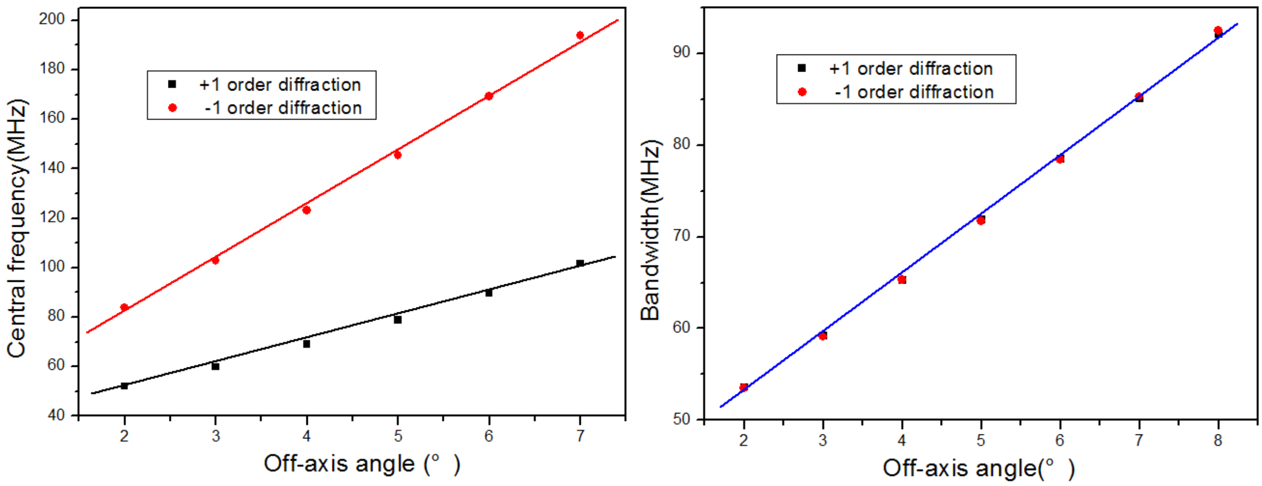


(a) (b)

Fig.2 Curves of incident angle with respect to the operating frequency under different off-axis angles (a) +1 order diffraction. (b) -1 order diffraction

The central frequency f_c of the AOD can be determined by the condition of $\frac{\partial \theta_i(f)}{\partial f} = 0$, and the off-axis angle corresponding to the frequency that meets the condition is named θ_{am}, the bandwidth of the AOD is calculated by the formula $\Delta f = f_H - f_L$ and the central frequency is calculated by the formula of $f_c = (f_H + f_L)/2$, where f_H and f_L are the two frequencies that meet the condition of $\theta_a(f) = \theta_{am} \mp 2\delta\theta_a$, herein the $\delta\theta_a$ is named as the walk-off angle and usually is set as 0.1°.

Based on analysis above, the operating properties of the central frequency and the bandwidth of the AOD have been determined, as shown in Fig. 3. From Fig. 3(a) it can be found that the central frequency of the AOD show strict linearity properties with respect to the off-axis angle both for the +1 order diffraction and the -1 order diffraction, where the gradient for the -1 order diffraction (22MHz per degree) is higher than that of the +1 order diffraction (9.93MHz per degree). The linearity relationship of the bandwidth with respect to the off-axis angle also can be observed from Fig.3 (b). Differing from the results of the central frequency, it is noted that there is hardly any difference of the gradients for the +1 order diffraction and the -1 order diffraction, which are both about 6.5MHz per degree.



(a) (b)

Fig.3 The linearity relationships of the central frequency and the bandwidth with respect to the off-axis angle
(a) The linearity properties of the central frequency under ± 1 order diffractions
(b) The linearity properties of the bandwidth under ± 1 order diffractions

Summary

In this paper the broadband operating mode of the tellurium dioxide AOD are systematically studied, the geometrical relations of the anisotropic acousto-optic interaction in the TOZ plane are determined based on the characterization of the acoustic properties of tellurium dioxide crystal. The theoretical calculation results show that the central frequency and the bandwidth of the AOD show strict linearity properties with respect to the off-axis angle of the ultrasonic wave, where the gradient of the central frequency under the +1 order diffraction is higher that under the -1 order diffraction and the gradient of the bandwidth is nearly the same both for the ± order diffractions. The research results are meaningful for the broadband design of anisotropic AOD with tellurium dioxide crystal.

Acknowledgement

This work is supported by the National Natural Science Foundation of China (11374089, 61308016), the Nature Science foundation of Hebei Province (A2012205085, F2012205076, A2012205023) and the Key project of Hebei Education Department (ZD20131014).

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