PHOTOTHERMAL TRANSFORMATION OF ENERGY IN HETEROGENEOUS COMPOSITE STRUCTURES: THE ANALYSIS OF PHOTODEFLECTIONAL RESPONSE

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The purpose of this work is to consider a mathematical model of photodeflection signal appearance in a composite object, a dielectric matrix with inclusions from a conducting material, under the action of a modulated electromagnetic radiation with the Gauss profile of its intensity. The analysis of characteristics of the photodeflection response of the non-uniform medium allows estimating the physical parameters describing the properties of various non-uniform structures.

1. Peculiarities of the Description of Composites

Recently, compound or composite samples are more and more often used alongside with classical materials. Composite materials are metal and non-metallic matrices (basis) with the given distribution of hardeners (fibers, disperse particles, etc.) in them; in this case, composite materials allow to efficiently use individual properties of components. Combining the volumetric contents of components, it is possible to purposefully obtain composite materials with required values of strength, thermal stability, the modulus of elasticity, and abrasive stability and to create composite materials with necessary magnetic, dielectric, radioabsorbing, and other special physical and operational properties.

As an example of composite (disperse) media, we mention Ti-based ceramics, magnetic cores from a pressed powder, "artificial dielectrics", and radioabsorbing materials. Such materials are composed from the dielectric matrix with alien absorbing particles dispersed in it with volumetric concentration $\theta \approx 0.1 \div 0.5$. Just such composite materials will be an object of our research. Electric properties of such a compound sharply differ from those of the basic (binding) dielectric. As a matter of fact, these "artificial dielectrics" are a macroscopical reproduction of usual dielectrics. One of the fundamental formulas of dielectrics physics – the formula of Clausius–Mossotti – has been originally obtained within the model of a dielectric as the totality of conducting balls separated from one another by the isolating media [2]. Their main feature is the expressed influence of a ratio of the radiation wavelength λ or the "skin-layer" depth δ and the particle radius a on the cross-section of absorption of a separate particle [3] and on the absorbing properties of a material as a whole [2].

For a composite medium, the concepts of volumetric parameters ε and μ are introduced. These parameters allow to get the correct results on the application of Maxwell's equations to the macroscopical area of such a material. Here, a volume is considered to be macroscopical if its size is much more than the average distance between particles of the filler. In addition, the wavelength in a composite material is considered to be so large that it is possible to neglect fast changes of the field on such distances. In the areas, whose size is very small, fast changes of the field from a point to a point are inevitable, especially near particles, and Maxwell's equations cannot be fair inside of the composite media if only it is not treated as homogeneous. Volumetric parameters ε and μ do not characterize completely such substance and are suitable for the description of its properties only as a volume on a whole [4].

The questions about the laser radiation absorption by such media require a detailed consideration. Particularly, the laws of transformation of the electromagnetic field energy into heat in the composite media have learnt insufficiently.

In this connection, this work is devoted to the investigation of the dissipative features of composite media by the method of laser photodeflection spectroscopy with the purpose of the analysis of thermophysical and dielectric parameters of the non-uniform samples.

2. Peculiarities of the electromagnetic energy absorption in a disperse medium

Let's consider features of the electromagnetic energy absorption in a disperse media. The amount of heat released in a single particle with volume V_i for unit time in the field of a plane electromagnetic wave with the intensity I is equal to $Q = I\sigma_s$, where σ_s is the absorption cross-section of a separate particle. In the case of conducting particles, of which the relation $\delta \ll a$ is characteristic, the following expression for the imaginary part of the magnetic polarizability [3] is valid:

$$\alpha''_M = \frac{1}{20\pi}\left(\frac{a}{\delta}\right)^2 = \frac{a^2\gamma\omega}{10c^2} \ll \alpha''_E. \quad (1)$$

Here, α''_E – the imaginary part of the electric polarizability of the particle; ω – light frequency; c – light velocity; and γ – specific conductivity of a particle. The electric polarizability $\alpha_E = \alpha'_E + i\alpha''_E$ of a particle of any form is determined by the permeabilities of substances of the particle, $\varepsilon_E = \varepsilon'_E + i\varepsilon''_E$, and the medium (matrix) surrounding it, ε_m.

In the case of well conducting particles of metals and alloys ($\delta \ll a$, $|\theta| \gg 1$), the radiation absorption has mainly "magnetic" character – $\alpha''_M \gg \alpha''_E$ even at $\mu_i = 1$, which is not always considered on the development of composite materials, whose structure includes powders of nonmagnetic materials and alloys.

Formula (1) describes the dependence of the polarizability of a single particle on its sizes. For the description of electric and magnetic parameters of real composite materials, it is necessary to consider the dipole interaction of the ensemble of spherical particles uniformly dispersed with the volumetric concentration θ in the dielectric matrix. By analogy to the known formula of Clausius–Mossotti [5], we write down

$$\frac{\mu^* - \mu_m}{\mu^* + 2\mu_m} = \frac{4\pi}{3} N V_i \alpha_M, \quad (2)$$

where μ^* – effective magnetic permeability of the disperse medium, μ_m – magnetic permeability of the matrix, and N – number of particles in unit volume of the material. By performing the necessary transformations and substitutions in expression (2), we get finally:

$$\mu^* = \mu_M\left(1 + \frac{3\theta}{\frac{\mu_P + 2\mu_M}{\mu_P - \mu_M} - \theta}\right) = \mu_M\left(\frac{1 + 2\theta M}{1 - \theta M}\right). \quad (3)$$

The expression for the effective permeability ε^* will become identical to (3), if we make the formal substitution $\mu \to \varepsilon$, $M \to L$:

$$\varepsilon^* = \varepsilon_M\left(1 + \frac{3\theta}{\frac{\varepsilon_P + 2\varepsilon_M}{\varepsilon_P - \varepsilon_M} - \theta}\right) = \varepsilon_M\left(\frac{1 + 2\theta L}{1 - \theta L}\right). \quad (4)$$

The parameters L and M describing the electric and magnetic polarizabilities are, respectively, equal to

$$L = \frac{\varepsilon_P - \varepsilon_M}{\varepsilon_P + 2\varepsilon_M}, \quad M = \frac{\mu_P - \mu_M}{\mu_P + 2\mu_M} \quad (5)$$

Thus, though in a less strict manner, we have obtained the known formulas for the effective parameters ε^* and μ^* deduced by Levin [4].

It is necessary to note that formulas (4) and (5) do not take a number of the features of real composite materials such as the difference of a form of particles from the spherical one, a randomness of their orientation, a dispersion of particles by size [6], and the formation of agglomerates into account. Moreover, the type of the volumetric distribution of particles, the anisotropic character of the distribution, and heterogeneity of particles themselves are not described as well. At the given stage of the work, we will restrict ourselves to the consideration of an ensemble of homogeneous spherical particles uniformly dispersed in the volume of the dielectric matrix.

On the basis of expressions (4) and (5), we analyzed the dependence of the dielectric permeability of composite materials on the volumetric concentration θ of particles of the powder. The result of calculations testifies that ε^* strongly increases with the concentration of dispersed particles. If we neglect losses in the dielectric matrix (at $\mathrm{Im}(\varepsilon_m) = 0$ and $\mathrm{Im}(\varepsilon^*) = 0$), the amount of heat released in unit volume of the disperse medium for unit time is defined by the formula [3]

$$Q_1 = \frac{\omega}{8\pi}\mu'' H^2, \quad (6)$$

where $\mu'' = \mathrm{Im}(\mu^*)$, and H – real amplitude of the magnetic field intensity in the medium. From expression (6) we find the amount of heat Q released in one dispersed particle:

$$Q = Q_1\frac{V_i}{\theta} = \frac{\omega}{6}\frac{a^3}{\theta}\mu'' H^2. \quad (7)$$

The maximum of the radiation absorption corresponds to an extremum of the function $\mathrm{Im}(F(\theta))$, where the function F characterizes a degree of the filling of the disperse sample. The quantity H is defined from the solution of the electrodynamic problem corresponding to the geometry of a specific sample made from a material with the parameters ε^* and μ^*.

On the basis of the solution of the system of equations, we calculated the profile of the temperature arising at the absorption of the exciting electromagnetic radiation modulated with a frequency Ω by the nonuniform object under study.

Then we calculated the normal and transversal components of the deviation of a trial beam [7] above the surface of the investigated object. For the normal component of the deviation angle, we have the expression

$$\Phi(\mathbf{r},t) = -\frac{1}{n_0}\frac{dn_0}{dT}\int\limits_z \frac{dT(\mathbf{r},t)}{dy}dz\,. \tag{8}$$

The transversal component of the deviation of a trial beam is as follows:

$$\Phi_{\rm tr}(\mathbf{r},t) = \frac{1}{n_0}\frac{dn_0}{dT}\int\limits_y \frac{dT(\mathbf{r},t)}{dz}dy\,. \tag{9}$$

In expressions (8) and (9), n_0 – refractive index of the detector medium, and $T(\mathbf{r},t)$ – temperature in the corresponding media which is set by the system of equations of heat conductivity.

The final expressions (8), (9), and the formulas for the temperature field above the surface of the investigated object, are a basis for numerical calculations. The integration of the mentioned expressions is made numerically with the use of the method of finite differences. The use of the implicit scheme of the method of finite differences allowed us to somewhat reduce the volume of calculations, which optimizes the work of the program in the course of time.

The example of a graphic visualization of the results of calculations of a photorefraction response is presented in Fig. 1. As follows from the presented plot, the maximum of the normal component of the signal amplitude is at the distance slightly exceeding the radius of an exciting beam. The time dependence of the signal amplitude is set by the exciting radiation modulation.

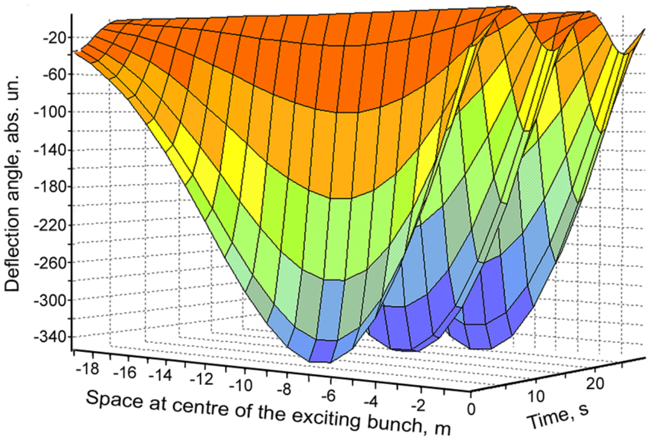

Fig. 1. Normal component of a photodeflection response near to the center of the exciting bunch

It is worth to note that the results of calculations of the dissipation of the electromagnetic radiation, temperature fields, and angles of deviation of the trial beam can be used not only in the case of the excitation of the sample under study by radiation of the optical range, but also for the exciting sources radiating in the radiorange (centimeter waves). The analysis of the literature data shows that it is possible to fabricate "artificial" dielectrics possessing rather high values of the dielectric permeability ($\varepsilon \approx 60$) and small dielectric losses in the field of centimeter waves, if powder-like metal particles are enough small and possess the high electric polarizability. The relative simplicity of the use of the sources of radioemission opens additional prospects of the use of the methods of photodeflection spectroscopy in the analysis of parameters of nonuniform composite media.

In the present work, we have developed a mathematical model describing the process of occurrence of the photodeflection signal in a composite sample under the influence of the modulated electromagnetic radiation with the Gauss structure of the intensity.

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1. B.C. Forget and D. Fournier, in *Photothermal characterization of semiconductors, Progress in Photothermal and Photoacoustic Science and Technology: Vol. 4, Semiconductors and Electronic Materials*, edited by A. Mandelis and P. Hess (SPIE Optical Engineering Press, Bellingham, 2000), P.200.
2. A.A. Manenkov and A.M. Prokhorov, Uspekhi Fiz. Nauk **148**, 179 (1986).
3. L.D. Landau and E.M. Lifshits, *Electrodynamics of Continuous Media* (Pergamon Press, New York, 1984).

4. L.A. Levin, *Theory of Wave Guides* (Radio i Svyaz, Moscow, 1981) (in Russian).
5. H.C. van de Hulst, *Light Scattering by Small Particles* (Wiley, New York, 1957).
6. Yu.I. Petrov, *Physics of Small Particles* (Nauka, Moscow, 1982) (in Russian).
7. D. Fournier, A.C. Boccara, and J. Badoz, Appl. Opt. **21**, No.11, 74 (1982).
8. E.A. Galst'yan and A.A. Ravaev, Izv. Vuz. Radiophys. **30**, 1243 (1987).

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ФОТОТЕРМІЧНЕ ПЕРЕТВОРЕННЯ ЕНЕРГІЇ В НЕОДНОРІДНИХ КОМПОЗИТНИХ СТРУКТУРАХ: АНАЛІЗ ФОТОДЕФЛЕКЦІЙНОГО ВІДГУКУ

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Резюме

В роботі розглянуто математичну модель виникнення фотодефлекційного сигналу в композитному об'єкті: діелектрична матриця – включення з провідного матеріалу, під дією модульованого електромагнітного випромінювання з гаусовим профілем інтенсивності. Аналіз характеристик фотодефлекційного відгуку неоднорідного середовища дає змогу оцінити фізичні параметри, які описують властивості різних неоднорідних структур.