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PHOTOACOUSTIC TRANSFORMATION AT OPPOSITELY DIRECTED INTERACTION ELECTROMAGNETIC WAVES IN THE MAGNETOACTIVE TWO-LAYER MEDIUM

TRANSFORMACJA FOTOAKUSTYCZNA PRZY ODDZIAŁYWANIU PRZECIWBIEŻNYCH WIĄZEK ELEKTROMAGNETYCZNYCH W MAGNETOAKTYWNYCH OŚRODKACH DWUWARSTWOWYCH

The paper treats the thermooptical sound generation in the magnetoactive two-layered medium on the condition of tunnel interference of electromagnetic waves. It were studied the conditions of complete suppression of the photoacoustic signal amplitude in response to the polarization type of oppositely interacting waves, the difference in their initial phases as well as the intensities of one of the oppositely interacted beams. The given paper provides an effective method of managing the thermooptical sound generation in the magnetoactive structural element during the tunnel electromagnetic interference of electromagnetic waves.

Keywords: photoacoustic signal gas-microphone method, magnetic circular dichroism, thermooptical sound generation, tunnel interference of electromagnetic waves

Celem pracy są badania nad foto-akustyczną generacją dźwięku w magnetoaktywnych układach dwuwarstwowych, w warunkach interferencji tunelowej fal elektromagnetycznych. Badano warunki całkowitego wytłumienia amplitudy sygnału fotoakustycznego w funkcji polaryzacji przeciwbieżnych, oddziałujących wzajemnie fal, ich faz początkowych oraz intensywności jednej z przeciwbieżnych wiązek. Praca przedstawia efektywną metodę sterowania termooptyczną generacją dźwięku w strukturach magnetoaktywnych, podczas tunelowej interferencji fal elektromagnetycznych.

1. Introduction

Oppositely directed interaction of light waves in an absorbing medium gives rise to a number of interesting phenomena which have significant practical applicability [1-5]. In the laser photoacoustic (PA) spectroscopy with the oppositely directed interaction of light beams, a high rise of the resultant signal amplitude permits to assume the PA analogue of the Josephson effect. This effect reveals itself in the typical quantum mechanic problems in the tunneling of elctrons and holes through a potential barrier.

The presence of spatial dispersion in the absorbing medium leads to a number of peculiarities in the study of thermooptical sound excitation [6-8], in the condition of tunnel electromagnetic interference [9, 10]. Therefore, considering the problems relating to the PA transformation mechanism during the interaction of light waves in the media with the Faraday effect is very challenging.

This paper studies the peculiarities of the PA signal formation by the gas-microphone method in magnetoactive two-layered specimens during the oppositely directed interaction of elliptically polarized amplitude-modulated electromagnetic waves.

2. Energy dissipation

The thermooptical sound excitation in the tested specimen occurs at an amplitude modulation frequency Ω, while the source of heat waves is the rate of dissipation of its own waves. It is determined on the basis of the exact solution of the boundary electrodynamic problem, we consider it in this work [5] like a naturally gyrotropic two-layered medium.

Let us find the complex amplitudes of circularly polarized components of eigenwaves in a two-layered magnetoactive specimen in the interaction of two flat monochromatic electromagnetic waves with the initial phases φ_0 and φ (see Figure 1).

Based on the Maxwell equations for flat electromagnetic waves [11]

$$\vec{D} = -\left[\vec{m}\vec{H}\right], \vec{B} = \left[\vec{m}\vec{E}\right],$$

as well as on the material equations for magnetoactive medium [12, 13]

$$\vec{D} = \varepsilon\vec{E}, \quad B = \mu\vec{H}, \quad \varepsilon = \varepsilon_0^{-1} + iG^{\times}, (\mu = 1), \qquad (1)$$

where $G^{\times}$ is antisymmetric complex second rank tensor, double to vector of magnetic gyration $\vec{G}$, the real part of which

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G'defines the specific rotation of the polarization plane, while the imaginary G'' is responsible for magnetic circular dichroism, based on the terms of circular polarization $\vec{E}_\pm = \pm i\left[\vec{n}\vec{E}_\pm\right]$, $\vec{H}_\pm = \pm i\left[\vec{n}\vec{H}_\pm\right]$ and the requirements of the continuity of tangential components of the electromagnetic fields at the media border section, let us solve the boundary problem in geometry shown in Figure 1 and to obtain the following,

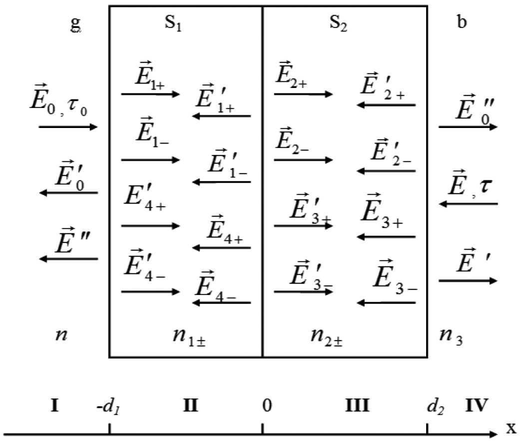

Fig. 1. Graph of oppositely directed interaction of two electromagnetic waves in magnetoactive two-layered specimens placed in cylindrical PA cell (d_1, d_2 depth of each magnetoactive element of a two-layer)

$$
\begin{aligned}
&E_{1\pm} = B^{(1)}C_\pm^{(1)}E_{0\pm}, E'_{1\pm} = C_\mp^{(1)}E_\pm,\\
&E_{2\pm} = A^{(1)}P_\pm^{(1)}E_{0\pm}, E'_{2\pm} = P_\mp^{(1)}E_\pm,\\
&E_{3\pm} = B^{(2)}C_\pm^{(2)}E_{0\pm}, E'_{3\pm} = C_\mp^{(2)}E_\pm,\\
&E_{4\pm} = A^{(2)}P_\pm^{(2)}E_{0\pm}, E'_{4\pm} = P_\mp^{(2)}E_\pm.
\end{aligned} \tag{2}
$$

Let us untroduce into (2) the following symbols:

$$A_\pm^{(1)} = \frac{n_{2\pm} + n_3}{n_{2\pm} - n_3}e^{-2i\varphi_{2\pm}}, \quad A_\pm^{(2)} = \frac{n_{1\pm} + n_1}{n_{1\pm} - n_1}e^{-2i\varphi_{1\pm}},$$

$$B_\pm^{(1)} = \frac{A_\pm^{(1)}(n_{1\pm} + n_{2\pm}) + (n_{1\pm} - n_{2\pm})}{A_\pm^{(1)}(n_{1\pm} - n_{2\pm}) + (n_{1\pm} + n_{2\pm})},$$

$$B_\pm^{(2)} = \frac{A_\pm^{(2)}(n_{2\pm} + n_{1\pm}) + (n_{2\mp} - n_{1\pm})}{A_\pm^{(2)}(n_{2\pm} - n_{1\pm}) + (n_{2\mp} + n_{1\pm})},$$

$$C_\pm^{(1)} = \frac{2ne^{-i\varphi}}{B_\pm^{(1)}(n_1 + n_{1\pm})\,e^{-i\varphi_{1\pm}} + (n_1 - n_{1\pm})\,e^{-i\varphi_{1\mp}}},$$

$$C_\pm^{(2)} = \frac{2n_3e^{-i\varphi_3}}{B_\pm^{(2)}(n_3 + n_{2\pm})\,e^{-i\varphi_{2\pm}} + (n_3 - n_{2\pm})\,e^{-i\varphi_{2\mp}}}$$

$$P_\pm^{(1)} = \frac{B_\mp^{(1)}C_\pm^{(1)} + C_\pm^{(1)}}{A_\pm^{(1)} + 1}, \quad P_\pm^{(2)} = \frac{B_\pm^{(2)}C_\pm^{(2)} + C_\pm^{(2)}}{A_\pm^{(2)} + 1}$$

$$\varphi = \frac{\omega}{c}n_1d_1,\ \varphi_{1\pm} = \frac{\omega}{c}n_{1\pm}d_1,\ \varphi_3 = \frac{\omega}{c}n_3d_2,\ \varphi_{2\pm} = \frac{\omega}{c}n_{2\pm}d_2,$$

$$E_{0\pm} = \frac{1}{\sqrt{2}}\frac{1+\tau_0}{\sqrt{1+\tau_0^2}}E_0, \quad E_\pm = \frac{1}{\sqrt{2}}\frac{1\pm\tau}{\sqrt{1+\tau^2}}E, \tag{3}$$

where E, E_0 and τ, τ_0 are according to tension of electric fields of the incident light waves and their ellipticity, respectively d_1, d_2 are the depths of layers, d_1, d_3 indicating the refraction of the nonabsorbent non-gyrotropic media I and IV; $n_{1\pm}, n_{2\pm}$ are complex factors of refraction of magnetoactive specimens II and III, respectively. The refraction factors $n_\pm$ correspond to two circularly polarized flat waves $\vec{E}_\pm$ with oppositely directed field vector rotation. The complex refraction factors of isonormal waves can be determined from the following expressions:

$$n_\pm = n'_\pm + in''_\pm = (\varepsilon_0^{-1} \pm \vec{n}\vec{G})^{-1/2} \approx \sqrt{\varepsilon_0} \mp G_x(\sqrt{\varepsilon_0})^2/2.$$

The energy dissipation in each layer is determined by the ratio:

$$Q = Q_+ + Q_-,$$

$$Q_\pm = \frac{\omega}{8\pi}\left\{\varepsilon''\left|\vec{E}\right|^2 - i\left[\vec{E}^*\vec{E}\right]G''_x\right\}, \tag{4}$$

Taking into account expression (2) in formula (4), let us determine the rate of energy volume dissipation in each layer of the magnetoactive two-layered medium:

$$Q_\pm = (Q_\pm + Q_\pm^{\mathrm{INT}})^{II} + (Q_\pm + Q_\pm^{\mathrm{INT}})^{III}, \tag{5}$$

$$(Q_\pm)^{II} = \frac{\omega}{8\pi}\left[R_\pm \exp(-\alpha_\pm x) + S_\pm \exp(\alpha_\mp x)\right], \tag{6}$$

$$
\begin{aligned}
\left(Q_\pm^{INT}\right)^{II} = \tfrac{\omega}{8\pi}\Big\{&T_\pm \cos\left(\tfrac{2\omega}{c}Re(n_{1\pm})x\right) + \\
&U_\pm \cos\left(\tfrac{2\omega}{c}Re(n_{1\pm})x + (\varphi - \varphi_0)\right)\Big\},
\end{aligned} \tag{7}
$$

$$(Q_\pm)^{III} = \frac{\omega}{8\pi}\left[V_\pm \exp(-\beta_\pm x) + W_\pm \exp(\beta_\mp x)\right], \tag{8}$$

$$
\begin{aligned}
\left(Q_\pm^{INT}\right)^{III} = \tfrac{\omega}{8\pi}\Big\{&X_\pm \cos\left(\tfrac{2\omega}{c}Re(n_{2\pm})x\right) + \\
&Y_\pm \cos\left(\tfrac{2\omega}{c}Re(n_{2\pm})x + (\varphi - \varphi_0)\right)\Big\},
\end{aligned} \tag{9}
$$

where$\alpha_\pm = \frac{2\omega}{c}n''_{1\pm}$, $\beta_\pm = \frac{2\omega}{c}n''_{2\pm}$.

Let us introduce the following symbols into (5) – (9):

$$R_\pm = N_{1\pm} f jE_{1\pm}j^2 + jE'_{4\pm}j^2 + 2Re(E_{1\pm}E'_{4\pm})\cos(\varphi_0 - \varphi)\,g,$$

$$S_\pm = N_{1\pm} f jE'_{1\pm}j^2 + jE_{4\pm}j^2 + 2Re(E'_{1\pm}E_{4\pm})\cos(\varphi_0 - \varphi)\,g,$$

$$T_\pm = N_{1\pm} f jE'_{1\pm}j^2 2Re(B_\pm^{(1)}) + jE'_{4\pm}j^2 2Re(A_\pm^{(2)})g,$$

$$U_\pm = N_{1\pm} f 2Re(E_{1\pm}E_{4\pm})2 + Re(E'_{1\pm}E'_{4\pm})g,$$

$$V_\pm = N_{2\pm} f jE_{2\pm}j^2 + jE'_{3\pm}j^2 + 2Re(E_{2\pm}E'_{3\pm})\cos(\varphi_0 - \varphi)\,g,$$

$$W_\pm = N_{2\pm} f jE'_{2\pm}j^2 + jE_{3\pm}j^2 + 2Re(E'_{2\pm}E_{3\pm})\cos(\varphi_0 - \varphi)\,g,$$

$$X_\pm = N_{2\pm} f jE'_{2\pm}j^2 2Re(A_\pm^{(1)}) + jE'_{3\pm}j^2 2Re(B_\pm^{(2)})g,$$

$$Y_\pm = N_{2\pm} f 2Re(E_{2\pm}E_{3\pm})2 + Re(E'_{2\pm}E'_{3\pm})g,$$

$$N_{j\mp} = \left(\varepsilon'' \pm G''_{jx}\right), \quad j = 1,\ 2.$$

Formulas (7) and (9) determine the interference components of energy dissipation in each layer.

3. Temperature field

Solution of the heat conductivity set of equations (10), analogically [14]

$$\frac{\partial^2 T}{\partial x^2} - \frac{1}{\beta_{s_1}}\frac{\partial T}{\partial t} = -\frac{1}{2k_{s_1}}Q^{II}\left(1 + e^{i\Omega t}\right), -d_1 \leqslant x \leqslant 0;$$

$$\frac{\partial^2 T}{\partial x^2} - \frac{1}{\beta_{s2}}\frac{\partial T}{\partial t} = -\frac{1}{2k_{s_2}}Q^{III}\left(1 + e^{i\Omega t}\right), 0_1 \leqslant x \leqslant d_2; \quad (10)$$

$$\frac{\partial^2 T}{\partial x^2} - \frac{1}{\beta_{s_1}}\frac{\partial T}{\partial t} = 0, \quad \begin{cases} \beta_i = \beta_0, -\infty < x < -d_1; \\ \beta_i = \beta_1, d_2 < x < +\infty, \end{cases}$$

Taking into account the standard boundary conditions, let us determine complex amplitude θ of temperature field at the border between the magnetoactive two-layer medium and the gas detector ($x = -d$):

$$\theta_\pm = \frac{1}{\Delta}\left(E_{1\pm}\theta_{1\pm} + E_{2\pm}\theta_{2\pm} + E_{3\pm}\theta_{3\pm} + E_{4\pm}\theta_{4\pm} + \theta_\pm^{INT}\right), \quad (11)$$

The following symbols are used in (11):

$$\theta_{1\pm} = (s_1 - s_2)(r_{1\pm} - 1)\,\eta_{1\pm}^{-1} + 2(s-1)(s + r_{1\pm})\,\xi_2^{-1} - 2(s+1)(s - r_{1\pm})\,\xi_2,$$

$$\theta_{2\pm} = (s_1 - s_2)(r_{1\pm} + 1)\,\eta_{1\pm} + 2(s-1)(s - r_{1\pm})\,\xi_2^{-1} - 2(s+1)(s + r_{1\pm})\,\xi_2,$$

$$\theta_{3\pm} = 2s\left((s+1)(1 - r_{2\pm})\,\xi_2 - (s-1)(1 + r_{2\pm})\,\xi_2^{-1} + 2(sr_{2\pm} - 1)\,\eta_{2\pm}\right),$$

$$\theta_{4\pm} = 2s\left((s+1)(1 + r_{2\pm})\,\xi_2 - (s-1)(1 - r_{2\pm})\,\xi_2^{-1} - 2(sr_{2\pm} + 1)\,\eta_{2\pm}^{-1}\right),$$

$$\theta_\pm^{INT} = \frac{2\left\{\left(Q_\pm^{INT}(0)\right)^{II} - \left(Q_\pm^{INT}(0)\right)^{III}\right\}\left[(s-1)\xi_2^{-1} + (s+1)\xi_2\right] + 4S\left[Q_\pm^{INT}(d_2)\right]^{III}}{k_{s1}\sigma_{s1}},$$

$$s_1 = (s-1)^2\,\xi_1\xi_2^{-1} - (s+1)^2\,\xi_1\xi_2,$$

$$s_2 = \left(s^2 - 1\right)\left(\xi^{-1}\xi_2 - \xi_1^{-1}\xi_2^{-1}\right),$$

$$\Delta = (s_0 + 1)\,s_1 + (s_0 - 1)\,s_2, \qquad \xi_j = \exp\left(\sigma_{sj} d_j\right),$$

$$\eta_{1+} = \exp(-\alpha_\pm d_1), \qquad \eta_{2+} = \exp(-\beta_\pm d_2),$$

$$s_0 = \frac{k_0\sigma_0}{k_{s1}\sigma_{s1}}, \qquad s = \frac{k_{s2}\sigma_{s2}}{k_{s1}\sigma_{s1}}, \qquad r_{1\pm} = \frac{\alpha_\pm}{\sigma_{s1}}, \qquad r_{2\pm} = \frac{\beta_\pm}{\sigma_{s2}}.$$

The term $\theta_\pm^{INT}$ in equation (11) implies the interference contribution of each layer into the energy dissipation, while pairs of quantities $E_{1\pm}$, $E_{2\pm}$ and $E_{3\pm}$, $E_{4\pm}$ define the total amplitude of the waves in layers one and two, respectively.

4. Numerical and graphic analyses

One can find the above mentioned formulas complicated and unwieldy. Therefore, to indentify interesting features (of PA signal formation) numerical analysis is necessary.

A significant role of the influence of medium gyrotropic properties on the process of formation of the PA signal in terms of oppositely directed interaction of electromagnetic waves is demonstrated. The PA response amplitude may increase by several orders when the parameter G' is changed; it determines the polarized plane specific rotation in the magnetic field (Figure 2). The limit amplitude at a certain G' is achieved by selecting the difference of phases $\Delta\varphi$, the ellipticity τ of interacting beams ($\tau_0 = 0, \tau = \pm 1$), the amplitude modulation frequencyΩ. Thus, the change of the real part of the magnetic gyration parameter provides an opportunity of effective PA signal management, whereas the reduced thermal impedance ratio leads to the absolute value rise of the detected gas resulting pressure.

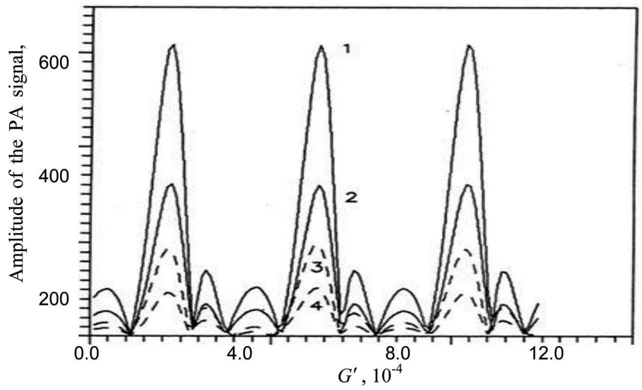

Fig. 2. PA signal amplitude dependence on real part of magnetic gyration parameter for different initial phases of interacting light beams; ($\Delta\varphi$, radians) 1, 3 – $\Delta\varphi = \pi/4$; 2, 4 – $\Delta\varphi = \pi/2$; 1, 2 – $s = 8,9$; 3, 4 – $s = 30,6$

The dichroic absorption of the magnetoactive specimen in question influences also the PA spectrum form, i.e. the PA response dependence of the magnetic circular dichroism G" displays extremes (Fig. 3), their value and position are determined by the change of the energy volume dissipation rate, on the one hand, and by the interference redistribution of the dissipating energy of interacting waves, on the other hand. In contrast to the natural gyrotropic medium in the magnetoactive medium, the absorbing specimen has the PA signal pattern of more complex nature at oppositely directed interaction of waves. The prognosticated PA signal suppression effect, when the intensity I_0 of one or another interacting beams changes, may be total or partial (Fig. 4 and 5). At the point of extreme the PA signal phase leaps at 180 degrees (Fig. 6). The position of the PA signal response minimal amplitude is significantly influenced by the thermal impedances ratio of the magnetoactive structure layers (Fig. 5). The effect of PA signal total or partial attenuation may be explained by the interference of backward heat waves inside the two-layer medium shifting the temperature field maximum from the specimen gas detection limit into the specimen to a distance which is farther apart than its thermal diffusion. It is the reason why the effective excitation does not take place. When the intensity of the light wave changes to the point where the maximum temperature field amplitude shifts to a distance equal to or less than the thermal diffusion length and there PA signal increases.

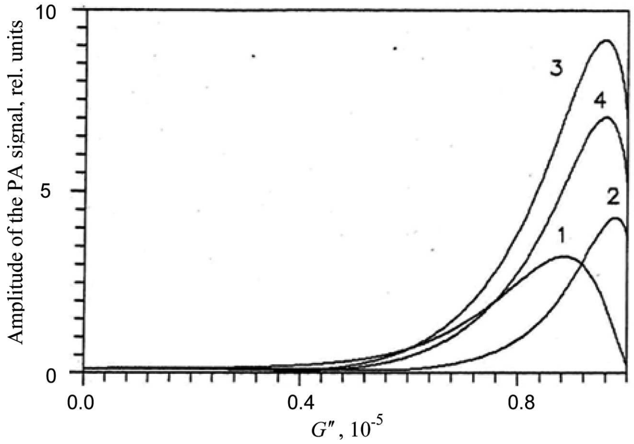

Fig. 3. PA signal amplitude dependence on imaginary part of magnetic gyration parameter for different initial phases of interacting light waves; ($\Delta\varphi$, radians) 1 – $\Delta\varphi = 0$; 2 – $\Delta\varphi = \pi/4$; 3 – $\Delta\varphi = \pi/2$; 4 – $\Delta\varphi = \pi$

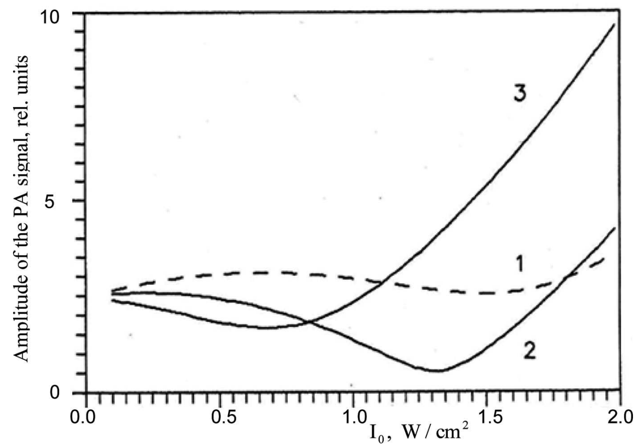

Fig. 4. PA signal amplitude dependence on intensity I_0 of one or another cross-interacting beam for different the initial phases; ($\Delta\varphi$, radians) 1 – $\Delta\varphi = 0$; 2 – $\Delta\varphi = \pi/4$; 3 – $\Delta\varphi = \pi/2$ ($S = 30.6$)

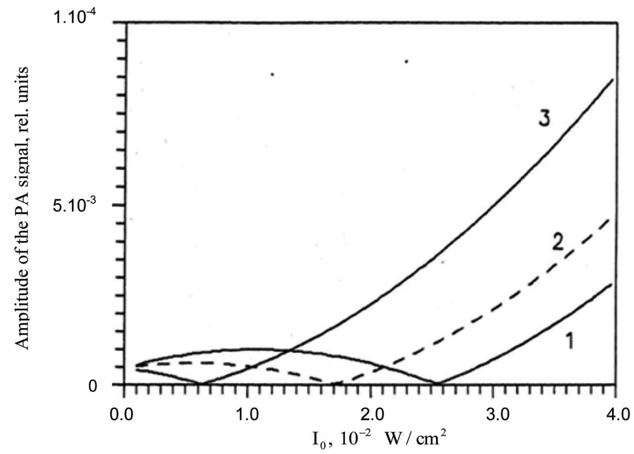

Fig. 5. PA signal amplitude dependence on imaginary part of intensity I_0 of one or another cross-interacting beam for different initial phases; ($\Delta\varphi$, radians) 1 – $\Delta\varphi = 0$; 2 – $\Delta\varphi = \pi/4$; 3 – $\Delta\varphi = \pi/2$ ($S = 3.9$)

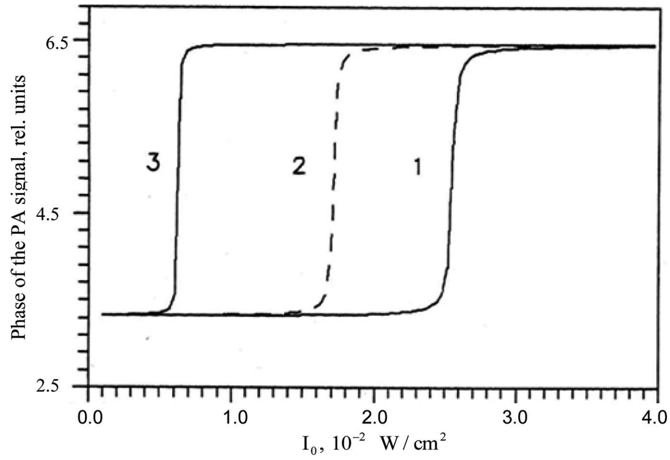

Fig. 6. PA signal phase dependence on imaginary part of intensity I_0 of one or another cross-interacting beam for different initial phases of interacting light waves; ($\Delta\varphi$, radians) 1 – $\Delta\varphi = 0$; 2 – $\Delta\varphi = \pi/4$; 3 – $\Delta\varphi = \pi/2$ ($S = 30.6$)

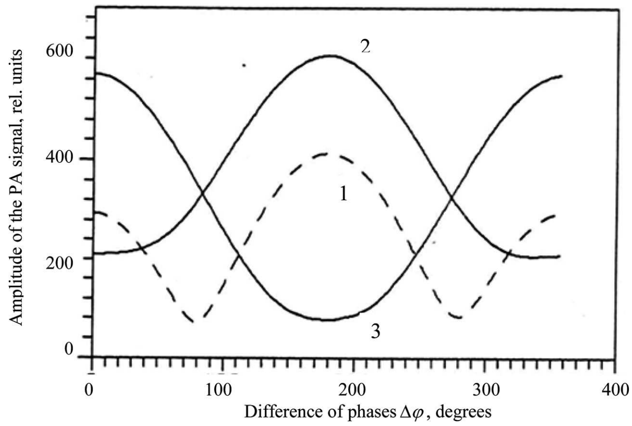

Fig. 7. PA signal amplitude dependence on different initial phases $\Delta\varphi$ of interacting light beams at different polarization ($\tau = 0$);$1 - \tau_0 = 0$; $2 - \tau_0 = +1$; $3 - \tau_0 = -1$

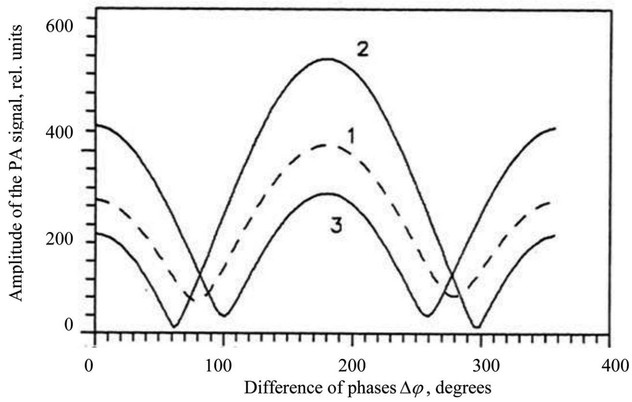

Fig. 8. PA signal amplitude dependence on different initial phases $\Delta\varphi$ of interacting light beams at different polarizations ($\tau_0 = 0$);$1 - \tau = 0$;$2 - \tau = +1$;$3 - \tau = -1$

Similar to the case of natural gyrotropic medium, the PA signal amplitude differs very significantly in the magnetoactive two-layer medium from the initial phases (Fig. 7 and 8), altering only the modulation depth. The polarization changes of interacting waves leads to an in-phase change in the signal amplitude (compare Fig.7 and 8).

These effects can be useful to produce devices for monitoring the amplitude-phase characteristics of the PA signal employing the methods based on the change of the external magnetic field intensity, the difference between the initial phases and the state of polarization of interacting light waves.

5. Conclusions

The accomplished study deals with the thermooptical sound generation in the magnetoactive two-layered medium during the tunnel interference of electromagnetic waves. the effect of the PA signal amplitude total suppression in response to the type of polarization of oppositely directed interaction waves, the difference of their initial phases, the intensity of one or two oppositely directed interaction beam have been studied.

Unlike the natural gyrotropic two-layer medium [5], the magnetoactive structure is characterized by a more efficient management of the useful resultant PA signal due to the change in the external magnetic field intensity which affects the real part of the magnetic gyration parameter G' by choosing appropriate different initial phases of the interacting waves (see Fig. 2). A significant PA response dependence on the magnetic circular dichroism G'' has been revealed. It has been shown that a distinguishing extreme observable on the graph of dependence $q = f(G'')$ is explained by two competing processes, the rate of change of energy volume dissipation, on the one hand, the interference redistribution of dissipating energy of the interacting waves, on the other hand,.

It is worth noting, that the finding permit to employ an effective method of monitoring the thermooptical sound generation in the magnetoactive structural component during tunnel interference of electromagnetic waves.

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