OPTICAL STRENGTH OF WEAKLY ABSORBING DROPS IN INTENSE LIGHT FIELDS

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It is well known that a water droplet located in a field of intense laser radiation of wavelength 10.6 μ absorbs this radiation (at this wavelength the absorption coefficient of the material is $\varkappa \sim 0.1$), heats up, and evaporates. The evaporation process occurs either with a monotonic reduction of the drop radius [1] or in an explosive manner [2] depending on the power density of the laser radiation. It is interesting to assess the various mechanisms of fragmentation of drops that can occur under the action of the strong light field in the pulse generated by ruby or neodymium lasers. The absorption coefficient of water at these wavelengths is: $\varkappa \simeq 3 \cdot 10^{-8}$ at $\lambda = 0.69$ μ, and $\varkappa \simeq 3 \cdot 10^{-6}$ at $\lambda = 1.06$ μ. Effects leading to the fragmentation of the drop will occur at those internal points where the intensity of the light field is at its greatest. The field distributuon over the volume of a large droplet of radius $2 \cdot 10^2$–$2 \cdot 10^3$ μ can be made nonuniform with the aid of a lense which focuses the laser radiation within the drop, the length of the focal region being a few tens of microns. As for a water drop of radius 2-60 μ, on account of diffraction effects such drops self-focus the laser radiation incident upon them onto several internal points [3].

It is shown in [3-6] that the electromagnetic field distribution within a weakly absorbing sphere calculated on the basis of the Mie theory has singularities and is very nonuniform. This occurs because of the appearance of diffraction maxima within the medium, where the light energy density is much greater than that of the incident radiation. A sample calculation of the optical field distribution within a transparent sphere for two values of the sphere radius (20 and 60 μ) is given in Fig. 1 [6], where E_0 is the electric field intensity of the incident light wave. Calculations show that the field distribution within small and large droplets is qualitatively the same. Two main maxima of the ratio of the internal electric field E to the external field E_0 are observed on the sphere diameter along the direction of the incident radiation, the maximum of the shadow hemisphere being greater than the maximum of the illuminated hemisphere.

We introduce the relative intensity $\gamma = (E/E_0)^2$ and determine the dependence of γ on the droplet radius. Figure 2 shows the intensity of the shadow maximum of electric field for various values of the parameter r_0/λ as determined in [4, 6], and by additional calculations (1, data of [4]; 2, data of [6], 3, additional calculations). Due to the diffraction nature of the phenomena, the magnitude of the intensity maxima varies strongly with small variations of the droplet radius. For tentative calculations, this dependence can be approximated by the method of least squares by the formula:

$$\gamma = 11.63(r_0/\lambda)^{0.65},$$

where the droplet radius r_0 and the wavelength λ are expressed in microns. The linear extent of the region of the maximum is measured in tens and units of microns.

When the droplet is subjected to laser radiation operating in the free-generation mode (i.e., pulse duration of the order of milliseconds), the energy in the pulse proves to be sufficient for heat dissipation to occur in the droplet even at such a small value as the absorption coefficient of water. Experiments on the action of laser radiation on droplets show that local superheating occurs in the droplets, which leads to the formation of vapor bubbles and then to the explosion of the droplets [6, 7], the times of formation of the critical nuclei of the bubbles being on the order of 10^{-9} sec. The conditions of the experiments and some results are listed in Table 1.

The threshold value of the intensity of the incident radiation required to induce shock

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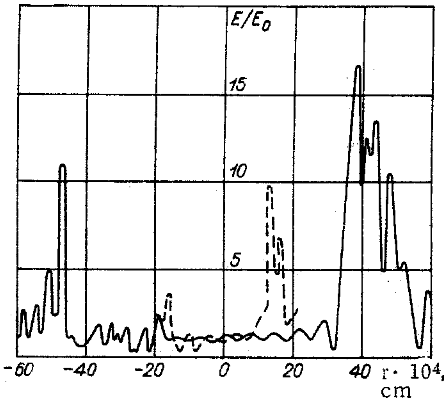

Fig. 1

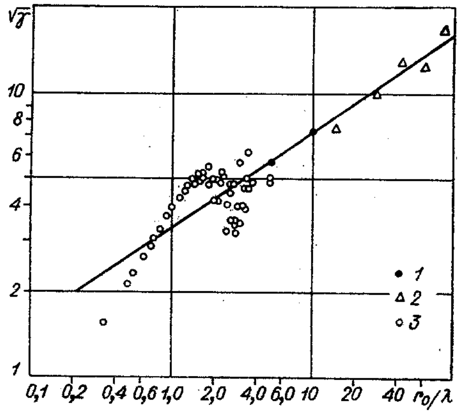

Fig. 2

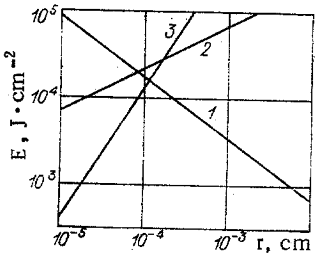

Fig. 3

TABLE 1

Experimental conditions	External lens [7]	Diffraction [6]
Laser wavelength, μ	1,06	0,69
Energy density in pulse, $J \cdot cm^{-2}$	$3{,}3 \cdot 10^3$	$2{,}8 \cdot 10^3$
Droplet diameter, μ	200	50—250
Time when droplet starts to explode, sec	$2{,}5 \cdot 10^{-5}$	$2{,}5 \cdot 10^{-4}$
Explosion-product separation velocity, m/sec	40—50	20

boiling of the liquid in the local regions of nonuniformity of the electromagnetic field can be estimated using the relationship

$$E = \int_0^t I_0(t')\,dt' \geqslant \rho \int_{T_0}^{T_*} \frac{c_p(T)\,dT}{\gamma(r_0)\,\alpha},$$

where I_0 is the intensity of the acting radiation; ρ is the density of the radiation; c_p is the isobaric specific heat of the liquid; α is the coefficient of absorption of the radiation; T_0 is the temperature of the surrounding medium; and T_* is the critical temperature of the liquid. This relationship is valid for $t \sim \tau_d \leqslant t_1$, where τ_d is the duration of the laser pulse; t_1 is the characteristic time scale of the process, equal to $l^2/4\chi$ (here l is the size of the nonuniformity, χ is the thermal diffusivity of water). Thus, for a droplet with r_0 = 50 μ, the energy density required to produce the critical temperature of 374°C within the droplet amounts to around 10^3 J • cm^{-2} for $\tau_d \sim 10^{-4}$ sec, which agrees with the experimental results. The pressure of the superheated vapor in the bubble at the critical temperature is ∿225 bar.

If the droplet is subjected to the action of the radiation from a Q-switched laser, the effects leading to the fragmentation of the droplet will depend not on the energy in the pulse but on the power. It is known that when a high-power laser monopulse is focused into water, phenomena such as optical breakdown [8] and stimulated Mandel'shtam—Brillouin scattering (SMBS) [9] are observed. It is of interest to assess the relevance of these phenomena in the fragmentation of a water droplet.

The characteristics of the phenomenon of optical breakdown in water can be determined on the basis of [8, 10, 11]. Breakdown occurs in the vicinity of the focus, the light accompanying the phenomenon of breakdown indicating that a plasma is formed near the center of the breakdown. The threshold of optical breakdown in water found by various authors varies in the range from $I_1 \sim 4 \cdot 10^8$ W • cm^{-2} [8] to $I_1 = 6.2 \cdot 10^{11}$ W • cm^{-2} [12], depending on the purity of the liquid employed in the experiments. The pulse energy density E_1 then amounts to about 8 J • cm^{-2} [8] and $3.1 \cdot 10^4$ J • cm^{-2} [12]. It is shown in [13] that the degree of purity of the liquid has a very pronounced effect on the breakdown threshold. Rapid expansion of the breakdown cavity next occurs, accompanied by the propagation of a spherical shock wave. The mean velocity of the shock wave in the period 3-15 μsec after the laser pulse equals the velocity of sound in water. The spherical cavity in the water grows in accordance with the Rayleigh model [11]. The pressure on the shock front increases with increasing laser energy [8].

Dielectric breakdown in a water droplet, the formation of shock waves, and droplet fragmentation were observed in [14]. The radiation of a monopulse ruby laser was focused by an external lens upon internal points of a water droplet of radius $5 \cdot 10^2$-$3 \cdot 10^3$ μ. The energy of the laser pulse was 0.5 J at a pulse duration of 50 nsec. The droplet begins to explode in less than 16 μsec. The pressure on the front of the shock wave fragmenting the droplet falls rapidly with increasing distance from the focal point and reaches ∿1600 bar at a distance of 0.5 mm from it. The greater the pressure on the shock front, the greater the explosion-product separation velocity and the greater the distance the explosion products travel.

Allowing for the nonuniformity of the optical field within a water droplet of radius $\leqslant 60$ μ, we can estimate the threshold of applicability of this droplet-fragmentation mechanism with the aid of the expressions: $E_2 = E_1/\gamma$ J • cm^{-2}; $I_2 = I_1/\gamma$ W • cm^{-2}. Since under natural conditions a droplet of micron dimensions does not contain foreign impurities, the results of Roach and Davies [12] may be used in the estimates. For a droplet of pure water with $r_0 = 60$ μ, $\gamma = 2.9 \cdot 10^2$, $E_2 \sim 10^2$ J • cm^{-2}, $I_2 \sim 2 \cdot 10^9$ W • cm^{-2}, and a pulse of duration $\sim 5 \cdot 10^{-8}$ sec is required.

It is known that stimulated Mandel'shtam–Brillouin scattering in liquids is accompanied by the appearance of intense hypersonic waves. The conversion of hypersound into heat as SMBS develops can be an additional mechanism of heat dissipation within the droplet. In large volumes of liquid the threshold power density necessary for SMBS to occur amounts to $\sim 10^9$ W • cm^{-2}. Determination of the SMBS threshold within a drop requires the solution of an internal boundary problem involving the nonlinear interaction of light and sound waves, a problem of considerable difficulty which lies outside the scope of the present work. In this connection, let us estimate the efficiency with which hypersound is converted into heat within the framework of stationary SMBS [15]. We determine the ratio of the powers at which heat is released due to the absorption of sound Q_s and light Q_l in the following manner:

$$\frac{Q_s}{Q_l} = \frac{\alpha_l I_s}{\alpha_s I_0} = \frac{\alpha_l \eta I_{St}}{\alpha_s I_0},$$

where I_s is the sound intensity; I_{St} is the intensity of the Stokes emissions; $\eta = (GI_0/2\alpha_l)(\Omega/\omega_0)$ is the light-into-sound conversion coefficient; G is the SMBS gain coefficient per unit length and intensity; Ω is the hypersound frequency; ω_0 is the frequency of the acting radiation; and α_l and α_s are the amplitude coefficients of absorption of the Stokes radiation and hypersound, respectively. Remembering that $I_{St} < I_0$, we have that $\frac{Q_s}{Q_l} < \frac{GI_0\Omega}{2\alpha_s\omega_0} < \left(\frac{Q_s}{Q_l}\right)_{max}$. By [15], for water $G = 0.64 \cdot 10^{-8}$ cm • W^{-1}, $\alpha_s = 3 \cdot 10^{-3}$ cm^{-1}, and $\Omega/\omega_0 \sim 10^{-5}$, so that $(Q_l/Q_s)_{max} = 1$ for $I_0 \sim 10^{11}$ W • cm^{-2}, which is close to the optical-breakdown threshold.

In addition to the above mechanism, weakly absorbing droplets can be fragmentized by the effect of unstable vibrations induced by ponderomotive forces [16, 17].

The vibrations of the surface of the drop have a discrete thermal spectrum, which leads to the appearance of combination frequencies in the spectrum of the scattered field. A self-consistent amplification of the surface vibrations and of the combination components of the light field occurs due to the presence of striction and the pressure jump on the drop surface caused by the surface jump in electromagnetic energy density. This effect, known as stimulated surface scattering of light [18], can lead to turbulization of the flow of liquid within the drop, i.e., to its disintegration. A numerical calculation of the nonlinear vibrations of a drop [17] carried out for the fundamental mode of vibration, corresponding to a two-sided uniform extension of the drop (approximation of a uniform internal electromagnetic field), leads to the following expression for the particle instability threshold for not too small drops ($r_0 \geqslant 1$ μ):

$$I_0 r_0 / 2\sigma c > 58.$$

The characteristic time required for the instability to build up is $t_2 \approx 2\Omega_0^{-1}$, where $\Omega_0 = (8\sigma/\rho r_0^3)^{1/2}$ is the fundamental frequency of the natural vibrations of the drop; σ is the coefficient of surface tension of the liquid; and c is the velocity of light. Figure 3 shows the energy consumption $E \sim I_0\tau_d$ required to fragment a drop for the various fragmentation mechanisms. The characteristic time $t_2 \ll t_1$ was taken as the time scale. The condition $\tau_d > t_2$ is imposed on the pulse duration. Curve 1 corresponds to shock boiling of the liquid; curve 2 characterizes the ponderomotive instability of the drop; and curve 3 determines the breakdown threshold of the material.

The small-perturbations solution [19] for the vibrations of a drop in a high-power light field shows that the maximum frequency shift of the combination radiation from the undisplaced line is given by

$$\Delta\omega_{max} = (\Omega_1^2 - 2\delta^2)^{1/2},$$

where Ω_1 is the frequency of the vibrations of the drop in the light field;

$$\Omega_1 = \Omega_0\left[1 - \frac{(\varepsilon_0 - 1)^2 (4 - \varepsilon_0) b_{ln} r_0 I_0}{\sigma \sqrt{\varepsilon_0}\, c\,(l-1)(l+2)}\right],$$

ε_0 is the dielectric constant of the material; $\delta = (l - 1)(2l + 1)\nu r_0^2$, ν is the kinematic viscosity of the liquid, $l \geqslant 2$, $|n| = 0, \ldots, l$; b_{ln} are the coefficients of the expansion of the jump in the ponderomotive forces in spherical functions. For $r_0 = 10^{-4}$ cm, $l = 2$, $n = 0$, $\Omega_1 = 2.4 \cdot 10^8$ sec^{-1}, $\delta = 5 \cdot 10^6$ sec^{-1}, $I_0 = 3 \cdot 10^9$ W/cm^2, and $\tau_d \gg \Omega_0$, we obtain $\Omega_1 \approx 0.9\Omega_0$.

An experimental study of the vibrations of a transparent drop in a light field is reported in [20]. The frequency of the surface waves coincided with the fundamental frequency of the natural vibrations of the particles. The parameters of the experiment are as follows: $I_0 \sim 10^6$ W/cm^2, $r_0 \sim 50$-$100\ \mu$, $\tau_d \sim 10^{-3}$ sec.

LITERATURE CITED

1. M. A. Kolosov, V. K. Rudash, A. V. Sokolov, and G. M. Strelkov, "An experimental study of the effect of intense infrared radiation on large water drops," Radiotekh. Élektron., No. 1 (1974).
2. P. Kafalas and A. P. Ferdinand, "Fog droplet vaporization and fragmentation by a 10.6-μ laser pulse," Appl. Opt., 12, No. 1 (1973).
3. V. N. Pozhidaev, "Possibility of exciting acoustic waves in a water droplet by means of giant laser pulses," Opt. Spektrosk., 31, No. 3, 478 (1971).
4. L. G. Astaf'eva, "Energy distribution in large weakly absorbing particles," Zh. Prikl. Spektrosk., 18, No. 3 (1973).
5. N. V. Bukzdorf, "Calculation of intensity of an electromagnetic field within a transparent dielectric sphere," Izv. Vyssh. Uchebn. Zaved., Fiz., No. 3 (1973).
6. N. V. Bukzdorf, V. A. Pogodaev, and L. K. Chistyakova, "Connection between nonuniformities of an internal optical field of a droplet and its explosion," Kvant. Élektron., 2, No. 5 (1973).
7. V. V. Barinov and S. A. Sorokin, "Explosions of water droplets under action of optical radiation," Kvant. Élektron., No. 2 (1973).
8. A. I. Ioffe, N. A. Mel'nikov, K. A. Naugol'nykh, and V. A. Upadyshev, "Shock wave accompanying optical breakdown in water," Zh. Prikl. Mekh. Tekh. Fiz., No. 3 (1970).
9. R. G. Brewer and K. E. Rieckhoff, "Stimulated Brillouin scattering in liquids," Phys. Rev. Lett., 13, No. 11 (1964).
10. M. P. Felix and A. T. Ellis, "Laser-induced liquid breakdown, a step-by-step account," Appl. Phys. Lett., 19, No. 11 (1970).
11. W. Lauterborn, "High-speed photography of laser-induced breakdown in liquids," Appl. Phys. Lett., 21, No. 1 (1972).
12. J. F. Roach and J. M. Davies, "Electric strength of some liquid dielectrics subjected to a Q-switched laser pulse," Proc. IEEE, 58, No. 9, 1398 (1970).
13. A. V. Butenin and B. Ya. Kogan, "Mechanism of optical breakdown of transparent dielectrics," Kvant. Élektron., No. 5 (1971).

14. A. A. Buzukov and V. S. Teslenko, "Pressure on shock front in near zone of laser-spark breakdown in water," Zh. Prikl. Mekh. Tekh. Fiz., No. 3 (1970).
15. V. S. Starunov and I. A. Fabelinskii, "Stimulated Mandel'shtam–Brillouin scattering and stimulated entropy (temperature) scattering of light," Usp. Fiz. Nauk, 98, No. 3 (1969).
16. A. A. Zemlyanov, "Stability of small vibrations of a transparent drop in a high-power light field," Kvant. Élektron., 1, No. 9 (1974).
17. A. A. Zemlyanov, "Deformation and stability of a transparent drop in a high-power optical field," Izv. Vyssh. Uchebn. Zaved., Fiz., No. 6 (1975).
18. F. V. Bunkin, A. A. Samokhin, and M. V. Fedorov, "Stimulated scattering of light by the surface of a liquid," Zh. Éksp. Teor. Fiz., Pis'ma Red., 7, No. 11 (1968).
19. R. Yu. Orlov, I. B. Skiran, and L. S. Telegin, "Investigation of breakdown of dielectrics by ultrashort laser pulses," Zh. Éksp. Teor. Fiz., 61, No. 2 (1971).
20. A. A. Zemlyanov and L. K. Chistyakova, "Possibility of fragmentation of transparent drop in an intense light field," in: Elements and Devices of Radio Electronics [in Russian], Izd. Tomsk Univ., Tomsk (1974).

ABSORPTION COEFFICIENTS OF SPARK-CHANNEL PLASMA IN A SOLID DIELECTRIC

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It is usually assumed [1-4] that a spark in a liquid radiates as a perfect black body (PBB). This assumption lies at the heart of the many estimates that have been made of the temperature of the spark channel in liquid dielectrics. The high particle density of the plasma column and the continuous emission spectrum give a certain basis for extending the PBB model to the case of sparks in solid dielectrics. However, the small radial dimensions of such sparks, especially in the initial phase of expansion (spark diameter 0.1-0.2 mm), may be insufficient to give the optical depth necessary for the PBB model.

In the work reported here we determined the absorption coefficients of the plasma of a spark channel in a KCl single crystal at two wavelengths λ = 330 and 370 nm. The KCl crystal chosen as the spark channel is accurately oriented along the crystallographic direction, thereby enabling the emission to be reliably directed onto the spectrograph slit.

The investigated spark-channel radiation was produced by discharging, across a "point–point" gap, an artificial line of wave impedance 3.5 Ω charged to 70 kV. The dimensions of the sample were 20 × 20 × 5 mm; the spacing between the electrodes was 5 mm.

The absorption coefficient was determined by transillumination of the investigated object with light from a source of known characteristics [5] (we used an ÉV-45 light source [6]). As shown in [5],

$$a_\lambda(t) = 1 - e^{-\alpha_\lambda(t)l(t)} = 1 - \frac{J_\lambda^\Sigma - J_\lambda^{\text{inv}}}{J_\lambda^{\text{st}}},$$

where a_λ is the spark-channel absorption coefficient at wavelength λ; α_λ is the index of absorption; l is the thickness of the plasma sheet; J_λ^{inv}, J_λ^{st}, J_λ^Σ are oscillograms of the intensity (spectral brightness at wavelength λ) of the investigated emission, of the standard source, and of the total light.

The absorption of standard-source light in the crystal was taken into account by recording J_λ^{st} with the sample present. The photoelectronic recording system (ISP-30 spectrograph, FÉU-36 photomultiplier, S1-17 oscilloscope) had a time constant τ = 40 nsec.

To check the dynamics of the filling of the input slit of the spectrograph with light and the calculation of the index of absorption α_λ, the spark channel was photographed by an SFR-2M high-speed photorecorder; illumination from the ÉV-45 was used to produce a shadow pattern.

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