Influence of temperature gradients on spectral transmission of acousto-optic tunable filters based on KH_2PO_4 crystal

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***Abstract*—we examined acousto-optic interaction in the KH_2PO_4 crystal used in devices providing control of optical radiation parameters. The crystal was applied in a wide-angle tunable acousto-optic filter capable of image processing in the ultraviolet region of spectrum. The filter operated at different temperature conditions because of changes of environmental temperature and also due to heating of the crystal by driving electric and acoustic power. As found experimentally and proved theoretically, changes in the temperature of the instrument and appearance of thermal gradients in the crystal volume sufficiently influenced on operation characteristics of the acousto-optic device.**

Keywords—tunable acousto-optic tunable filter; KH_2PO_4 crystal; temperature variation; thermal shifts, spectral transmission

I. INTRODUCTION

It is known that good optical properties of the single crystal potassium dihydrogen phosphate (KH_2PO_4 or KDP) provided a possibility to use the material for fabrication of acousto-optic (AO) devices operating in the ultraviolet region of electromagnetic spectrum [1-4]. All other known so far efficient birefringent materials that are frequently used in acousto-optics, e.g., tellurium dioxide, are not transparent in the ultraviolet spectral range [1-6]. That is why, the first successful solution of the problem of light beam control in the ultraviolet spectral domain was obtained by means of an instrument based on the potassium dihydrogen phosphate crystal. The crystal was used in a tunable acousto-optic filter designed and fabricated on base of the wide-angle AO interaction geometry in the material. As a result, the KDP-based filter provided reliable processing of optical images in the ultraviolet and visible light [1-4].

Unfortunately, the crystal is not so perfect from the acousto-optic point of view. It demonstrates relatively low acousto-optic efficiency as compared to the single crystal tellurium dioxide [5,6]. The low material AO figure of merit resulted in limited diffraction efficiency and poor operation characteristics of the KDP devices. In order to overcome the difficulty in the imaging filter, it was necessary to increase, to a few watts, the driving electric power applied to the device. It automatically increased power of travelling acoustic waves propagating in the crystal.

It is evident that the acoustic power is absorbed in an AO cell. The absorbed power heats a crystal and leads to inhomogeneous temperature distribution in the crystal volume. As a result, the crystal elastic constants are changed, directly impacting the acoustic wave velocity and hence the AO phase matching conditions: for a given optical wavelength, the matching acoustic frequency is shifted [5,6].

The shift of acoustic matching frequency in the examined KDP filter and distortion of its transmission function due to the acoustic absorption was first observed in [3]. However, the effect was described and examined mainly qualitatively without reliable theoretical background. In the present paper, we carry out a more detailed simulation and theoretical analysis of the thermal problem.

II. MODELLING OF TEMPERATURE DISTRIBUTION

The distribution of temperature in the filter AO cell was calculated by solving the stationary heat conduction problem. In the analysis, the initial conditions and the conditions at the borders of the cell were set based on the following reasonable assumptions. A piezoelectric transducer of the cell is fed by the electric RF power while this power heats the crystal. Moreover, it was considered that not only the transducer heats the AO cell but so does the propagating acoustic wave too. It is evident that resulting from the acoustic absorption, a distributed heat source is created in the volume of the crystal. As for the conditions at the crystal borders, we examined two different types of them. In the first case, it was considered that only rear and bottom facets of the AO cell were in contact with a metallic housing of the AO filter. These facets had fixed temperature. All other faces of the crystal were free from the thermal contact. In the second scenario, we assumed that all faces of the KDP cell had the thermal contact with the housing.

The thermal problem was solved in the traditional way. We calculated distribution of the temperature in the crystal volume over the coordinates x, y and z. The system of

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differential equations for the temperature distribution $T(x,y,z)$ in the first case of the border conditions was written as:

$$\begin{cases} -\left(k_1\frac{\partial^2T}{\partial x^2}+k_1\frac{\partial^2T}{\partial y^2}+k_3\frac{\partial^2T}{\partial z^2}\right)=0 \\ -n\left(-k_1\left(\frac{\partial T}{\partial x}+\frac{\partial T}{\partial y}\right)-k_3\frac{\partial T}{\partial z}\right)=h(T_0-T) \\ -n\left(-k_1\left(\frac{\partial T}{\partial x}+\frac{\partial T}{\partial y}\right)-k_3\frac{\partial T}{\partial z}\right)=h(T_0-T)+Q_0 \\ T=T_0 \end{cases} \tag{1}$$

where k_1=1.75 W/(m^2·K) and k_3=1.3 W/(m^2·K) are the thermal conductivity coefficients, T_0 is the ambient temperature, q_0 is the acoustic power measured in W/m^2, h – is the thermal diffusivity coefficient, n – are the projections of the vector normal, Q_0 is the distributed heat source power produced by acoustic power absorption in crystal.

The first equation in the system (1) represents the stationary heat equation. It is written stating that in the KDP crystal, thermal conductivity coefficient k_1 along the X crystallographic axis and the k_3 coefficient describes the thermal conductivity along the Z axis. The second equation in (1) models the heat flow through the free facets of the AO cell. The third equation simulates the distributed heat source having the power Q_0. The equation describes the heat of the transducer. Finally, the fourth equation in the system (1) sets the boundary conditions for the facets that are in contact with the metallic housing of the AO filter.

The results of the temperature simulation in the cell at 3W of the driving acoustic power in the case of the first scenario of the boundary conditions are presented in Fig. 1. In the figure, the external cuboid indicates the shape and dimensions of the used AO cell (2.0x2.0x4.0 cm). The internal cuboid schematically shows the shape of the acoustic beam in the crystal volume (0.6x3.0 cm). The cross-section of the simulated distribution of the temperature is also shown in the picture. The left facet of the crystal has the thermal contact with the metallic filter housing, while all other facets are free. The carried out simulation showed that in the case of the acoustic power 3W, the difference in temperatures inside the KDP crystal is limited to 11 □C.

III. INFLUENCE OF TEMPERATURE ON PARAMETERS OF DIFFRACTION

The AO diffraction regime we were examining was observed in the (010) of the KDP crystal. A slow shear acoustic wave propagated along a direction at the cut angle α =9^0 relatively to the axis [100] in the (010) plane [1,2]. The dependence of acoustic wave velocity V on the crystal cut angle α and on the temperature is defined as [7]:

$$V=\sqrt{\frac{c_{66}(T)}{\rho}cos^2\alpha+\frac{c_{44}(T)}{\rho}sin^2\alpha} \tag{2}$$

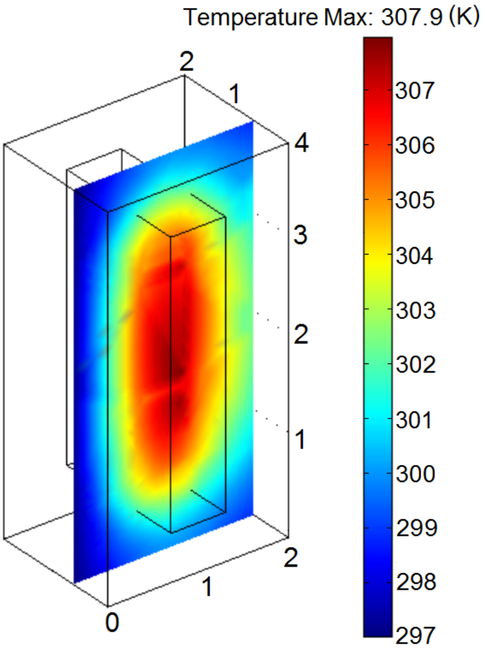


Fig. 1. Distribution of temperature in the volume of the AO cell.

where ρ=2338 kg/m^3 is the density of KDP, c_{44} and c_{66} are the coefficients of elastic tensor [7-9] and T is the local temperature of the crystal.

As known, KPD is optically negative because the refractive indices are related to each other as $n_o > n_e$. Taking into consideration all crystalline parameters depending on the temperature, we wrote the following equation illustrating Bragg phase matching condition during AO interaction:

$$f(T)=\frac{V(T)}{\lambda}\left\{\sqrt{n_o^2(T)-n_d^2(T)\cos\theta_B}-n_d(T)\sin\theta_B\right\} \tag{3}$$

In the above expression, n_d is the refractive index of the diffracted light, λ is the optical wavelength and θ_B is the Bragg angle. The equation (3) was used for the temperature influence analysis on the device operation. As for the dependences of the refractive indices in KDP on the temperature, they were discussed in [10,11].

First, we examined the dependence of the acoustic velocity V on the temperature. This dependence is given by (2). Data on the elastic coefficients and their variation with the temperature could be found in [8,9]. The corresponding $V(T)$ dependences are presented in Fig. 2. The calculations show that the magnitude of the velocity V reduces with the growth of the temperature.

Data summarized in Fig. 2 were used to determine the shift of the acoustic phase matching frequency df caused by the temperature variations. We obtained, at the wavelength of light λ=350 nm, the following result df/dT=-0.104 MHz/K. It means that the corresponding shift of the optical wavelengths at λ=350 nm was equal to +0.23 nm/K.

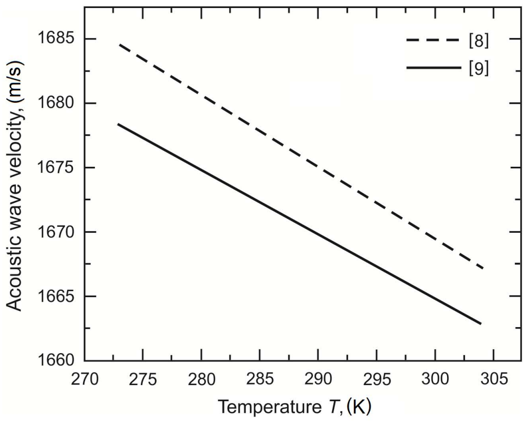


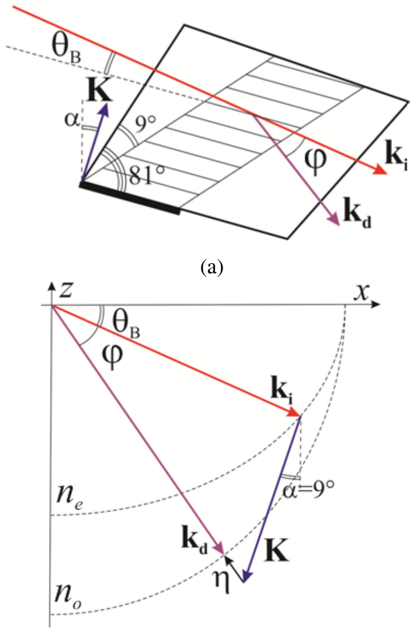
Fig. 2. Variation of acoustic wave velocity with temperature.

IV. CALCULATION OF TRANSMISSION FUNCTION

The results of the investigation of the filter in the references [3,4] prove that not only the shift *df* of the transmission function was registered in the experiments but also a distortion of the transmission function curve ζ(*f*), the filter passband broadening *Δf* and the decrease of the diffraction efficiency were observed. In order to evaluate quantitatively these effects, we solved the following modified system of coupled wave equations:

$$\begin{cases} \dfrac{dC_0}{dx} = -\dfrac{q(T)}{2} C_1 exp(j\eta(T)x) \\ \dfrac{dC_1}{dx} = \dfrac{q(T)}{2} C_0 exp(-j\eta(T)x) \end{cases} \qquad (4)$$

where the coefficient q and the mismatch vector length η [12,13] depend on the temperature. Consequently both mentioned parameters vary from point to point in the volume of the crystal. It is stated that the X-axis is parallel to the light propagation direction and C_0 and C_1 are the amplitudes of light in the zero and first diffraction orders.



(a)

(b)

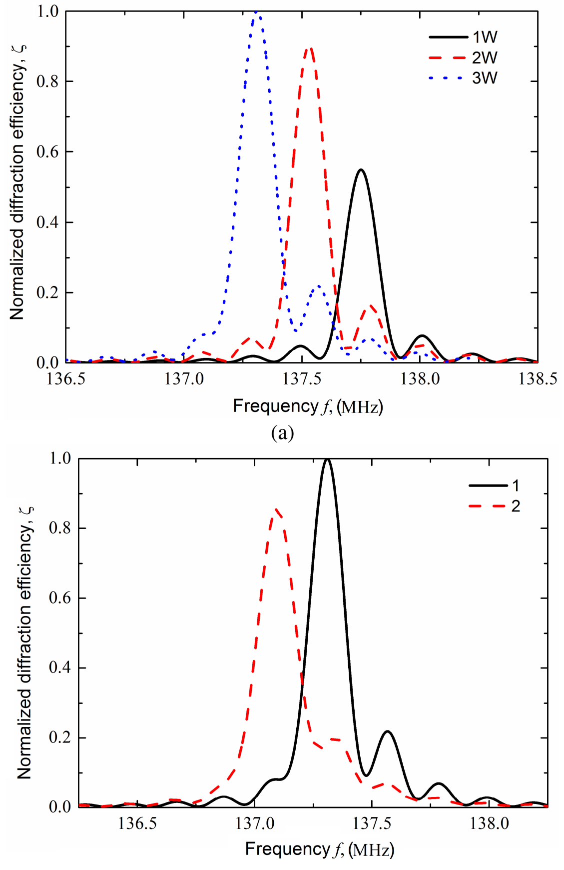
Fig. 3. Acousto-optic tunable filter in KDP
a – configuration of KDP cell; b – wave vector diagram of interaction.

Fig. 3a shows configuration of the KDP that was experimentally examined in [3,4] and theoretically considered in this paper. Fig. 3b shows the wave vector diagram of AO interaction in this cell [1,2]. This diagram was used for definition and evaluation of the mismatch vector η length. In the diagram, $\mathbf{k_i}$, $\mathbf{k_d}$ are the wave vectors of the incident, and the diffracted light while $\mathbf{K}$ is the wave vector of sound.

The AO mismatch vector length was defined by the following equation [12,13] :

$$\eta = K\sin\varphi + k_i\cos(\varphi + \theta_B) - \\ -\sqrt{k_d^2 - [k_i\sin(\varphi + \theta_B) - K\cos\varphi]^2} \qquad (5)$$

The calculations were carried on base of the above equation at the optical wavelength 350 nm and the power of the acoustic wave 1.0 W, 2.0 W and 3.0 W. It was considered that the optical beam passed through the cell at the distance



(a)

(b)

Fig. 4. Calculated curves of transmission function
a - first type of border conditions; b - transmission functions at 3W acoustic power for the first (curve 1) and second (curve 2) type of border conditions.

0.5 cm with respect to the plane of the transducer. The results of the carried out modeling and calculations related to the filter transmission function are summarized in Fig. 4.

Data in Fig. 4a show the filter transmission functions for the first type of the border conditions when only the rear and bottom faces of the AO cell are in the thermal contact with the metallic housing. It means that these facets of the AO filter have fixed temperature equal to environmental temperature. Our simulations predict appearance of the shift of the transmission function δf_t . This shift increases with the acoustic power. The calculated magnitude of the frequency shift at the driving power 3W is δf_t=0.5 MHz. As for the experimentally obtained result, it was wider δf_e=0.8 MHz but still in the tolerable limits.

Our mathematical model also predicted the experimentally registered broadening of the filter passband Δf. In the examined KDP filter, the passband was equal to Δf=150 kHz in the case of a homogeneous distribution of the temperature in the crystal volume. The experimentally registered passband magnitude Δf_e equals to 250 kHz. As for the result of modeling, it gives the magnitude Δf_t = 170 kHz. It should be noted that our calculations also explain origin of the asymmetry of the curve illustrating the transmission function. The carried out analysis definitely proves that asymmetry appears due to the inhomogeneity of the temperature distribution in the crystal.

Fig. 4b represents results of comparison specially carried out in order to reveal difference in thermal impact on the filter spectral transmission in the case of two types of the conditions at the borders. The comparison was carried out at equal levels of the driving power 3.0W. The curve *1* in Fig. 4b was obtained for the first type of the crystal heating when only rear and bottom faces of the AO cell were in the thermal contact with the metallic housing of the filter. It means that the temperature of the facets was fixed equal to the environmental temperature. The curve *2* in Fig. 4b was calculated for the second type of the border conditions when all faces of the cell had the contact with the housing. As seen in the figure, the second type of the border conditions result in higher temperature gradients in the AO cell. Moreover the gradients cause stronger frequency shifts of the transmission function δf_t=1.0 MHz and also stronger broadening of the passband Δf_t = 190 kHz, as compared to the uniform heating.

V. CONCLUSION

The problem of heating and inhomogeneous distribution of temperature over the body of the KDP-based AO filter was examined. Mathematical model of the cell heated by the driving acoustic power was proposed. The calculations were carried for the AO filter applying the wide angle AO interaction geometry providing processing by the instrument of optical images. Influence of the crystal temperature on the diffraction characteristics was investigated in details.

It was shown that the temperature inhomogeneity inside the AO cell influences the acoustic wave velocity and the refractive indices of the crystal. It causes the dependence of the AO interaction parameters on the local coordinates in the body of the device. In whole, it affects all basic operation parameters of the instrument, i.e., the shape of the spectral transmission function, the optical wavelength of maximum transmission and the width of the spectral passband.

The carried out comparison of the two types of the thermal conditions at the filter facets, when only two and when all facets of the filter cell contact with the metallic housing, reveal difference in the filter operation. We proved that the second type of the conditions at the border causes higher temperature gradients and thermal inhomogeneity in the crystal. Both these effects lead to undesirable changes and even to distortions of the transmission function.

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