OPTICAL GENERATION OF SOUND BY AN ENSEMBLE OF INCLUSIONS REGULARLY ARRANGED IN A DIELECTRIC MATRIX

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The photo-acoustic effect in systems consisting of light-absorbing macroparticles regularly arranged in a dielectric matrix has been studied. Two limit cases of the incident light modulation have been examined. The advantage of the illumination with light pulses and the opportunity to use the photo-acoustic effect for diagnostics have been demonstrated.

Recently, studying the phenomenon of the optical generation of sound in various media considered as the primary element of a saser [1], the coherent emitter of sound, has become actual. The sound in the medium is generated as a result of the sequence of energy conversion processes: absorption of light by a substance — pulse heating of current carriers — cooling — generation of elastic waves owing to the illumination of the medium with modulated light (the photo-acoustic effect). Of special interest are materials that consist of macroparticles embedded into dielectric matrices which are transparent to light [2—4]. Such systems are promising media for the generation of sound, because, provided certain conditions, the efficiency of acoustic generation in them is considerably higher than that in continuous materials. Moreover, by selecting materials with necessary thermal and elastic characteristics, as well as by varying the dimensions of inclusions, the spectral composition of sound can be affected.

Of special interest are systems, where inclusions are arranged regularly. Such systems can be two- or three-dimensional. Zeolites [5, 6] and liquid crystals [7, 8] are the examples of dielectric matrices, where inclusions can be arranged regularly. The regular locations of inclusions and the capability of every inclusion to generate sound individually are important for the behavior of such systems. Provided that the arrangement of acoustic sources is regular, there is an opportunity, by varying the sound frequency and the intersource space interval, to synchronize the acoustic emission and to achieve a coherent sound signal emitted by such a specimen. For this purpose, a number of tasks are to be solved, one of which is finding the sound signal generated by all regularly placed inclusions at an arbitrary point of the specimen.

This work aimed at determining the shape of a sound wave at an arbitrary point of the matrix in the case where sound-generating inclusions are arranged regularly in a plane.

In order to solve the problem, consider the system which consists of semiconducting inclusions embedded into a dielectric matrix. They are located in a single plane to form a square lattice. The width of the energy gap for clusters, E_g^i, is supposed narrower than that for matrix electrons, E_g^m. The system is illuminated with a laser-generated flux

$$I = I_0 f(t) \tag{1}$$

which is directed perpendicularly to the plane, where the clusters are located; $f(t)$ is the modulation function which will be specified in due course.

Suppose that the energy of a laser emission quantum satisfies the condition $E_g^i < \hbar\omega < E_g^m$, so that the matrix is transparent to light, and only intrinsic nonequilibrium current carriers in the semiconducting material are excited. A temperature wave propagates in the matrix, which leads to the sound generation. Let us determine the shape of a sound wave in the matrix at a distance z_0 from the cluster plane.

Long-wave acoustic vibrations of the insulator are described by the displacement vector $\vec{u}(\vec{r}, t)$ which satisfies the equation

$$\rho \frac{\partial^2}{\partial t^2} u_i = \sum_{j=1}^{3} \frac{\partial}{\partial x_j} \sigma_{ij}, \tag{2}$$

where ρ is the density of the medium, and σ_{ij} are the components of its stress tensor. Taking the temperature expansion into account, σ_{ij} looks like

$$\sigma_{ij} = k \left[\sum_{\alpha} \varepsilon_{\alpha\alpha} - \beta (T^m - T^0) \right] \delta_{ij} +$$

$$+2\mu\left[\varepsilon_{ij}-\frac{1}{3}\delta_{ij}\sum_{\alpha}\varepsilon_{\alpha\alpha}\right]. \qquad (3)$$

In this formula, k and μ are the uniform compressibility and shear moduli, respectively; β is the coefficient of thermal expansion; $T^m(t,\vec{r})$ is the temperature of the matrix at the point $\vec{r}$ and the time t; T_0 is the matrix temperature in the absence of a light flux; and

$$\varepsilon_{ij}=\frac{1}{2}\left(\frac{\partial}{\partial x_j}u_i+\frac{\partial}{\partial x_i}u_j\right) \qquad (4)$$

are the components of the strain tensor.

Let us classify the acoustic vibrations according to whether they are longitudinal or transverse, with the velocities $c_L=\sqrt{\frac{3k+4\mu}{3\rho}}$ and $c_T=\sqrt{\frac{\mu}{\rho}}$, respectively, and write down the displacement vector in the form

$$\vec{u}=\vec{u}_L+\vec{u}_T, \qquad \mathrm{rot}\vec{u}_L=0, \qquad \mathrm{div}\vec{u}_T=0. \qquad (5)$$

Then, from formulae (2)—(5), we obtain

$$\Delta\vec{u}_L-\frac{1}{c_L^2}\frac{\partial^2\vec{u}_L}{\partial t^2}=\frac{k\beta}{\rho c_L^2}\vec{\nabla}\delta T^m \qquad (6)$$

for longitudinal vibrations, where the notation $\delta T^m=T^m-T_0$ was introduced. Similarly, for transverse vibrations,

$$\Delta\vec{u}_T-\frac{1}{c_T^2}\frac{\partial^2\vec{u}_T}{\partial t^2}=0. \qquad (7)$$

Nanoclusters become heated up almost instantaneously. Therefore, one may assume that, owing to the thermal expansion, the nanocluster radius depends on the temperature variation stimulated by the absorption of the incident light:

$$R(t)=a(1+\beta\delta T^m(t,r=a)). \qquad (8)$$

Presenting the displacement vector of longitudinal acoustic vibrations in the form

$$\vec{u}_L=\vec{\nabla}\Psi, \qquad (9)$$

we obtain the following equation to determine the scalar function Ψ:

$$\Delta\Psi-\frac{1}{c_L^2}\frac{\partial^2\Psi}{\partial t^2}=\frac{k\beta}{\rho c_L^2}\delta T^m. \qquad (10)$$

The solution of Eq. (10) consists of two terms: the solution of the corresponding homogeneous equation with the boundary condition that stems from the temperature dependence of cluster dimensions (8) and the partial solution of the inhomogeneous equation (10). The former is responsible for the pulsating mechanism of the sound generation, which is connected with the oscillations of cluster dimensions under the action of light with modulated intensity; and the latter for the acoustic generation in the matrix through the thermoelastic mechanism, which is stimulated by a modulated thermal flux that flows from clusters into the matrix and generates acoustic vibrations in it owing to its thermal expansion. The pulsating mechanism is capable to generate both longitudinal and transverse acoustic vibrations. Since the equation for the transverse displacement is homogeneous, the thermoelastic mechanism does not generate transverse vibrations. Below, we consider only the generation of sound waves in the matrix that is connected with the pulsating mechanism.

The solution of the homogeneous equation, corresponding to Eq. (10), looks like

$$\Psi_P(t,r)=\frac{1}{r}\Phi\left(t-\frac{r-a}{c_L}\right), \qquad (11)$$

where a is the cluster radius, and Φ is an arbitrary function, the specific form of which is determined making use of the boundary condition obtained from Eq. (8):

$$(\vec{u}_L\frac{\vec{r}}{r})=\frac{\partial\Psi(t,r=a)}{\partial r}=a\beta\delta T^m(t,r=a). \qquad (12)$$

For the potential of the pulsating mechanism of the sound generation, we obtain the solution

$$\psi_P(t,r)=-\frac{a^2}{r}c_L\beta\exp\left[-\frac{c_L}{a}\left(t-\frac{r-a}{c_L}\right)\right]\times$$

$$\times\int\limits_{-\infty}^{t-\frac{r-a}{c_L}}\exp\left(\frac{c_L}{a}\tau\right)\delta T^i(\tau)d\tau, \qquad (13)$$

where the notation $\delta T^i(t)=\delta T^m(t,r=a)$ is used. At large distances from the cluster ($r\gg a$, the long-distance field asymptote) and low frequencies of the light flux modulation ($\omega<\frac{c_L}{a}$), expression (13) can be simplified as

$$\psi_P(t,r)=-\frac{a^3}{r}\beta T^i\left(t-\frac{r}{c_L}\right). \qquad (14)$$

Expression (14) determines the contribution of an individual cluster to the generation of longitudinal acoustic vibrations (caused by the pulsation of cluster dimensions) at a large distance from it. In order to take the acoustic emission of the whole ensemble of nanoclusters into account, one should substitute r in formula (14) by $|\vec{r}-\vec{r}_i|$, where $\vec{r}_i$ is the position of the i-th cluster center, and sum up over all the clusters. Then, the resulting signal at the point of observation looks like

$$F(t,r) = -a^3\beta \sum_i \frac{T^i\left(t - \dfrac{|\vec{r}-\vec{r}_i| - a}{c_L}\right)}{|\vec{r}-\vec{r}_i|}. \quad (15)$$

If we denote the constant of the square lattice, the points of which are occupied by clusters, as d_0, then $\vec{r}_i = (d_0 n_i, d_0 m_i, 0)$, where n_i and m_i are integers. In this case, $|\vec{r}-\vec{r}_i| = d_0\sqrt{n_i^2+m_i^2+z^2}$, where $z = \dfrac{z_0}{d_0}$. As a result, we obtain

$$F(t,r) = -\frac{a^3\beta}{d_0}\sum_{n_i=1}^{\infty}\sum_{m_i=1}^{\infty}\frac{T^i\left(t - \dfrac{d_0}{c_L}\sqrt{n_i^2+m_i^2+z^2}\right)}{\sqrt{n_i^2+m_i^2+z^2}}. \quad (16)$$

Provided that the indices n_i and m_i in Eq. (16) varied continuously, one can switch from summation to integration. In this case, any information concerning the structure of the illuminated system would be lost. Therefore, while switching from the sum to the integral, we take advantage of the exact Poisson formula, similarly to what was done at developing the theory of de Haas—van Alphen oscillations [9]. The Poisson formula is written down in the form

$$\sum_{n=1}^{\infty} f(n) = \int_0^{\infty} f(x)dx + 2\sum_{s=1}^{\infty}\int_0^{\infty} f(x)\cos(2\pi s x)dx. \quad (17)$$

Substituting the notations of the indices n_i and m_i by x and y, respectively, and applying formula (17), we obtain

$$F(t,r) = -\frac{a^3\beta}{d_0}\int_0^{\infty}\frac{T^i\left(t - \dfrac{d_0}{c_L}\sqrt{x^2+y^2+z^2}\right)}{\sqrt{x^2+y^2+z^2}}dxdy \times$$

$$\times \left[1 + 2\sum_{s=1}^{\infty}\cos(2\pi s x)\right]\left[1 + 2\sum_{k=1}^{\infty}\cos(2\pi k y)\right]. \quad (18)$$

By integrating over the angular variable in the cylindrical coordinate system, the axis of which coincides with the direction of illumination, we obtain

$$F(t,r) = F_0(t,r) - \frac{8\pi a^3\beta}{d_0}\int_0^{\infty}\frac{\rho d\rho T^i\left(t - \dfrac{d_0}{c_L}\sqrt{\rho^2+z^2}\right)}{\sqrt{\rho^2+z^2}} \times$$

$$\times \left[\sum_{k=1}^{\infty} J_0(2\pi k\rho) + \sum_{k=1}^{\infty}\sum_{s=1}^{\infty} J_0(2\pi\sqrt{k^2+s^2}\,\rho)\right], \quad (19)$$

where

$$F_0(t,r) = -\frac{2\pi a^3\beta}{d_0}\int_0^{\infty}\frac{\rho d\rho T^i\left(t - \dfrac{d_0}{c_L}\sqrt{\rho^2+z^2}\right)}{\sqrt{\rho^2+z^2}} \quad (20)$$

is the resulting signal at a particular point taking no oscillations into account, and J_0 the Bessel function of the zeroth order. Making the substitution

$$u = t - \frac{d_0}{c_L}\sqrt{\rho^2+z^2}, \quad (21)$$

we reduce expression (19) to

$$F(t,r) = -\frac{8\pi a^3\beta c_L}{d_0^2}\left[\sum_{k=1}^{\infty}\int_{-\infty}^{t-\frac{z_0}{c_L}} J_0\left(2\pi k\rho(u)\right)T^i(u)du + \right.$$

$$\left. + \sum_{s=1}^{\infty}\sum_{k=1}^{\infty}\int_{-\infty}^{t-\frac{z_0}{c_L}} J_0\left(2\pi\sqrt{k^2+s^2}\,\rho(u)\right)T^i(u)du\right] + F_0(t,r), \quad (22)$$

and expression (20) to

$$F_0(t,r) = -\frac{2\pi a^3\beta c_L}{d_0^2}\int_{-\infty}^{t-\frac{z_0}{c_L}} T^i(u)du, \quad (23)$$

where, in accordance with Eq. (21),

$$\rho(u) = \sqrt{\frac{c_L^2}{d_0^2}(t-u)^2 - z^2}. \quad (24)$$

The dynamics of an inclusion was shown in works [2, 4] to be governed by its temperature, so that

$$T^i(t) = \frac{\sigma I}{4\pi a K^m} = \frac{\sigma I_0}{4\pi a K^m} f(t), \tag{25}$$

where σ is the cross-section of absorption, and K^m the heat conductivity of the matrix.

In order to find the temperature, the modulation function $f(t)$ has to be specified. It is reasonable to examine two limit cases of modulation, namely, a smooth modulation (with a low frequency ω) and a modulation by either a single δ-like pulse or a sequence of such pulses. So, let the function $f(t)$ look like

$$f(t) = \begin{cases} \delta(t) \\ 1 + \cos(\omega t) \end{cases}. \tag{26}$$

Consider the case where a short laser pulse, which can be approximated by the δ-function, illuminates the system of semiconducting nanoclusters embedded into a dielectric matrix. It was shown in work [4] that, if the system is illuminated by a short light pulse, the pulse of temperature may approximately be regarded as possessing the same shape as the laser pulse has. Therefore, it is possible to take $f(u) = \delta(u)$.

If the system is illuminated with a single δ-like pulse, then, taking into account Eq. (24), expressions (22) and (23) become of the forms

$$F(t,r) = -\frac{2a^2\beta c_L \sigma I_0}{K^m d_0^2}\left[\sum_{k=1}^{\infty} \int_{-\infty}^{t-\frac{z_0}{c_L}} J_0\left(2\pi k \rho(u)\right)\delta(u)du + \right.$$
$$\left. + \sum_{s=1}^{\infty}\sum_{k=1}^{\infty} \int_{-\infty}^{t-\frac{z_0}{c_L}} J_0\left(2\pi\sqrt{k^2+s^2}\,\rho(u)\right)\delta(u)du\right] + F_0(r,t), \tag{27}$$

and

$$F_0(r,t) = -\frac{a^2\beta c_L \sigma I_0}{2K^m d_0^2} \int_{-\infty}^{t-\frac{z_0}{c_L}} \delta(u)du, \tag{28}$$

respectively.

The potential–displacement coupling is expressed by formula (9). Since the system possesses the axial symmetry, the gradient can be substituted by the operator $\frac{d}{dz_0}$. Changing over to the resulting displacement, we obtain

$$U = \frac{dF}{dz_0} = U_0 + U_1, \tag{29}$$

where

$$U_0 = U_0(r,t) = \frac{dF_0}{dz_0} = \frac{a^2\beta c_L \sigma I_0}{2K^m d_0^2}\delta\left(t - \frac{z_0}{c_L}\right) \tag{30}$$

is the resulting displacement with no oscillations being taken into account, i.e. in the case where the double sum (16) is replaced by a double integral, not using the Poisson formula;

$$U_1 = \frac{4\pi a^2\beta\sigma\ I_0 z_0}{K^m d_0^2\sqrt{(c_L t)^2 - z_0^2}}\left[\sum_k k J_0\left(\frac{2\pi k\sqrt{(c_L t)^2 - z_0^2}}{d_0}\right) + \right.$$
$$\left. + \sum_s\sum_k \sqrt{k^2+s^2}\, J_0\left(\frac{2\pi\sqrt{k^2+s^2}\sqrt{(c_L t)^2 - z_0^2}}{d_0}\right)\right] \tag{31}$$

are the oscillatory terms which are of interest for us; and J_1 is the Bessel function of the first order. Let us introduce the notations $X = \frac{c_L t}{d_0}$ for the reduced time and $z = \frac{z_0}{d_0}$ for the distance from the point of observation to the plane in terms of the lattice constant units (this distance will be called the "depth" below). Figures 1,*a, b, c* expose the dependences of the dimensionless quantity

$$U_1^* = \frac{z}{\sqrt{X^2 - z^2}}\left[\sum_{k=1}^{P} k J_0\left(2\pi k\sqrt{X^2 - z^2}\right) + \right.$$
$$\left. + \sum_{s=1}^{\frac{P}{\sqrt{2}}}\sum_{k=1}^{\frac{P}{\sqrt{2}}} \sqrt{k^2+s^2} J_0\left(2\pi\sqrt{k^2+s^2}\ \sqrt{X^2 - z^2}\right)\right], \tag{32}$$

on X at several depths z. Here, P is the number of oscillatory modes which have been taken into account (there is no reason to consider all the modes; suffice it to make allowance for some of the lowest ones). The analysis of the plots brings us to the conclusion that the contribution of vibrations becomes weaker as the depth increases, i.e. the regular arrangement of sound wave sources affects the resulting displacement and, therefore, the sound intensity within the range of depths that are comparable with the lattice constant. At substantial

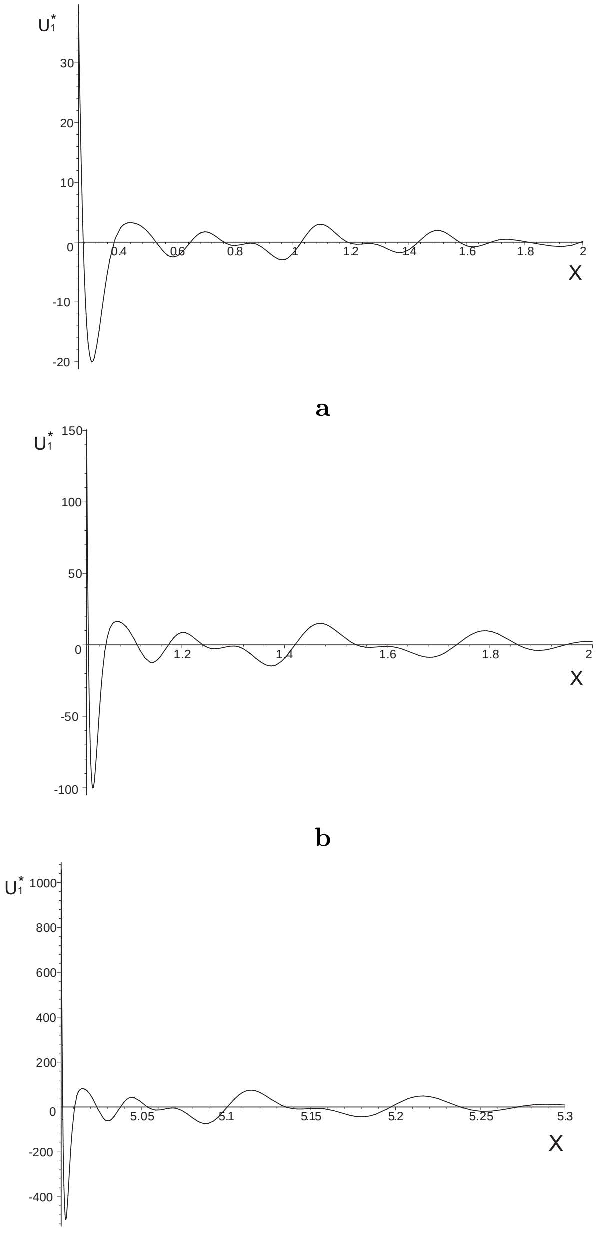

Fig. 1. Time dependence of the resulting displacement $U_1^*(X)$. The time X is expressed in terms of $\frac{d_0}{c_L}$ units, and the displacement U_1^* in terms of $\frac{K^m d_0^2}{4\pi a^2 \beta\sigma I_0}$ ones. The number of oscillatory modes $P = 5$. The distance to the point of observation $z = 0.2$ (a), $z = 1$ (b), $z = 5$ (c)

depths, vibrations are unobservable, so that the case of a continuous plane that emits sound is realized. The time

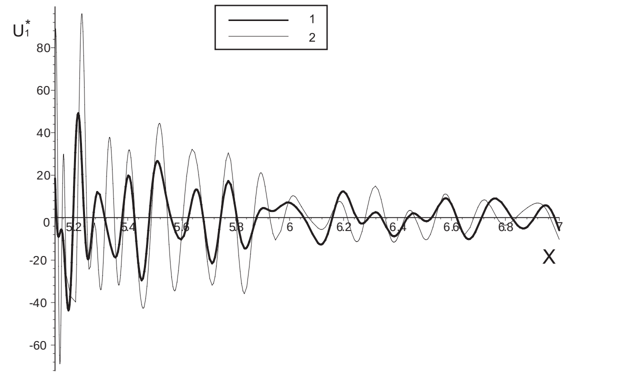

Fig. 2. Dependences $U_1^*(X)$ for 1 (*1*) and 2 (*2*) pulses of illumination. $P = 5$, and $z = 5$

of vibration damping is reciprocal to the depth. This testifies that an appreciable contribution to the acoustic generation is made by a bounded area of the plane, where the inclusion is located.

Qualitatively, the plots are similar. In each plot, the first maximum, which occurs at the time reference point $X = z$, is followed by oscillations that contain a sequence of local maxima. This makes possible to forecast the synchronization and amplification of the sound wave intensity, provided that the system is illuminated with a series of short δ-like pulses. For this purpose, the periodicity of pulses should be synchronized with that of the appearance of the local maxima of oscillations. For a sequence consisting of at least 3 to 4 pulses, this task is feasible, in principle.

Figure 2 compares the $U_1^*(X)$ dependences on illuminating the system by one or two pulses. One can easily see that the two-pulse illumination enhances the sound generation by approximately a factor of two. There is an opportunity to achieve the synchronization for a sequence of 3 to 4 pulses.

Thus, modulating the flux of light, which is used to illuminate the system, by a sequence of short δ-like pulses, one can amplify the oscillations of the generated light wave intensity. On the other hand, the dependence of the sound generation on the system geometry opens an opportunity to apply the photo-acoustic effect for diagnostics.

Now, consider the case of illuminating the system of semiconducting nanoclusters embedded into a dielectric matrix with a modulated light flux, the intensity of which is described by a harmonic function. Then, making use of Eq. (25) and examining only the oscillating component of the incident light flux, we may take

$$f(u) = \cos(\omega u), \tag{33}$$

where ω is the modulation frequency. After easy transformations, we obtain the following expression for the resulting displacement:

$$U=\frac{a^2\beta\sigma I_0}{2d_0^2K^m}z\Bigg[\int\limits_{-\infty}^{X-z}Bdv+$$

$$+4\sum_{k=1}^{\infty}\int\limits_{-\infty}^{X-z}BJ_0\left(2\pi k\sqrt{(X-v)^2-z^2}\right)dv+$$

$$+4\sum_{s=1}^{\infty}\sum_{k=1}^{\infty}\int\limits_{-\infty}^{X-z}BJ_0\left(2\pi\sqrt{k^2+s^2}\sqrt{(X-v)^2-z^2}\right)dv\Bigg], \quad (34)$$

where $\Omega=\dfrac{\omega d_0}{c_L}$ and

$$B=\frac{\cos(\Omega v)}{(X-v)^2}-\Omega\frac{\sin(\Omega v)}{(X-v)}. \quad (35)$$

For the guess values $d_0\approx10^{-6}$ m, $c_L\approx10^3$ m/s, and $\omega\approx10^3$ Hz, we obtain $\Omega\ll1$, so that the second term in expression (35) can be neglected. Additionally, we may take $\cos(\Omega v)$, as a slowly varying function, outside each integral sign in Eq. (34) and substitute it by $\cos[\Omega(X-z)]$. (Note that these speculations are valid only for the modulation frequencies $\omega\ll c_L/d_0$.) In this case, it is also worthwhile dealing with several lowest modes. We confine ourselves to five lowest oscillatory modes, i.e. take $P=5$ and ultimately obtain

$$U=\frac{a^2\beta\sigma I_0}{2d_0^2K^m}z\cos(\Omega(X-z))\times$$

$$\times\Bigg[1+4\sum_{k=1}^{5}\int\limits_{-\infty}^{X-z}\frac{J_0\left(2\pi k\sqrt{(X-v)^2-z^2}\right)}{}(X-v)^2dv+$$

$$+4\sum_{s=1}^{5}\sum_{k=1}^{5}\int\limits_{-\infty}^{X-z}\frac{J_0\left(2\pi\sqrt{k^2+s^2}\,\sqrt{(X-v)^2-z^2}\right)}{(X-v)^2}dv\Bigg]. \quad (36)$$

Taking the long-distance asymptotic expansion of the Bessel function

$$J_0(x)\sim\sqrt{\frac{2}{\pi x}}\cos\left(x-\frac{\pi}{4}\right)+O(x^{-\frac{3}{2}})$$

into account, we see that the oscillatory terms in expression (34) decay as $X^{-\frac{5}{2}}$. This means that the temporal dependence of the resulting displacement looks like

$$U=\frac{a^2\beta\sigma I_0}{2d_0^2K^m}z\cos(\Omega(X-z)). \quad (37)$$

The contribution of oscillatory terms is very small, and the amplification of the signal is impossible.

Thus, the results of this work demonstrate that the regular arrangement of semiconducting light-absorbing inclusions in a dielectric matrix, which is transparent to light, stimulates the emergence of oscillating components in the optically generated sound. One of two mechanisms of acoustic generation – the pulsating one — has been considered. Oscillations have been analyzed in two limit cases of signal modulation: the smooth low-frequency harmonic modulation and the modulation with a short δ-like pulse. It has been shown that,

— if the system is illuminated with a sequence of δ-like pulses, the synchronization and amplification of the sound can be achieved;

— in order to register sound waves, it is more convenient to place the detector at short distances from the plane, where inclusions are regularly arranged in the form of a lattice, because the effect indicated above is more pronounced at depths that do not exceed the lattice constant;

— the photo-acoustic effect can serve as the basis for the sound wave generation and make diagnostic researches possible, because, knowing the thermal and elastic characteristics of both the matrix and the inclusions, as well as the shape of the function that modulates the incident light flux, and analyzing the shape and the intensity of the generated acoustic waves, the conclusions concerning the structure of the system under investigation can be drawn.

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ОПТИЧНА ГЕНЕРАЦІЯ ЗВУКУ АНСАМБЛЕМ ПЕРІОДИЧНО РОЗМІЩЕНИХ ВКЛЮЧЕНЬ У ДІЕЛЕКТРИЧНІЙ МАТРИЦІ

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Р е з ю м е

Проведено теоретичне дослідження фотоакустичного ефекту в системах, що складаються з періодично розміщених у діелектричній матриці поглинаючих світло макрочастинок. Розглянуто два граничні випадки модуляції падаючого світлового потоку. Показано переваги імпульсного опромінення системи та можливість використання фотоакустичного ефекту для діагностики матеріалів.