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Design of far-infrared acousto-optic tunable filter based on backward collinear interaction

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ABSTRACT

The paper proposes a design of acousto-optic cell applying backward collinear interaction and acoustic mode transformation in a KRS-5 crystal. This cell may serve as an acousto-optic tunable filter for far-infrared spectral range and is able to operate both with collimated optical beams and with divergent beams forming images. The problem of acoustic mode transformation by wave reflection from the crystal facet away from symmetry planes has been solved. Polarization properties of the backward collinear interaction in optically isotropic media are discussed.

1. Introduction

Acousto-optic devices are efficient in control of electromagnetic radiation parameters. One of the most commonly used types of such devices is the acousto-optic tunable filter that provides separation of the electromagnetic radiation (including optical images) into a single or a few spectral components [1,2]. The maximum spectral resolution of the acousto-optic filters is achieved by using the collinear acousto-optic interaction and can be as high as 10^4 [2].

A relevant problem nowadays is the experimental implementation of the so-called backward collinear interaction regime that was theoretically studied in a few papers [3–6]. In case of the backward collinear interaction, wave vectors of the incident and the diffracted electromagnetic waves are directed opposite to each other and collinear with the acoustic wave vector. Such geometry provides maximal acousto-optic interaction length which is related to the electromagnetic wavelength bandwidth. Another advantage of the backward collinear regime is the possibility to implement it in optically isotropic materials which is not possible in the conventional low-frequency collinear interaction [1,3].

The backward collinear interaction is observed at hypersonic wave frequencies that are inversely proportional to the radiation wavelength. In commonly used acousto-optic materials this frequency amounts values up to 10 GHz for the visible and near-infrared spectral regions [3,4]. This circumstance allows practical application of the backward collinear filters only in the far-infrared wavelength range (20 μm and longer), where the acoustic frequencies are decreased to acceptable values. Since the existing acousto-optical devices reliably operate at the wavelengths no longer than 15 μm [7], the backward collinear interaction allows to extend their application area. In general, designing acousto-optical devices operating with far-infrared radiation is a relevant problem. The undoubted interest to this spectral region is particularly stimulated by practical demands e.g. the quantum-cascade lasers developed in recent years [8].

The KRS-5 crystal (thallium halide solid solution) is an optimal material for implementation of the backward collinear interaction [9]. This crystal is transparent in the wavelength region $\lambda = 0.5 \div 50\,\mu$m and possesses good acousto-optic properties. Its figures of merit reach values as high as $M_2 = 1200 \times 10^{-15}\,\mathrm{s}^3/\mathrm{kg}$ and $M_2 = 600 \times 10^{-15}\,\mathrm{s}^3/\mathrm{kg}$ in the visible and far-infrared regions, correspondingly [9]. These magnitudes of the figure of merit are comparable with the best acousto-optic materials [1]. Nowadays there are well-developed techniques of growth and treatment of the high-quality KRS-5 single crystals [10]. Some recent papers have thoroughly considered the acoustic [11] and acousto-optic [9] properties of this crystal in the (0 0 1) and (1 1 0) planes. It was shown that despite the cubic symmetry and optical isotropy of the KRS-5 crystal, it possesses considerable anisotropy of acoustic and acousto-optic properties. This allows implementing it in various geometries of acousto-optic interaction.

The present paper is devoted to design of the backward collinear acousto-optic filters based on (0 0 1) and (1 1 0) planes of KRS-5 crystal. According to the results of paper [9], there are optimal directions of the backward collinear interaction in the crystal where the acousto-optic figures of merit reach maximal values. However, direct application of these results is rather problematic. A characteristic feature of the backward collinear acousto-optic cell is that the diffracted electromagnetic radiation propagates opposite to the incident one. That is why the conventional design of acousto-optic cell and position of a

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piezotransducer on a crystal facet opposite to an optical facet inevitably leads to reflection of the electro-magnetic radiation from a ground transducer electrode. This circumstance causes difficulties in separation of the incident and diffracted radiation, and in some cases makes this separation impossible. Moreover, the most optimal interaction geometry requires application of a shear or a quasi-shear acoustic wave. Generation of such wave is accompanied by further technical difficulties.

In the present paper, we suggested a solution of both problems that is the launching of a longitudinal acoustic wave and its transformation into a shear wave after the reflection from an adjacent facet of a wedge-shaped cell. The diffraction of the electromagnetic radiation by the shear ultrasonic wave takes place in the same crystal. A similar method of generation of a quasi-shear wave has been described in the paper [12] for a non-collinear acousto-optic cell. In the collinear geometry, such technique allows to remove a piezotransducer from the path of the electromagnetic radiation. We solved the task of finding energy reflection coefficients for all three reflected acoustic waves and found crystal cut angles that provide propagation of the shear wave in the required direction. The possibility to transform over 86% of the longitudinal wave energy into the shear wave in the direction determined by the maximal acousto-optic figure of merit has been proved. In this paper, the most important parameters of the device such as the diffraction efficiency, the frequency bandwidth and the angular aperture have been estimated. The possibility to develop a far-infrared imaging filter based on the backward collinear interaction is also considered in this paper.

2. General scheme of acousto-optic cell

There are a number of optimal directions in the KRS-5 crystal, in which figures of merit of the backward collinear diffraction have maximal values [9]. The most interesting one is the direction in (1 1 0) plane that is 37° tilted from the [0 0 1] axis. In case of the collinear diffraction by shear acoustic wave, the acousto-optic figure of merit has the value $M_2 = 130 \times 10^{-15}\,\mathrm{s}^3/\mathrm{kg}$ and the acoustic frequency is equal to $f = 240$ MHz for the 20μm wavelength. The acoustic attenuation constant at this frequency has the value about 6 dB/cm. When the radiation wavelength is tuned from 10μm to 40μm, the acousto-optic figure of merit decreases from $140 \times 10^{-15}\,\mathrm{s}^3/\mathrm{kg}$ to $90 \times 10^{-15}\,\mathrm{s}^3/\mathrm{kg}$, while the ultrasonic wave frequency does it from 490 MHz to 120 MHz, correspondingly.

According to the scheme proposed in Fig. 1a, the acousto-optic cell has a shape of a prism, and its three facets are marked as P, O and R. On the P facet, there is a piezoelectric transducer PT that generates the longitudinal acoustic wave. This wave falls on the R facet and reflects from it. The reflection is accompanied by a transformation of the longitudinal wave into the shear wave with a high reflection coefficient. It should be mentioned that there is a 16° energy walk-off of the shear wave in (1 1 0) plane, as shown at Fig. 1b. The radiation enters the crystal through the optical facet marked by O. The optical beam direction is orthogonal to the wave surface of the shear wave but not to the R facet. Thus the zero diffraction order radiation reflects aside from the R facet and it doesn't mix with the diffracted one. In addition, the optical facet is orthogonal to both of the incident and the diffracted optical beams, and therefore they do not refract on this facet. Due to the normal incidence, the optical transparency coefficients are equal to each other for any radiation polarization. The Fresnel transparency coefficient exceeds the 80% value and it can be additionally increased by anti-reflection coating of the optical facet.

The primary task in calculating acoustic parameters of the cell was finding of acoustic wave velocities, polarizations and also the energy ratio between the waves. As it is known, an acoustic wave incident on a free crystal surface can produce up to three reflected waves [13]. In our case, the direction of one of the reflected waves (namely the shear one) was known. The task was to find orientation of the reflection facet and the direction of the incident wave that would provide convenient and efficient generation of the desired acoustic wave.

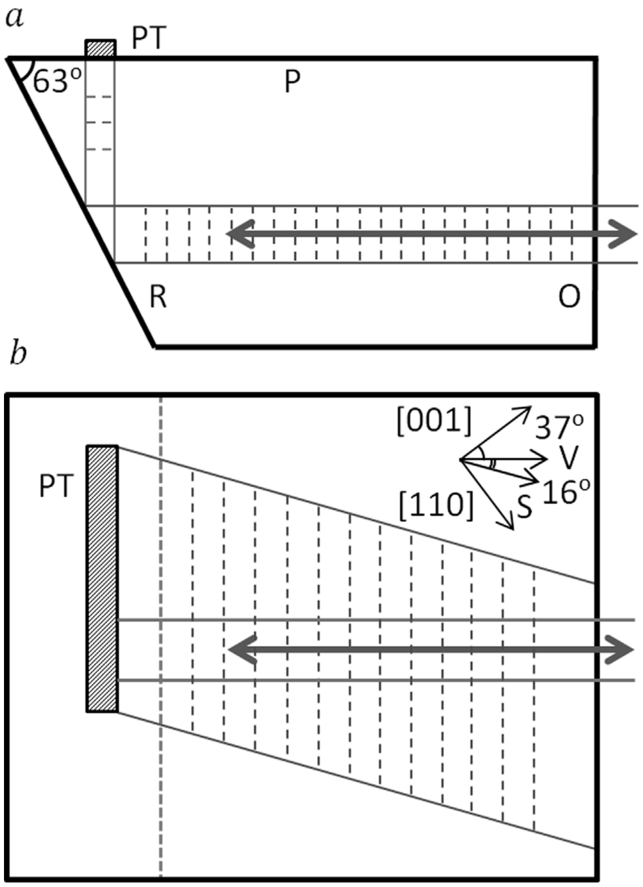

Fig. 1. Scheme of collinear acousto-optic cell: (a) – side view and (b) – top view.

The initial longitudinal wave was considered to be produced along the crystal main direction [1 1 0]. In this case, the longitudinal acoustic mode is the pure one, which allows avoiding a simultaneous generation of two acoustic modes by a single transducer and the corresponding energy loss into unwanted beam. Thus, we found the reflective facet R orientation by known directions of the incident and diffracted modes.

As known, as many as three acoustic modes with mutually orthogonal polarizations may propagate along a certain direction in a crystal. In order to find polarization and phase velocity vectors of these waves, one should solve the Christoffel equation [13,14]:

$$(c_{ijkl}b_jb_k-\rho V^2\delta_{il})a_l = 0, \tag{1}$$

where c_{ijkl} are the components of crystal elastic tensor, b_i is the wave normal vector of the acoustic wave component, a_i is the polarization vector component, ρ is the medium density, V is the phase velocity of the acoustic mode, δ_{il} is the unit tensor. In our analysis it is convenient to consider the slowness curve which is the dependence of the value on $\vec{b}$ vector direction [13].

In order to describe the reflection of an acoustic wave from the free edge of the crystal, it is necessary to construct a section of the slowness surface by the plane of propagation of the waves. In this case, it is the plane marked by S symbol and determined by the wave vectors $\overrightarrow{K}^{inc}$ of the incident wave and $\overrightarrow{K}^{ref1}$ of the shear one. The orientation of this plane relatively to crystallographic axes is shown in Fig. 2a, while the slowness curve in this plane is shown in Fig. 2b. The orientation of the reflective facet R could be found from the condition of equality of the projections OA of incident and desirable reflected wave vectors. The R facet plane is orthogonal to Fig. 2b plane. We found that the reflection