Ultrasonics 91 (2019) 45–51

Contents lists available at ScienceDirect

Ultrasonics

journal homepage: www.elsevier.com/locate/ultras

Examination of the temperature influence on phase matching frequency in tunable acousto-optic filters

S.N. Mantsevich[a,b,*], E.I. Kostyleva[a]

[a] Physics Department, M.V. Lomonosov Moscow State University, GSP-2, Vorobevy Gory, 119991 Moscow, Russia
[b] Space Research Institute (IKI), 84/32 Profsoyuznaya, 117997 Moscow, Russia

ARTICLE INFO

Keywords:
Acousto-optic interaction
Acousto-optic phase matching condition
Temperature
Tellurium dioxide
Acoustic beam attenuation
Phase matching temperature shift

ABSTRACT

The temperature effect on the acousto-optic (AO) phase matching condition was examined both theoretically and experimentally on an example of wide-angle acousto-optic filter fabricated from tellurium dioxide crystal. It was shown that the AO crystal temperature variation changes the acoustic wave velocity that is involved into the AO interaction and shifts the phase matching frequency of AO diffraction. The AO phase matching frequency shift temperature coefficient was introduced, characterizing the magnitude of the frequency shift. The examination of frequency shift magnitude was carried for the optical wavelength band from 440 nm to 1.52 µm. It was shown that the temperature coefficient decreases with increasing the optical wavelength. A method was introduced that makes it possible to calculate the temperature shift coefficients for the real AO devices in a wide range of optical wavelengths. The coefficients obtained with the proposed method are in good agreement with the experimental data. Ultrasound attenuation was also examined in the given AO cell. Attenuation caused by the acoustic power absorption is the main mechanism leading to the appearance of the inhomogeneous temperature distribution inside the AO cell during the operation.

1. Introduction

Optoelectronic devices operating on the basis of acousto-optic (AO) effect are widely used for optical radiation control and its spectrum analysis nowadays [1].

Such advantages of AO devices are a small size, the absence of moving parts, comparatively low power consumption and high reliability make them attractive for the fabrication of compact spectral analysis instruments. Such devices may be used not only in laboratory conditions but also outdoors and even in space [2–8]. One of the peculiarities that arise when using AO instruments outside the laboratory and strongly affecting the parameters of acousto-optical devices is a wide operation temperature range. In space it may exceed 100 K. Due to the difficulties with AO crystal temperature stabilization the problem of AO crystal temperature influence on the AO devices characteristics arises. The solution of this problem is important especially for the AO tunable filters (AOTFs). It will allow avoiding the mistakes during the experimental data analysis associated with the recognition of various substances buy their optical radiation absorption bands. These mistakes are caused by the observed displacement of the examined substances absorption bands due to a change in the temperature of the AO crystal [9].

There are two mechanisms that influence on the AO cell temperature. The first one is the heating or cooling of the AO crystal under the action of ambient temperature [2,10,11]. The second one is the inhomogeneous heating of the AO cell upon the absorption of the acoustic beam power by the material of the AO cell [12–14]. The AO device temperature may be stabilized in the first case, the equalization of temperature gradients during the AO cell operation seems to be much more difficult.

The AO devices are usually fabricated from the crystalline materials that have strong anisotropy of various physical properties. For example, the most popular AO material – tellurium dioxide is known for its extremely high acoustic anisotropy [15,16].

The crystalline media characteristics which are important for AO interaction realization (namely the acoustic wave velocity and the refraction indices) depend on temperature [17–20]. Hence, the characteristics of AO devices depend on temperature also [7,10,12,21]. Theoretical and experimental examination of temperature influence on TeO_2 AOTF operation was carried for the wide range of optical radiation wavelengths. We have also measured the acoustic beam attenuation to examine the inhomogeneous temperature distribution occurring inside the TeO_2 AO cell during the operation.

---

[*] Corresponding author at: Physics Department, M.V. Lomonosov Moscow State University, GSP-2, Vorobevy Gory 1, bd. 2, 119991 Moscow, Russia.
E-mail address: snmantsevich@yahoo.com (S.N. Mantsevich).

https://doi.org/10.1016/j.ultras.2018.07.016
Received 14 May 2018; Received in revised form 22 July 2018; Accepted 24 July 2018

2. The examination of crystal temperature effect on AO phase matching condition

2.1. Basic relations

The crystal temperature influences mainly the acoustic wave propagation velocity [17–20,22]. This may be explained in the following way. It is known that the acoustic wave velocity in the crystal may be defined by solving the Christoffel equation:

$$|\Gamma_{jk} - \rho V^2 \delta_{jk}| = 0 \tag{1}$$

where ρ – is the density, V – acoustic wave phase velocity, δ_{jk} – Kronecker delta, and Γ_{jk} defined as $\Gamma_{jk} = c_{ijkl} n_i n_l$ – is the second-rank tensor. The elastic modules matrix elements c_{ij} change with temperature in the following way:

$$\frac{dc_{ij}}{dT} = \gamma_{ij} c_{ij} \tag{2}$$

where γ_{ij} – are the elements of thermal coefficients matrix for c_{ij}. Based on the evidences [17–20], one may consider that the temperature dependence $c_{ij}(T)$ is linear. It was shown in papers [10,22] that the best correspondence between the theoretical calculations and experimental results is obtained by using the $c_{ij}(T)$ data presented in [19]. The values of TeO_2 elastic modules c_{ij} and their thermal variation dc_{ij}/dT are presented in Table 1.

In the presented investigation the temperature influence examination was carried for the wide-aperture AOTF fabricated from TeO_2 crystal with 10.5° cut-angle. The AO interaction is realized in $(1\bar{1}0)$ plane, the incident optical radiation has extraordinary polarization. Solving the Eq. (1) it is possible to obtain that the acoustic energy walk-off angle along the chosen direction is as high as 54.6°; the slow shear acoustic wave velocity is 716 m/s for the 10.5° cut-angle.

Using the Eqs. (1) and (2) for the case of slow acoustic wave propagating at 10.5°to the crystallographic [1 1 0] axis the following temperature coefficient showing the variation of ultrasound wave velocity with temperature was obtained: 0.06 m/s·K^{-1}. This value seems to be rather low, but it is enough to influence AO diffraction characteristics significantly. We need to mention here that both acoustic wave velocity and its variation with temperature [22] depend on the chosen direction in TeO_2 crystal.

It is convenient to use wave vector diagram method for the AO interaction description [23]. The following relation takes place for wave vectors of incident $\vec{k_i}$ and diffracted $\vec{k_d}$ optical waves and acoustic wave vector $\vec{K}$ in the case of phase matching condition fulfilled:

$$\vec{k_d} = \vec{k_i} + \vec{K} \tag{3}$$

where $|\vec{k_i}| = 2\pi n_i/\lambda$; $|\vec{k_d}| = 2\pi n_d/\lambda$; $|\vec{K}| = 2\pi f/V$, f – ultrasound frequency, V – ultrasound velocity and λ – optical radiation wavelength.

The wave vector Eq. (3) may be illustrated by the following drawing, presented in Fig. 1.

The n_o and n_e are the segments of refractive indices surfaces cross sections by the $(1\bar{1}0)$ plane, $\alpha = 10.5$Â°, $\theta_i = 25$Â°.

Using the presented vector diagram it is possible to obtain the equation that defines the AO interaction phase matching frequency. It will be the following in the case of extraordinary polarization of incident optical beam:

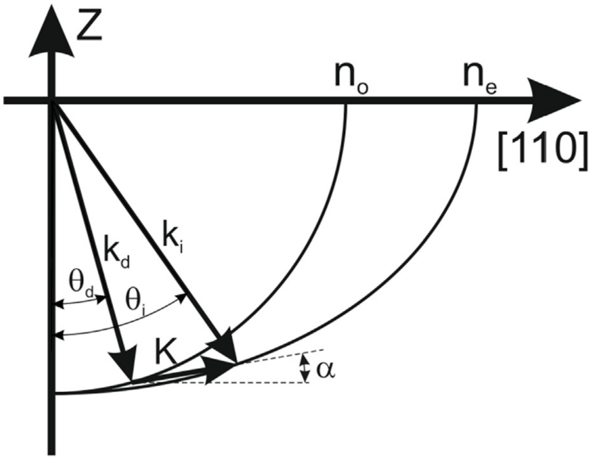

Fig. 1. The wave vector diagram of the AO interaction geometry being examined.

$$f = \frac{V(T)}{\lambda}\{\sqrt{n_o^2 - n_i^2 \cos\Theta_B} - n_i \sin\Theta_B\}, \tag{4}$$

where n_i is the refraction coefficient for the incident optical beam, T is the crystal temperature and Θ_B is the Bragg angle.

In fact, the values of the refraction indices also depend on the temperature, but there is no reliable data allowing taking into account their variation with temperature for paratellurite in IR region. Also the effect of their variation on the AO synchronism frequency is much less than the ultrasound wave velocity change. So we will consider n_i and n_o to be constant and depending only on the optical wavelength.

The TeO_2 refraction indices were calculated with the following equation [24]:

$$n^2 = 1 + \frac{C_0\lambda^2}{\lambda^2 - C_2^2} + \frac{C_1\lambda^2}{\lambda^2 - C_3^2} \tag{5}$$

where λ is the optical radiation wavelength in µm, and C_i coefficients values are presented in Table 2 [24].

The n_i value was calculated by taking into account the TeO_2 optical activity [25]:

$$n_i = \frac{(n_o + dn)n_e}{\sqrt{n_e^2(\sin\varphi)^2 + (n_o + dn)^2(\cos\varphi)^2}} \tag{6}$$

where dn is the variation caused by optical activity and $\varphi = 90 - \theta_i$ is the angle measured from [1 1 0] axis in $(1\bar{1}0)$ plane defining the incident optical wave propagation direction in crystal.

2.2. Experimental and computation results

The experimental part of the study was carried with the help of AO cell fabricated from TeO_2 crystal with cut-angle $\alpha = 10.5$Â°, and $\Theta_B = -14.5$Â°. This geometry corresponds to wide-aperture AO interaction geometry [26,27]. The AO interaction length in the chosen AO cell was 0.7 cm. The AOTF passband is about 330 kHz. Various types of lasers were used as the optical radiation sources – gas lasers with 440 nm, 633 nm, 1.15 µm, 1.52 µm (He-Cd and He-Ne lasers

Table 1
The TeO_2 elastic modules and their temperature variation.

c_{ij},10^{10}N/m^2 at 20 °C temperature		$\frac{dc_{ij}}{dT}$, 10^8N/m^2·K^{-1}
c_{11}	5.612	−0.144
c_{12}	5.155	−0.157
c_{13}	2.303	−0.038
c_{33}	10.571	−0.324
c_{44}	2.668	−0.030
c_{66}	6.614	−0.226

Table 2
The C_i coefficients for evaluation of paratellurite refraction coefficients.

	C_0	C_1	C_2	C_3
n_o	3.71789	0.07544	0.19619	4.61196
n_e	4.33449	0.14739	0.20242	4.93667