NONLINEAR ABSORPTION OF OPTICAL RADIATION ENERGY BY MICROPARTICLES IN A TRANSPARENT DIELECTRIC

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Nonlinear absorption of energy and thermal processes during interaction of optical radiation pulses with microparticles in a transparent dielectric are theoretically studied, taking into account temperature dependence of the thermal and optical parameters.

Much attention has been paid in recent years to thermal and optical processes during interaction of intense optical radiation with heterogeneous media containing small particles that absorb and scatter the radiation energy. This is connected with the need to study the interaction of optical radiation with transparent dielectrics containing absorbing microparticles [1-3], aerosols [4], heterogeneous biological tissues containing pigment particles [5], etc. Nonlinear absorption and scattering of incident radiation energy by a particle and by the thermal halo formed around the particle, heat exchange between the heated particles and the surrounding medium with nonlinear thermal conductivity, phase changes (melting), etc. are thereby taken into account. Studies of the interaction of radiation with optical materials in order to monitor their qualities have aroused particular interest. Such nondestructive methods are used for this as laser ultramicroscopy [3], study of radiation scattering by a microparticle [3, 6], and irradiation of microparticles (inclusions) heated by ultrashort radiation pulses [7], etc. A new method of nondestructive testing proposed in [8] is adiabatic calorimetry of optical materials heated by a radiation pulse with variable length, leading to nonlinear absorption of the pulse's energy by the microparticles in the material. In the present paper nonlinear energy absorption processes and heat exchange during interaction of optical radiation with absorbing microparticles in a transparent dielectric are theoretically examined. Comparison of the theoretically determined values of energy absorbed by microparticles of different sizes with the absorbed energy measured by calorimetry and solution of the reverse problem allows one in principle to determine the average size and concentration of the microparticles (inclusions) in the optical material.

Optical radiation with irradiance j_ε and wavelength λ falls on a spherical particle of radius r_0 located in a (dielectric) medium. The balance equation of the particle energy in the approximation of a uniformly preheated particle and ideal contact of the particle with the dielectric, taking into account radiation scattering by the thermal halo around the particle, has the form in the Rayleigh–Gans approximation [5, 9]:

$$\rho_0 V_0 c_0(T_0)\frac{dT_0}{dt} = \frac{1}{4}(1 - S_h) I_0 K_a S_0 - \bar{j}_\varepsilon S_0,$$

$$\bar{j}_\varepsilon = \bar{j}_T + \varepsilon_S \sigma (T_0^4 - T_\infty^4), \quad \bar{j}_T = -\varkappa \left.\frac{\partial T}{\partial r}\right|_{r=r_0}, \tag{1}$$

$$S_h = \pi k^4 \int_0^\pi (1+\cos^2\Theta)\sin\Theta d\Theta \left[\int_{r_1}^\infty dr r^2 (n_\lambda^2 - n_0^2)\, \frac{\sin\left(2kr\sin\frac{\theta}{2}\right)}{2kr\sin\frac{\theta}{2}}\right]^2.$$

The equation of nonlinear thermal conductivity for the medium surrounding the particle, in a spherical coordinate system with origin at the center of the particle, has the form [9]:

$$\rho c(T)\frac{\partial T}{\partial t} = \frac{1}{r^2}\frac{\partial}{\partial r}\left(\varkappa(T) r^2 \frac{\partial T}{\partial r}\right) + q(T). \tag{2}$$

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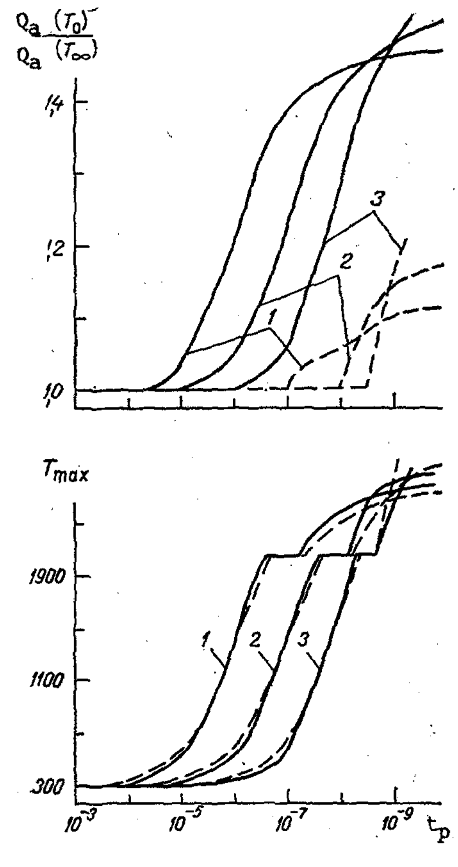

Fig. 1

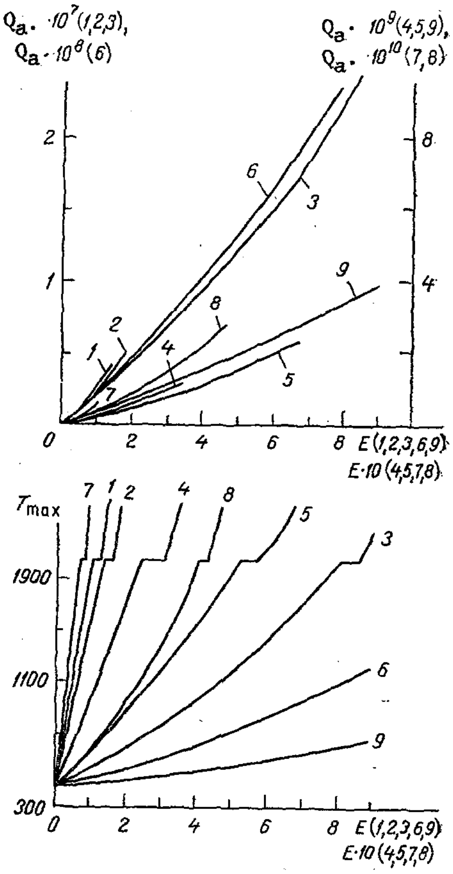

Fig. 2

Fig. 1. Dependences of $Q_a(T_0)/Q_a(T_\infty)$ and T_{max} on t_p for particles with r_0 = 1 μm (1); 0.3 μm (2); 0.1 μm (3); calculated with $K_a(T_0)$ from Eq. (5a) (continuous curves), corresponding to E = 1.5, 0.35, and 0.09 J/cm², $Q_a(T_\infty) \times 10^{-7}$ = 0.29, 7.98×10^{-2}, and 3.39×10^{-4} J and with $K_a(T_0)$ from Eq. (5b) (dashed curves) corresponding to E = 2, 0.47, 0.125 J/cm², $Q_a(T_\infty) \times 10^{-7}$ = 0.379, 1.06×10^{-2}, and 4.67×10^{-4} J. T_{max} in K, t_p in sec.

Fig. 2. Dependence on energy density E of $Q_a(T_0)$ and T_{max} of particles with r_0 = 1 μm (1-3), 0.3 μm (4-6), 0.1 μm (7-9) at $t_p = 10^{-9}$ sec (1, 4, 7), 10^{-7} sec (2, 5, 8) sec, and 10^{-5} sec (3, 6, 9). Q_a in J, E in J/cm².

Energy q deposited in the medium surrounding the particle is determined from the expression:

$$q(T) = \begin{cases} 0, & T < T_s; \\ \dfrac{3}{4}\dfrac{(1 - s_h) I_0 K_a}{r_1}, & T \geqslant T_s, \end{cases} \tag{3}$$

where r_1 is found from the condition $T(r_1) = T_s$ or $r_1 = r_0$ at $T_0 < T_s$. The possibility of forming a spherical region of melted dielectric around the microparticle is taken into account. $K_a(K_{a\infty})$ is thereby calculated from Mie's theory taking into account diffraction for homogeneous particles at $T_0 < T_s$ or two-layered particles (with a melted region) at $T_0 > T_s$. The approximation of uniform q(T) across the volume with $r_0(r_1)$ is used, which is satisfied for r_0, $r_1 \lesssim \lambda$ with an error of $\lesssim$ 30% [4]. The system of Eqs. (1) and (2) has the following initial and boundary conditions:

$$T_0(t = 0) = T_\infty, \quad T(r,\ t = 0) = T_\infty, \quad T(r = r_0,\ t) = T_0, \quad T(r \to \infty,\ t) = T_\infty. \tag{4}$$

We note that examining the action of a radiation pulse on a collection of microparticles in a dielectric in the single particle approximation is justified when $N_0^{-1/3} > \sqrt{4\chi t_p}$, for example for $t_p = 10^{-6}$ sec with $N_0 < 10^{10}$ cm^{-3}, when the thermal fields of the single microparticles practically do not interact after time t.

Calculated Results. Numerical calculations of the system of Eqs. (1)-(4) were carried out to study nonlinear absorption of radiation energy by microcrystals and their heat exchange. For simplicity platinum, present in optical glasses melted in platinum vessels, was selected as the material of the microparticles. Thermal and optical properties of platinum were taken from [10]. Empirical relations were used for $K_a(T_0)$ [3]:

$$K_a = K_{a\infty} \exp(0{,}1 \cdot (T_0 - T_\infty)/T_\infty), \quad T_0 \geqslant T_\infty, \tag{5a}$$

and [17]:

$$K_a = K_{a\infty} \; T_\infty \leqslant T_0 < T_m \; ; \quad K_a = K_{al}, \; T \geqslant T_m \, , \tag{5b}$$

where $K_{a\infty} = K_a(T_\infty)$; K_a, was calculated to be between about 1.5 $K_{a\infty}$ and 2 $K_{a\infty}$ from Mie's theory using of the optical parameters of liquid platinum evaluated from its spectral emissivity. Optical glass K8, whose dependences of thermal and optical parameters on temperature were taken from [11-13], was selected as the dielectric material.

Radiation energy was selectively absorbed by the microparticles, with a weaker absorption by the surrounding dielectric. Therefore, during the action of the radiation pulse, the temperature rise of the particle with time above the temperature of the surrounding medium leads to an increase in heat exchange between the particle and its surroundings, and in the process of this absorption by the particle energy is transmitted to the medium. The characteristic heat exchange time for a particle with radius r_0 can be evaluated from the formula $t_{ex} \sim r_0^2/4\chi$, with $\chi = 1.9 \cdot 10^{-3}$ cm^2/sec [12] and r_0 = 0.1, 0.3, or 1 μm, $t_{ex} \sim 1.31 \cdot 10^{-8}$, $1.18 \cdot 10^{-7}$, or $1.31 \cdot 10^{-6}$ sec. The relation between radiation pulse duration t_p and characteristic heat exchange time of the particle t_{ex} determines the character of the interaction process. The calculated dependences of $Q_a(T_0) = \pi r_0^2 I_0 \int_0^t K_a(T_0)dt$ and T_{max} of particles with r_0 = 0.1, 0.3, or 1 μm, interacting with radiation pulses with λ = 1.06 μm at constant pulse energy density $E = I_0 t_p$ = const and with t_p varying in the interval $\sim 10^{-4}$-10^{-10} sec, are shown in Fig. 1. The shape of $I_0(t)$ during the pulse is taken as a square wave, and the initial temperature as T_∞ = 300 K. In this case the radiation pulse interacts with the particle for $t_p \gg t_{ex}$ while heat exchange is occurring between the particle and its surroundings, and, during the action of the pulse, heat output from the particle practically compensates heat input into the particle by absorption of radiation energy, and T_0 is close to T_∞. Thereby the absorbed energy $Q_a \approx \pi r_0^2 I_0 K_{a\infty} t_p \approx \pi r_0^2 K_{a\infty} E$ does not depend on t_p at E = constst and is practically constant. At $t_p \geq t_{ex}$ the temperature of the particle at the termination of the pulse T_{max} begins to grow, which leads to nonlinear absorption and an increase of Q_a with increasing t_p. At $t_p \ll t_{ex}$ the interaction of the radiation pulse with the particle is accompanied by a substantial superheating of the particles relative to the surroundings, with a significant decrease and even disappearance of appreciable heat exchange between the particles and their surroundings after the time of the pulse. Nonlinear absorption of radiation energy by the particle thereby occurs with increasing T_0 during the pulse, due to an increase in absorption efficiency with rise in temperature from Eq. (5), a decrease in heat output from the particles with shortening of t_p, but also with a possible decrease of the thermal conductivity coefficient of the dielectric with rise in temperature. At r_0 = 1 μm and $t_p \leq 10^{-9}$ sec, the approach of Q_a to saturation is observed. It follows from Fig. 1 that with $K_a(T_0)$ from Eq. (5a) the beginning of nonlinear absorption, equal to $\sim 10^{-2}$ t_{ex}., is determined by the particle radius r_0 and by the relation of t_p and t_{ex}. Use of $K_a(t_0)$ from Eq. (5b) puts the beginning of nonlinear absorption by the particle at the moment of reaching $T_0 = T_m$ and the decrease of $Q_a/Q_{a\infty}$.

The calculated dependences of Q_a and T_{max} on energy density are shown in Fig. 2 for $K_a(T_0)$ from Eq. (5a), r_0 = 0.1, 0.3, and 1 μm and $t_p = 10^{-5}$, 10^{-7}, and 10^{-9} sec. In this case heating is considered up to $T_{max} \sim 2.5 \cdot 10^3$ K, inasmuch as optical breakdown occurs upon radiative heating to $T > 2.5 \cdot 10^{-3}$ K in K8 glass [11]. At constant r_0 an increase of t_p from 10^{-9} sec to 10^{-7} sec to 10^{-5} sec has the result that growth of T_0 up to some constant temperature T_{max} requires an increase in E by almost an order of magnitude. At constant t_p a decrease of r_0 from 1 to 0.1 μm leads to a sharp decrease of the value of E required to

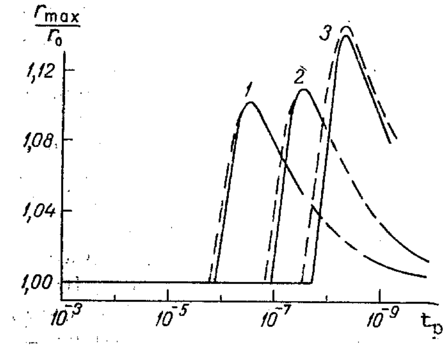

Fig. 3. r_{max}/r_0 versus t_p for particles witeh r_0 = 1 (1), 0.3 (2), and 0.1 (3) μm, calculated with $K_a(T_0)$ (5a) (solid curves) and E = 1.5, 0.35, and 0.09 J/cm^2, respectively, and with $K_a(T_0)$ (56) (dashed curves) and E = 2, 0.47, and 0.125 J/cm^2, respectively$\cdot t_p$, sec.

heat the particle to some constant temperature. Such behavior is explained by a peculiarity of heating and of heat exchange of small particles upon variation of t_p, r_0, and E. Energy absorption by a particle essentially depends on t_p, r_0, and E. Fig. 2 allows one to evaluate the range of the variable E required for heating a particle of the given size to a definite temperature and the absorption at this energy. The presence of a step in the $T_0(t)$ curves in Fig. 1 and 2 is due to the finite time to melt a particle with a given r_0 and the finite energy needed for this. Examination of the dependence of $Q_a(t_p)$ at E = const allows one to estimate the average size $\bar{r}_0$ of the microparticles in the dielectric and the energy Q_a absorbed by the particle with $\bar{r}_0$ on the basis of a comparison of t_p and $t_{ex} \approx \bar{r}_0^2/4\chi$. Comparison of the calculated energy absorption $S_a = V\bar{N}_0Q_a(\bar{r}_0)$, where V is the known illuminated volume of an optically thin dielectric layer, with the value of the energy absorption measured calorimetrically allows one to evaluate the average particle concentration $\bar{N}_0$.

In order to explain the influence of the temporal form of the pulse on the heating of the particles, calculations were carried out with a Gaussian dependence of $I_0(t)$ with $K_a(T_0)$ from Eq. (5) and the former values of the variables. With $t_p \sim 10^{-4}$-10^{-9} sec, and using a Gaussian dependence, $I_0(t)$ leads to a minor deviation in the values of Q_a and the other parameters. Consequently, a square wave dependence of $I_0(t)$ can be used in calculations and for estimates.

Heat exchange between a heated particle and the surrounding dielectric leads to formation of a temperature profile (thermal halo) falling from T_0 on the surface of the particle to $\sim T_\infty$ with increasing r. The presence of T(r) and the dependence on temperature of the dielectric's index of refraction $n_\lambda(T)$ leads to scattering of the radiation by the thermal halo. As T rises from T_∞ to T_s ~1300 K the index of refraction of K8 glass grows almost linearly, and its variation at $T_s \approx 1300$ K amounts to $\Delta n_\lambda \approx 8\cdot10^{-3}$ [11]. We note that at T_∞ and $\lambda = 1.06$ μm the value of the index of refraction of K8 glass equals $n_\lambda = 1.506$. The scattering cross section of the halo S_h in the process of heating and heat exchange with a particle with r_0 = 1 μm at $t_p = 10^{-5}$ sec and increasing E from 1 to 9 J/cm^2 thereby grows from $S_h \sim 1.8\cdot10^{-9}$ cm^2 to $\sim 1.1\cdot10^{-7}$ cm^2 and is a maximum for all variations in the calculations. However even in this case S_h amounts to $\leq$ 0.1 of the cross section of attenuation of the radiation by the particle — i.e., its contribution does not exceed 10% in the attenuation of the radiation. S_h also falls significantly upon decrease of t_p and of particle size r_0 in connection with a decrease in size of the thermal halo (the region with increased temperature.) Consequently, scattering by the thermal halo has practically no influence on propagation of the radiation in the given case at $r_0 \leq 1$ μm and tp $\lesssim 10^{-5}$ sec.

Upon heating the particle above T_s ~1300 K a spherical region of melted dielectric is formed near it. The size of the region of melting grows during the pulse and reaches its maximum r_{max} at t_p. The peculiarity of nonlinear energy absorption and heat exchange of the particles mentioned above leads to growth and subsequent shrinkage of r_{max} with decreasing t_p (see Fig. 3). The dependences of n_λ and $\varkappa_\lambda$ on T for K8 glass were taken from [11, 13]. Upon varying T from ~1300 K to ~2500 K, variation of the efficiency K_a on account of the influence of melting on radiation absorption and taking into account $n_\lambda(T)$ and $\varkappa_\lambda(T)$ [11, 13] constitutes ~2% for the maximum melt thickness. Thus the influence in this case of the formation of a melted region in the K8 glass around the particle upon the variation of its absorptive properties and of the energy deposition is small, and it is possible to account for the absorption of energy only by a microparticle with K_a from Eq. (5). We shall show what estimate can be made in each specific case of the influence of the thermal halo and of the melted region on the variation of the optical properties of a microparticle in the dielectric. Experimentally it seems suitable to avoid melting the microparticle and the surrounding dielectric to prevent the onset of changes in the optical material.

As calculation results show, it is possible to neglect radiative cooling of the particle at T_0 < 3000 or 4000 K in comparison with heat output from thermal conductivity. Eq. (1) with Eq. (4) can be solved analytically in some cases by neglecting radiative cooling of the particle and the influence of the thermal halo and of the melted region on the heating of the particle.

Analytic Solution. In the general case it is possible to present the dependence of $\varkappa(T)$ over a wide temperature interval with a good degree of precision for a specific property of the (material) medium in the form of the approximate formulas [2-4, 9]:

$$\varkappa = \varkappa_\infty (T/T_\infty)^a \tag{6a}$$

$$\varkappa = \varkappa_\infty \exp(\varepsilon (T - T_\infty)), \tag{6b}$$

where $\varkappa_\infty = \varkappa(T = T_\infty)$, a, and ε = const. Within a radiation pulse of duration $t_p > t_{ex}$ acting on the particle, it is possible to express the heat exchange with the surrounding medium in a quasistationary approximation. A quasistationary solution of Eq. (2) for q = 0, $\partial T/\partial t \approx 0$, taking Eq. (6) into account, was obtained in [9] and the expressions for j_T have the following form corresponding to Eqs. (6a) and (6b):

$$a \neq -1 \qquad \bar{j}_T = \frac{\varkappa_\infty T_\infty}{(a+1) r_0} \left[\left(\frac{T_0}{T_\infty} \right)^{a+1} - 1 \right], \tag{7a}$$

$$a = -1 \qquad \bar{j}_T = \frac{\varkappa_\infty T_\infty}{r_0} \ln \frac{T_0}{T_\infty}, \tag{7}$$

$$\bar{j}_T = \frac{\varkappa_\infty}{\varepsilon r_0} [\exp(\varepsilon (T_0 - T_\infty)) - 1]. \tag{7b}$$

By neglecting the indicated processes at K_a = const, and taking Eqs. (4), (6), and (7) into account, Eq, (1) can be solved analytically for several cases. For example, at $\varkappa(T)$ we have, from Eq. (6a) and I_0 = const:

$$\begin{aligned} a = 0 \qquad & T_0 = T_\infty + \frac{I_0 K_a r_0}{4\varkappa_\infty} [1 - \exp(-Bt)], \\ a = 1 \qquad & T_0 = T_\infty A \frac{A + 1 - (A-1)\exp(-ABt)}{A + 1 + (A-1)\exp(-ABt)}, \end{aligned} \tag{8}$$

where

$$A = \left(\frac{I_0 K_a r_0}{2\varkappa_\infty T_\infty} + 1 \right)^{1/2}; \quad B = \frac{3\varkappa_\infty}{\rho_0 c_0 r_0^2}.$$

We note that the solution in Eq. (8) with a = 0 was also obtained in [14], and an approximate analytical solution for $T_0(t)$ with a = −1 was obtained in [3]. At $\varkappa(T)$ from Eq. (6b), I_0 = const, K_a = const, Eq. (1) has the analytic solution

$$T_0 - \frac{1}{\varepsilon} \ln \frac{C \exp(\varepsilon (T_0 - T_\infty)) - 1}{C - 1} = \frac{B}{\varepsilon C} t + T_\infty, \tag{9}$$

where

$$C = \frac{4\varkappa_\infty}{\varepsilon I_0 K_a r_0 + 4\varkappa_\infty}.$$

Upon taking into account the dependence on temperature of the radiation absorption efficiency K_a of the particle from Eq. (5a) and $\varkappa(T)$ from Eq. (6b), the system of Eqs. (1) and (2) has the following solution:

$$T_0 = T_\infty + \frac{B}{\varepsilon} t + \frac{1}{\varepsilon} \ln \frac{1 + D \exp(\varepsilon(T_0 - T_\infty))}{1 + D}, \quad (10)$$

where $D = I_0 K_a \varepsilon r_0 / 4\varkappa_\infty - 1$. With the temperature dependence

$$K_a = K_{a\infty} \left(\frac{T_0}{T_\infty}\right)^d \quad (11)$$

the solution of Eq. (1) taking $\varkappa(T)$ into account from Eq. (6a) with d = a + 1 has the form

$$a = 0 \qquad T_0 = \frac{T_\infty}{\Lambda}[1 - (1 - \Lambda)\exp(-B\Lambda t)],$$

$$a = 1 \qquad T_0 = \frac{T_\infty}{\Lambda^{1/2}} \frac{\Lambda^{1/2} - 1 + (\Lambda^{1/2} + 1)\exp(B\Lambda^{1/2} t)}{1 - \Lambda^{1/2} + (\Lambda^{1/2} + 1)\exp(B\Lambda^{1/2} t)}, \quad (12)$$

where

$$\Lambda = 1 - \frac{I_0 K_{a\infty} r_0 (a + 1)}{4\varkappa_\infty T_\infty}.$$

With a radiation pulse duration of $t_p \ll t_{ex}$, it is possible to neglect heat output from the particle during the action of the pulse. At constant K_a, I_0, and $j_T = 0$, the solution of Eqs. (1) and (4) has the form (see also [15]):

$$T_0 = T_\infty + \frac{3 I_0 K_a t}{4 \rho_0 c_0 r_0}.$$

Using $K_a(T_0)$ from Eq. (5a), Eq. (1) without heat exchange has the form

$$T_0 = T_\infty - \frac{1}{\varepsilon} \ln\left(1 - \frac{3 K_{a\infty} \varepsilon I_0 t}{4 \rho_0 c_0 r_0}\right), \quad (13)$$

while with $K_a(T_0)$ from Eq. (11)

$$d \neq 1 \qquad T_0 = T_\infty \left(1 + \frac{3 I_0 K_{a\infty}(1 - d)}{4 \rho_0 c_0 r_0 T_\infty} t\right)^{\frac{1}{d-1}},$$

$$d = 1 \qquad T_0 = T_\infty \exp\left(\frac{3 I_0 K_{a\infty}}{4 \rho_0 c_0 r_0 T_\infty} t\right).$$

In some cases it is possible to obtain analytic expressions for $Q_a = \pi r_0^2 I_0 \int_0^t K_a dt$ taking account of the dependence of $K_a(T_0)$ and $T_0(t)$. For example, with $K_a(T_0)$ from Eq. (11) and a = 0 in Eq. (12),

$$Q_a = \pi r_0^2 I_0 K_{a\infty} \frac{1}{\Lambda}\left[r + \frac{1 - \Lambda}{B\Lambda}(\exp(-B\Lambda t) - 1)\right],$$

and with $K_a(T_0)$ from Eq. (5a), taking into account Eq. (13) without heat exchange, we obtain

$$Q_a = \frac{4\pi r_0^3 \rho_0 c_0}{3\varepsilon} \ln \frac{1}{1 - \frac{3 K_{a\infty} \varepsilon I_0 t}{4 \rho_0 c_0 r_0}}. \quad (14)$$

An estimate of T_{max} and Q_a according to Eqs. (13) and (14) for t = 10^{-9} sec, r_0 = 1 μm, and E = 1.5 J/cm^2 at $K_{a\infty}$ = 0.603 gives $T_{max} \approx 3.9 \cdot 10^3$ K and Q_a = 0.56 erg, which exceeds the calculated values (see Fig. 1) by a factor of ~1.3-1.5. The given analytic solutions do not take into account melting of the particle, which also leads to the indicated discrepancies between the analytic and calculated results.

Determination by methods of nondestructive testing of the size distribution function $f(r_0)$ of the microparticles (inclusions) in the optical material has substantial interest. The following new method can be used for this purpose. With $\lambda = 1.06$ μm, the coefficient of attenuation of radiation by the optical material in the medium amounts to $\sim 10^{-3}\text{-}10^{-4}$ cm^{-1} [11, 13]. Consequently, samples with dimensions $\lesssim 10^3\text{-}10^4$ cm will be optically thin for the given radiation, and all the microparticles will be irradiated by radiation of constant initial intensity I_0. Scattering of radiation by microparticles with $r_0 \gtrsim 1/3\lambda$ is usually strongly elongated forward in the direction of the incident radiation, and radiation scattered by the microparticles escapes from the calorimeter along with the transmitted radiation. The energy S_a absorbed by the particles in the region of propagation of a beam of radiation with known volume V equals:

$$S_a = V \int_0^\infty Q_a(r_0,\ t_p\ E) f(r_0)\, dr_0, \tag{15}$$

for which $\int_0^\infty f(r_0)dr_0 = N_0$. To approximate $f(r_0)$ it is possible to use the multigroup approximation with k for the groups of particles, and Eq. (15) thereby takes the form

$$S_a = V \sum_{i=1}^{k} Q_{ai}(r_{0i},\ E, t_p) f_i(r_{0i}). \tag{16}$$

As shown in the given reference, the value of Q_a depends nonlinearly on t_p for E = const or on E for t_p = const. Acting on a sample of optical material inserted into a calorimeter with k radiation pulses with different t_p at E = const or with different E at t_p = const with nonlinear absorption of radiation energy by the microparticles, one can make k measurements of the energy S_a absorbed by the calorimeter. In this case Eq. (16) gives a system of k linear equations with k unknown values of $f_i(r_0)$ (k weights of the groups of microparticles) in some range of Δr_{0i} of the variation of particle sizes. Values of $Q_{ai}(r_{0i})$ are determined by the methods given in the present work.

In order to check this method, calculations were carried out for nonlinear absorption by a system of microparticles with radii lying in the range 0.1-0.9 μm. Five groups of particles were used with r_{0i} = 0.1, 0.3, 0.5, 0.7, 0.9 μm and corresponding weights f_i = 0.1, 0.2, 0.4, 0.2, 0.1 at $N_0 = 1$ cm^{-3}. Five values of S_a were calculated for the energy absorbed by the system of particles in unit volume at $E = 9 \cdot 10^{-2}$ J/cm^2 =const and at five values of t_p = 1, 2, 4, 6, 8 ns. Five solutions of Eq. (16) by the method of Gaussian elimination [16] gave the following results: f_i = 0.0998, 0.2001, 0.4003, 0.1997, 0.1001. An analogous study was conducted with $t_p = 10^{-8}$ sec = const and five values of E, which also gave good agreement between initial and calculated values of f_i. For successful application of the given method it is necessary to know the material of the microparticles, its optical and thermal properties over a wide temperature interval, and an approximate range of the microparticle dimensions. Calorimetric measurements of energy absorbed by the particles with variable t_p and E = const or with variable E and t_p = const and solution of Eq. (16) with the corresponding Q_a allows one to determine the scattering of the particles as a function of their dimensions.

In the present work a method has been theoretically established of pulsed laser calorimetry for nondestructive testing of the quality of optical materials, i.e., for determination of mean dimensions and concentrations of microparticles (inclusions), and a new method has been presented of determining the distribution of the microparticles as a function of their dimensions.

NOTATION

r_0, particle radius; I_0, radiation intensity; λ, radiation wavelength; r, radial coordinate; ρ_0, c_0, density and heat capacity of particle; $V_0 = 4/3\pi r_0^3$, particle volume; T_0, particle temperature; S_h, scattering cross section of heat halo; K_a, radiation absorption efficiency of the particle; $S_0 = 4\pi r_0^2$, surface area of the particle; j_ε, irradiance; j_T, irradiance of output from thermal conductivity; ε_s, surface emissivity of the particle; σ, Stefan–Boltzmann constant; Θ, scattering angle; n_λ, index of refraction of medium; n_0, initial value of index of refraction of medium; $k = 2\pi/\lambda$, wave vector; ρ, c, density and heat capacity of medium; T_s, softening (or melting) temperature of dielectric; T_∞, initial temperature; $\varkappa$, χ, coefficients of thermal conductivity and temperature conductivity of medium; t_p, duration of radiation pulse; Q_a, absorbed energy; T_{max}, maximum temperature of particle; t, time; N_0; particle concentration; T, temperature; T_m, melting temperature of particle material.

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