A R C H I V E S O F M E T A L L U R G Y A N D M A T E R I A L S
Volume 54 2009 Issue 4

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**LASER PHOTOACOUSTIC SPECTROSCOPY OF THE PIEZOCERAMIC MATERIALS**

**LASEROWA SPEKTROSKOPIA FOTOAKUSTYCZNA MATERIAŁÓW PIEZOCERAMICZNYCH**

The aim of the work is the investigation of photoacoustic transformation in piezoceramic materials and piezocrystals of various classes of symmetry. It is considered the case thermal mechanism of excitation of thermoelastic waves by various Bessel light beams polarization modes. Within the range of modulation frequency 100kHz- 1MHz the resonance phenomena are found. It's showed that the amplitude of the resonance curves substantially depends on the radial distribution of the velocity of the Bessel light beams energy dissipation, on the type of polarization modes and on the geometric dimensions of the piezoelectric crystal, which acts also as a piezodetector.
We can state that the results obtained by the resonance photoacoustic transformation can be used to improve the resolution of methods of photoacoustic spectroscopy and microscopy.

Celem pracy są badania nad fotoakustyczną transformacją w materiałach piezoceramicznych oraz piezokryształach o różnych klasach symetrii. W pracy rozpatrywano termiczny mechanizm wzbudzania termosprężystych fal przez różne mody polaryzacyjne wiązek Bessela. W zakresie częstotliwości modulacji 100kHz-1MHz obserwowano zjawiska rezonansu. Wykazano, iż amplituda krzywych rezonansu w znacznym stopniu zależy od radialnego rozdziału prędkości rozpraszania energii wiązek Bessela, od typu modów polaryzacyjnych oraz od wymiarów geometrycznych kryształu piezoelektrycznego, który pełni także funkcję piezodetektora.

## 1. Introduction

The impact of an amplitude modulated optical radiation on piezoelectric ceramics can lead to loose of the low-frequency sound signal, and the sample under investigation is acting also as a detector of the photoacoustic signal [1, 2]. Piezoceramic materials have a number of unique properties and, in some cases they are preferable to natural piezocrystals [3]. One significant advantage is the ability to manufacture piezoceramics in a form of elements of different geometry. Electronic devices based on piezoceramics (piezoelectronic devices) like e.g. piezoresonators, piezotransformers, piezogenerators, acoustic delay lines, etc., are widely used in radio-electronics, acoustooptics, automation, computing and measurement technology.

It is known [4] that the piezoelectric properties reveal exclusively non-centrosymmetrical crystals, many of which have natural or forced (Faraday effect) gyrotropy [5]. In this context, it is interesting to study the photoacoustic transformation in the naturally gyrotropic piezocrystals of different classes of symmetry, absorbing radiation of the amplitude modulated Bessel light beams. It should be noted, that the challenge is similar to the one, we have seen for the case of excitation of the photoacoustic signal by a plane electromagnetic wave [2].

The following review will be conducted for the case when the heat is the main trigger mechanism of thermoelastic waves by various polarization modes of the Bessel light beams. The use of Bessel light beams due to their wide range of specific properties, in particular, the diffractionless of propagation, self-effect, the rise of the radial component of the dissipative medium, etc., which opens up broad prospects for their use for nondestructive testing in nanotechnology, nonlinear and integrated optics, biophysics and medicine [6, 7]. The features of the photoacoustic resonant excitation of the signal, as well

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as the photodeflection response in the heterogeneous and gyrotropic environments were examined in [8-10]. Experimental study of the impact of technological elastic stresses on the type of photoacoustic signals in silicon nitride ceramics was carried out in [11].

The purpose of the communication is to explore the features of the thermooptical excitation of sound by Bessel light beams in gyrotropic piezoelectric crystal and piezoceramic materials.

Let us suppose that the amplitude modulated Bessel radiation beam falls on the absorbing cubic piezocrystal of class 23 along the crystallographic direction [110]. In accordance with the ratios of Dugamel-Neiman type, which in the matrix notation for the case has the form [12]:

$$\begin{aligned} \sigma_6 &= C_{44}^E U_{66} - e_{14}^T E_3 - \lambda_1^E \theta, \\ D_3 &= e_{13}^T U_{66} + \varepsilon_{14}^s E_3, \end{aligned} \tag{1}$$

modulated absorption of the beam gives rise to the thermoelastic fluctuations and, through a reverse piezoeffect to a potential difference on the verge of the piezocrystal sample.

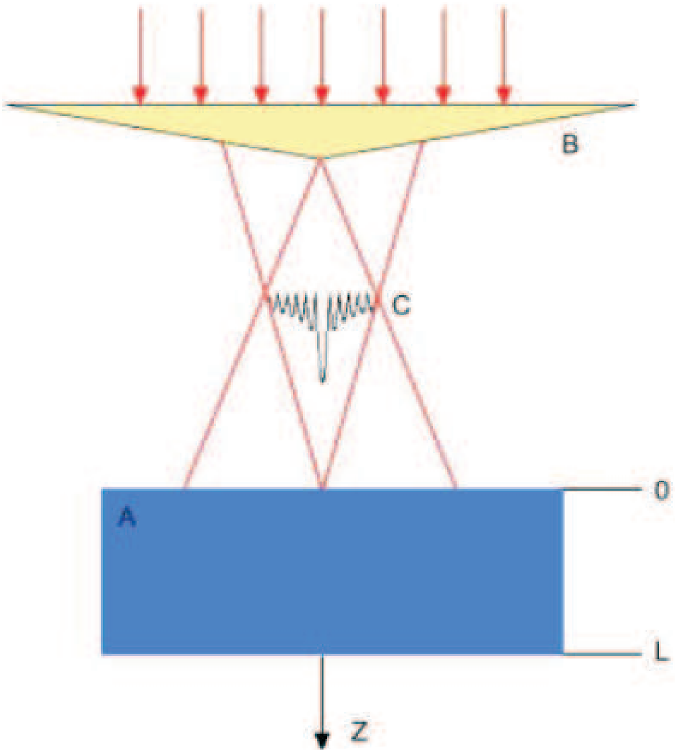


Fig. 1. Scheme of photoacoustic signal registration: A – piezoelectric sample, B – axicon, C – Bessel light beam

In relations (1) the following designations are used [13]: $\sigma_6$ is the elastic stress tensor component, $C_{44}^E$, $e_{44}^T$ are components of tensors of the elastic coefficients; $\lambda_1^E$, $\varepsilon_{14}^s$ are components of tensors of thermal stress and permittivity, $\theta$ is the periodic component of temperature field. Indices E, T, S denote the components of tensors are taken at a constant value of electric field, temperature and strain, respectively.

To find the distribution of the temperature field in a gyrotropic piezocrystal we have to use the heat conduction equation:

$$\frac{\partial^2 T}{\partial z^2} - \frac{1}{\beta}\frac{\partial T}{\partial t} = -\frac{Q_{\pm}^{TE}}{2k}(1 + e^{i\Omega t}) \tag{2}$$

Where $\beta = k/\rho C$, ρ is the density, C is the specific heat of the piezocrystal sample, $Q_{\pm}^{TE}$ is the velocity of the dissipation of the circular TE-mode of the Bessel light beam, $\Omega = 2\omega$ is the frequency of the amplitude modulation of the Bessel light beam. The relation for $Q_{\pm}^{TE}$ was obtained previously [8] and has the following form:

$$\begin{gathered} Q_{\pm}^{TE} = \frac{\omega|\varepsilon|\varepsilon_2}{2\pi} A_{\pm} e^{-2k_{z_{\pm}} z} \\ A_{\pm} = \left(\frac{m}{q\rho}\right)^2 J_m^2(q\rho) + J_m'^2(q\rho) + \frac{2mk_0 k_{z\pm}\gamma_1}{q^3\rho} J_m(q\rho) J_m'(q\rho), \end{gathered} \tag{3}$$

where $J_m(q\rho)$ is the Bessel function of first kind of order $m$, $J_m'(q\rho) = \frac{\partial J_m(q\rho)}{\partial \rho}$, $q = k_0\sqrt{\varepsilon}\sin\alpha$, $k_0 = \frac{\omega}{c}$, $\alpha_{\pm}$ is the angle of obliquity of the Bessel light beam (half angle at the vertex of the cone of the wave vectors), $\gamma = \gamma' + i\gamma''$ is the complex parameter of the gyration, real part of which $\gamma'$ defines the rotation of the polarization plane and the imaginary part $\gamma''$ defines circular dichroism, $k_{z\pm} = k_0 n_\pm \cos\alpha = k'_{z\pm} + ik''_{z\pm} n_\pm = \sqrt{\varepsilon} \pm \gamma$, $\varepsilon = \varepsilon' + i\varepsilon''$ is complex premittivity of the sample, $k''_{z\pm} = \frac{\varepsilon''}{2\sqrt{\varepsilon'}} \pm \gamma''$. The dependence of the Bessel light beam energy dissipation on mode of radiation is presented in Fig. 2.

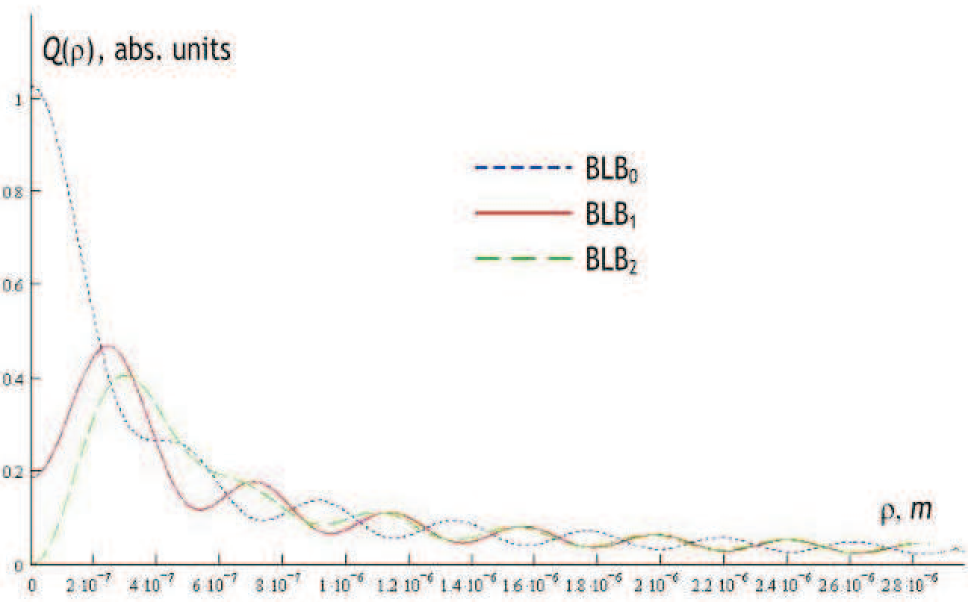


Fig. 2. The dependence of the Bessel light beam energy dissipation on the radial coordinate and the mode of radiation

Having completed the solution of the heat conduction equation (2), taking into account (3), one can obtain the following ratio for the time-dependent component of the periodic temperature field in the piezocrystal sample.

$$\theta^{TE}_{(z,t)} = U_0 e^{-\sigma z} - E^{TE}_{+} e^{-\alpha_+ z} - E^{TE}_{-} e^{-\alpha_- z} \quad (4)$$

where $\alpha_\pm = frac(4\pi)\alpha\left(\frac{\varepsilon''}{2\sqrt{\varepsilon'}}\right)$, $E^{TE}_\pm = fracQ^{TE}_\pm \alpha^2_\pm - \sigma^2$, $\sigma = (1+i)a$, $a = \sqrt{\frac{\Omega}{2\beta}}$ is – the coefficient of the thermal diffusion, $\mu = a^{-1}$ is the thermal diffusion length in the sample and U0 is the constant defined by the thermophysical, dissipative and geometric parameters of the investigated sample.

Considering further that the elastic deformations is caused by the dissipation of energy of the TE-circular modes of the Bessel light beam, the following equation is true:

$$\frac{\partial^2 U^{TE}_\pm}{\partial z^2} - \frac{\rho}{C_0}\frac{\partial^2 U^{TE}_\pm}{\partial t^2} = -\frac{\lambda}{C_0}\frac{\partial^2 \theta^{TE}_\pm}{\partial z^2}, \quad (5)$$

This solution enables us to find the distribution of the stress fields in the piezoelectric sample.

In [14] it is showed that in a cubic gyrotropic crystal, two circular Bessel light beams with different wave vectors $\vec{k}_+$, $\vec{k}_-$ and the angles of obliquity but with the same obliquity parameters $q = q_+ = q_-$ propagate.

Assuming a harmonic modulation of the Bessel light beam falling on the sample, in (5), for elastic stresses we can write:

$$U^{TE}_\pm(z,t) = U^{TE}_\pm(z) e^{i\Omega t} \quad (6)$$

that makes it possible to obtain from (5) the equation

$$\frac{\partial^2 U^{TE}_\pm}{\partial z^2} + k^2 U^{TE}_\pm = A^{TE}_\pm \exp\left(-2k''_{z_\pm} z\right), \quad (7)$$

where the symbol, $k = \rho\frac{\Omega^2}{C}$ is the wave number of elastic wave, and

$$A^{TE}_\pm = -\frac{\omega|\varepsilon|\varepsilon'' k''_{2_\pm}}{\pi}\left[\left(\frac{m}{q\rho}\right)^2 J^2_m(q\rho) + J'^2_m(q\rho) + \frac{2mk_0 k'_{z\pm}\gamma'}{q^3\rho} J_m(q\rho) J'_m(q\rho)\right].$$

Having completed the solution of the equation (7) under various boundary conditions: free ($\sigma(0) = 0$, $\sigma(\ell) = 0$), clamped ($U(0) = 0$, $U(\ell) = 0$), alternately loaded ($\sigma(0) = 0$, $U(\ell) = 0$), ($\sigma(\ell) = 0$, $U(0) = 0$) crystal boundaries, and also benefited from the relations for the potential difference induced in the piezoelectric sample length $\ell$,

$$V_{\pm}^{TE} = -\int_{0}^{\ell} E_{3_{\pm}}^{TE}(z)dz \tag{8}$$

$$E_{3_{\pm}}^{TE}(z) = -h_0 U_{\pm}^{TE},\ h_0 = -\frac{e_{33}^{T}\lambda_0^{E}}{\varepsilon_{33}^{S} C_o},\ C_o = C_{33}^{E} + (e_{33}^{T})/\varepsilon_{33}^{S}, \tag{9}$$

one can obtain the following expressions for the amplitudes of the differential photoacoustic signal $\Delta V^{TE} = V_{+}^{TE} - V_{-}^{TE}$ :

1. free boundaries ($\sigma(0) = 0$, $\sigma(\ell) = 0$):

$$\Delta V^{TE} = -h_0\left[V_0 - k\ \mathrm{tg}\left(\frac{k\ell}{2}\right)(B_{+}^{TE}(e^{-\alpha_{,}\ell} + 1) - B_{-}^{TE}(e^{-\alpha_{t}\ell} + 1))\right]; \tag{10}$$

2. one-way right loading of the sample ($\sigma(0) = 0$, $U(\ell) = 0$):

$$\Delta V^{TE} = -h\left[V_0 - k\ \mathrm{tg}(k\ell)(B_{+}^{TE} - B_{-}^{TE}) - \frac{\cos(k\ell) - 1}{\cos(k\ell)}(A_{+}^{TE}e^{-\alpha_{+}\ell} - A_{-}^{TE}e^{-\alpha_{-}\ell})\right]; \tag{11}$$

3. one-way left loading of the sample ($\sigma(0) = 0$, $U(\ell) = 0$);

$$\Delta V^{TE} = -h\left[V_0 - k\ \mathrm{tg}(k\ell)(B_{+}^{TE}e^{-\alpha_{+}\ell} - B_{-}^{TE}e^{-\alpha_{-}\ell}) - \frac{\cos(k\ell) - 1}{\cos(k\ell)}(A_{+}^{TE} - A_{-}^{TE})\right]; \tag{12}$$

4. clamped boundaries ($U(0) = 0$, $U(\ell) = 0$)

$$\Delta V^{TE} = 0 \tag{13}$$

In equations (10) – (13) the following designations are used:

$$V_0 = A_{+}^{TE}(\exp(-\alpha_{+}e) - 1) - A_{-}^{TE}(\exp(-\alpha_{-}e) - 1),$$
$$A_{\pm}^{TE} = A/(\alpha_{\pm}^2 + k^2),\ B_{\pm}^{TE} = A/\alpha_{\pm}^2,$$
$$A = \frac{\omega|\varepsilon|\varepsilon''}{2\pi}\left[\left(\frac{m}{q\rho}\right)^2 J_m^2(q\rho) + J_m'^2(q\rho)\right]$$

The ratio for A is issued in disregard of the small size – the product of the parameters for the permittivity parameter of the gyrotropy ($\varepsilon' \sim 10^{-2} \div 10^{-3}$, $\gamma' \sim 10^{-5}$).

The analysis of the obtained relations shows that there is occurrence of the resonance phenomena within the range of modulation frequency 100kHz – 1MHz of the incident radiation in the case of clamping of the frontal boundaries of crystals of class 23. The nature of the resonance curves substantially depends on the geometric dimensions of the piezoelectric crystal, which acts also as a detector.

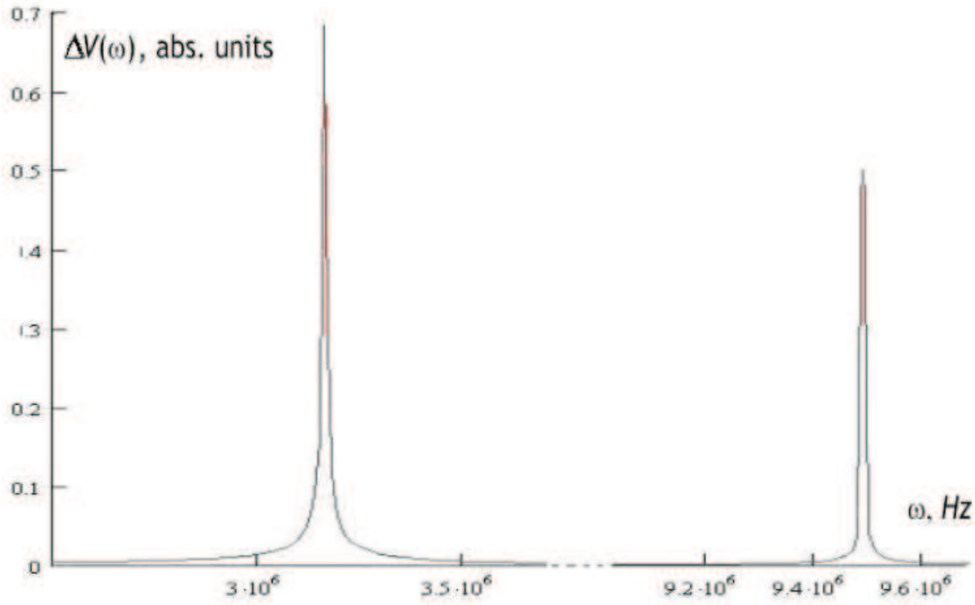


Fig. 3. The dependence of the photoacoustic signal amplitude on the Bessel light beam amplitude modulation frequency

The amplitude of the resonance curves depends on the radial velocity distribution of the energy dissipation, the explicit form of which is determined by the type of the Bessel light beam polarization modes.

It should be noted that there are no principal difficulties for the implementation of the calculations of the TH-mode of the Bessel light beam, for the synthesis of the obtained results, for the case of the single-axle crystals of classes 3, 4, 6, in the distribution of the modulated radiation along the axis of the highest symmetry and for the case of piezoceramic materials (hexagonal class of symmetry 6mm) as well as the layered piezoelectric structures.

In conclusion, we can state that the results obtained by the resonance photoacoustic transformation can be used to improve the resolution method of photoacoustic spectroscopy and microscopy.

The work was carried out with a support of the State Complex Program of Scientific Researches ≪Photonics 3.03≫ and within the frames of a grant from the Belarusian Republican Foundation for Fundamental Research NoΦ08MC-052.

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*Received: 10 September 2009.*