ON THE INTEGRAL TRANSMISSION OF DROPLET MEDIA FOR PULSED CO_2 LASER RADIATION

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The problem of propagation of intense focused laser beams in water aerosols under conditions of regular and explosive vaporization of drops and optical breakdown of the medium is studied. The effect of the parameters of the laser radiation as well as the type and microstructure of the aerosol medium on the integral transmission of the beam channel is investigated. An interpretation of the existing experimental data is given.

The propagation of pulsed laser radiation in droplet media (fog, drizzle, rain) belongs to a class of problem in nonlinear optics In which the multiple-factor nature and nonadditivity of the processes affecting the transmission of the radiation channel are strongly pronounced. The interaction of the radiation with the medium along the propagation path strongly depends on the type and microphysical properties of the specific meteorological formation as well as on the energy parameters of the beam, the structure of the beam, the temporal regime, and the conditions of focusing. The purpose of this work is to analyze the effect of these factors on the optical characteristics of the channel (the integral transmission) under conditions of explosive vaporization of droplet media.

1. We shall study the transfer coefficient (integral transmission) of a droplet medium whose attenuation coefficient a depends nonlinearly on the intensity of the beam I: $\alpha = \alpha(I)$. The energy transfer coefficient T_e of an aerosol medium for laser radiation is given by the relation

$$T_e(z,t) = \frac{E(z,t)}{E(0,t)} = \frac{\iint\limits_{-\infty}^{\infty} d^2R \int\limits_0^t I(\vec{R}', z, t')dt'}{\iint\limits_{-\infty}^{\infty} d^2R \int\limits_0^t I(\vec{R}', 0, t')dt'}. \tag{1}$$

The beam energy E satisfies the conservation law

$$\frac{\partial E(z,t)}{\partial z} = - \iint\limits_{-\infty}^{\infty} d^2R \int\limits_0^t \alpha(I)\, I(\vec{R}', z, t')dt', \tag{2}$$

where $\vec{R}$ and z are the transverse and longitudinal coordinates in the beam, respectively, and t is the time. If the breakdown threshold is reached in the medium,[1] then the attenuation coefficient in a water aerosol is determined by the accumulating nonlinearity, and it may be assumed to be equal to $\alpha = \alpha(J_u, \omega)$, where $J_u = \alpha_n\omega_u/\rho_L C_p t_u$ is a parameter characterizing the rate of heating of the drops by the radiation[3]; ω is the energy density in the beam; α_n, ρ_L, and C_p are the absorption coefficient, the density, and the isobaric heat capacity of water; ω_u is the total energy density in the radiation pulse; and,

$$t_u = \omega_u^{-1} \int\limits_0^{\infty} t' I(t')dt'$$

is the duration of the pulse. In this case Eq. (2) can be put into the form

$$\frac{\partial E(z,t)}{\partial z} = - \iint\limits_{-\infty}^{\infty} d^2R \int\limits_0^{\omega(\vec{R},z,t)} \alpha(J_u, \omega')d\omega. \tag{3}$$

It follows from Eq. (3) that

$$T_e(z,t) = 1 - \frac{1}{E(0,t)} \int\limits_0^z dz' \iint\limits_{-\infty}^{\infty} d^2R \int\limits_0^{\omega(\vec{R},z,t)} \alpha(J_u, \omega')d\omega . \tag{4}$$

It follows from here that from the viewpoint of increasing the transmission of the radiation channel it is important to minimize the factor $\int\limits_0^{\omega} \alpha d\omega'$. This is achieved by filling the channel as much as possible with radiation and by realizing the most favorable conditions for bleaching. The dependence $\alpha(\omega)$ can be constructed theoretically based on models of explosive vaporization or it can be determined experimentally. In what follows the numerical experiments were performed using the models developed in Refs. 1 and 3 for the aerosol attenuation coefficient $\alpha(\omega)$.

2. In studying the propagation of radiation under conditions of explosive vaporization of aerosol particles we shall take into account the wind-induced motion of the medium. This imposes a restriction on the time available for studying the process $t \ll t_v = R_0/v_0$, where R_0 is the transverse scale of variation of intensity in the beam and v_0 is the wind velocity (perpendicular to the beam). For $R_0 \sim 10^{-2}$ m and $v_0 \le 10$ m/sec $t_v \ge 10^{-3}$ sec. Since the duration of CO_2 laser pulses usually does not exceed ~ 40 μsec,[4] the condition under which the wind motion of the medium can be neglected is always satisfied for such sources. Neglecting the wind makes the problem cylindrically symmetric. In addition, in the situation under analysis the effects of multiple scattering of light as well as the refraction effects engendered in the laser-beam channel by the perturbation of the dielectric constant of the medium will be neglected.[1]

The starting point for analysis of the propagation of intense laser beams un dispersed media, where there are no refraction effects, is the equation of transfer of intensity

$$\frac{\partial I}{\partial z} + \vec{\Theta}\nabla_{\vec{R}} I + I\nabla_{\vec{R}}\vec{\Theta} = -\alpha I, \tag{5}$$

supplemented by an equation for the "diffraction" ray

$$\frac{d\vec{R}_d}{dz'} = \vec{\Theta}(z'); \quad \frac{d\vec{\Theta}(z')}{dz'} = \frac{1}{2}\nabla_{\vec{R}}\left[\frac{\Delta_{\vec{R}}A}{k^2 A}\right]. \tag{6}$$

The boundary conditions are: $I(z = 0) = I_0$; $\vec{R}_d(z' = z) = \vec{R}$; $\dfrac{d\vec{R}_d(z'=0)}{dz'} = \vec{\Theta}_0$. Here $\vec{\Theta} = \nabla_{\vec{R}}\varphi / k$ is the transverse component of the vector of the direction of transfer of the energy in the beam; φ is the effective phase and A is the effective amplitude of the wave; and, k is the wave number. The radiation is assumed to be coherent. At the inlet of the medium the profile of the intensity is assumed to be Gaussian:

$$I_0 = I^0(t)\exp(-R^2/R_0^2); \quad I^0(t) = I_{max} f(t),$$

where the function $f(t)$ characterizes the temporal structure of the laser radiation, which is assumed to be of the following form:

$$f(t) = t/t_0, \quad t \le t_0; \quad f(t) = \exp\left[-(t-t_0)nt_0\right], \quad t > t_0,$$

where n and t_0 are parameters. We shall assume that the attenuation does not strongly effect the diffraction of the beam ($\alpha_0^{-1} \ll kR_0^2$), so that in Eq. (6) we shall use for A the linear approximation

$$A = \frac{A_0}{g(z')}\exp\left[-R^2/2R_0^2 g^2(z')\right], \tag{7}$$

where $g(z) = \left[(1 - z/F)^2 + z^2/k^2R_0^4\right]^{1/2}$ is the dimensionless width of a Gaussian beam and F is the radius of curvature of the phase $z = 0$.

Integrating Eq. (6) we obtain

$$\vec{\Theta}(R_d, z') = \frac{\vec{R}_d(z')}{g(z')}\cdot\frac{dg(z')}{dz'}; \quad \vec{R}_d(z') = \frac{\vec{R}\cdot g(z)}{g(z')}. \tag{8}$$

The expression (8) permits writing for the beams under study an equation for I in the integral form:

$$I(\vec{R}, z, t) = I^0(t)\exp\left[-R^2/R_0^2 g^2(z) - \tau_N(\vec{R}, z, t)\right], \tag{9}$$

where $\tau_N = \int_0^z \alpha(\vec{R}_d(z'), z', t)dz'$ is the nonlinear optical thickness calculated on the "diffraction" ray.

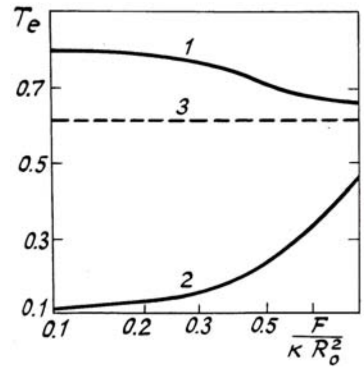

FIG. 1. The transfer factor of fog (1) and rain (2) as a function of the focal length. The curve 3 shows the level of T_e in a nonattenuating medium.

We shall now study the results of numerical experiments on the propagation of focused CO_2 laser pulses in droplet media with different turbidity and with different optical weather. The form of the model dependence of the attenuation coefficient $\alpha(\vec{R}, z, t)$ was chosen for a specific meteorological formation (fog or rain). In; addition, in the numerical calculations the conditions of focusing and the starting size of the beam were varied.

3. The effect of the conditions of focusing of the beam on the transmission of fog (γ-distribution[5] with the parameters $a_m = 3$ μm and $\mu = 10$) with an initial optical thickness $\tau_0 = 0.5$ is shown in Fig. 1, where the dependence of the transfer coefficient T_e, calculated in the focal plane ($z/F = 1$), on the dimensionless focal length $\bar{F} = F/kR_0^2$ is presented for a fixed value of the beam energy E at the inlet into the medium. One can see that, for fogs, increasing the sharpness of focusing of the radiation (decreasing the parameter $\bar{F}$) reduces the energy losses. The value of the transfer coefficient for focused beams can be up to ~ 20% higher than for collimated beams. This is a consequence of the fact that in the case of stronger focusing of radiation the threshold value ω_{exp} for explosion of particles, which, as follows from the results of Refs. 2 and 3, in a fog leads to bleaching of the fog, is reached in a large region of the beam.

The analogous dependence $T_e(\bar{F})$ for rain (a_m = 700 μm, μ = 1, and τ_0 = 0.5) is of the opposite character. Here higher values of the integral transmission are realized for collimated beams, since explosive vaporization of large raindrops results in a sharp increase of the attenuation of the medium.[3]

4. In the numerical experiments the aerosol; parameters corresponding to one and same the state, of turbidity were varied together with the parameters of the beam.

Thus for fogs whose initial distribution function is close to a γ-distribution, one and the same value of the meteorological visibility S_M, for example, S_M = 0.5 km, is realized for different parameters of the microstructure a_m = 5 μm, μ_1 = 4 and particle number density N_{01} = 10 cm^{-3} and a_m = 2 μm, μ_1 = 10 and N_{02} ~ 10^3 cm^{-3}.

The effect of the initial microstructure of the fog of the conditions of propagation of radiation is illustrated in Fig. 2, which shows the dependence of the transmission for the two types of fog examined above on the energy density of the focused beam ω_f (in a nonattenuating medium). It is obvious that in a fog with, on the average, larger particles, higher values of T_e are realized with a fixed value of ω_f. This is attributable to the fact that in the case of explosive fragmentation of relatively large drops into many small drops the total attenuation decreases additionally owing to the decrease in the relative fraction of scattering radiation.

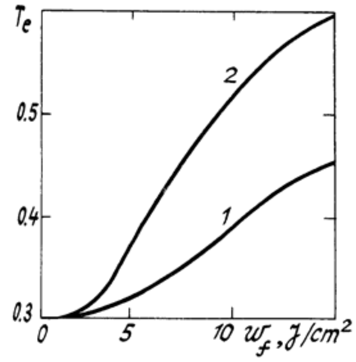

FIG. 2. The transfer factor of fog (τ_0 = 1.2) with the parameters a_m = 2 μm, μ = 10, N_0 = 10^3 cm^{-3} (1) and a_m = 5 μm, μ = 4, N_0 = 10 cm^{-3} (2) versus the laser energy density.

5. In studying the propagation of focused laser radiation in real meteorological formations it is important to take into account the solid-phase background aerosol, since it determines the probability of optical breakdown of the medium. In specifying the physical situation along the propagation path it is also important to know the lifetime of the state of the optical weather prior to the moment of measurement. In the case of an established fog the solid-phase fraction is inundated with water and washed away. The investigations showed that inundation has virtually no effect on the appearance of breakdown in the case of strong radiation.[11] The number density of the course fraction N_{cf} has a much stronger effect. It is well known that the number density of particles of the background aerosol and especially the coarse fraction of the aerosol ($a \geq 1$ μm)[5] decreases significantly as the duration of one or another meteorological formation increases. Because of this, in the numerical experiments, in addition to varying the parameters of the distribution function of the water aerosol, the number density of the coarsely dispersed fraction of the background aerosol N_{cf} was also varied.

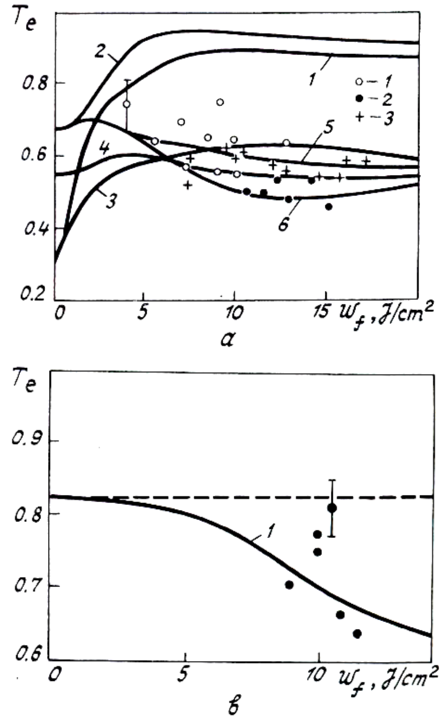

FIG. 3. The experimental dependence of the transmission of fog (a) with τ_0 = 1.2 (1′), 0.6 (2′), and 0.4 (3′) (the solid lines show the theoretical calculation with τ_0 = 1.2 (1, 3), 0.6 (4), and 0.4 (2, 5, 6)) and rain (b) with τ_0 = 0.2 (1) as a function of the energy density of a focused laser beam (the dashed line shows the radio for a nonattenuating medium).

Figure 3a shows a number of realizations of the numerical experiment for different initial optical thicknesses of fog (τ_0 = 1.2; 0.6, and 0.4) as well as the corresponding experimental data from Refs. 6 and 7. The attenuation of radiation by the plasma produced by optical breakdown, initiated by particles of the background aerosol, was taken into account using the model of adjusted parameters.[8] The threshold intensity for breakdown was assumed to be equal to I_{bd} = 10^8 W/cm^2 (Ref. 1). Calculations were performed for a series of values of the number density of the coarse fraction of the background aerosol: N_{cf} = 10^{-4} (1), 10^{-3} (2, 3), 5 · 10^{-3} (4),

10^{-2} (5), and 10^{-1} (6). It turned out that the theoretical curves agree best with experiment for $N_{cf} = 10^{-3}$ ($\tau_0 = 1.2$), $5 \cdot 10^{-3}$ ($\tau_0 = 0.6$), and 10^{-2} cm^{-3}($\tau_0 = 0.4$).

It follows from the figure that the final integral transmission of the fog is characterized primarily by the number density of the course fraction N_{cf}, which determines the number density of plasma foci. As the radiation energy density ω_f is increased from 5 to 15 J/cm^2 ($\tau_0 = 0.4$) the transmission does not decrease significantly, since all centers of plasma formation are activated, and the energy in the pulse is too low for initiation of. optical breakdown on the finely dispersed fraction of the background aerosol ($a \leq 1$ μm).

The dependence $T_e(\omega_f)$ under the conditions of rain is shown in Fig. 3b. The ensemble of raindrops was modeled by a γ-distribution with the parameters $a_m = 700$ μm and $\mu = 1$. Such a distribution function approximates quite well the real spectra of rains.[9] The number density of the Course fraction of the background aerosol was assumed to be zero. Comparing Figs. 3a and 3b show that for an established fog ($N_{cf} \to 0$) the transmission always increases as the radiation energy increases. This is attributable to the fact that the extinction cross section of particles decreases, as they are fragmented.[2,3] When the threshold of explosive regimes is exceeded under the conditions of rain the transmission decreases, because the total geometric cross section of large raindrops increases when the drops are broken up.[3]

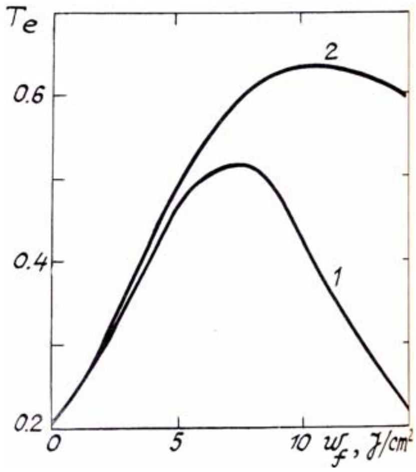

FIG. 4. The transmission of fog ($\tau_0 = 1.6$) as a function of the energy density for propagation of a single pulse of radiation (1) and for periodic-pulse radiation (2).

6. We shall consider the question of the propagation of a sequence of laser pulses through a turbid medium. Existing experimental data show that the use of doubled pulses in the atmosphere under conditions of breakdown on particles of a solid aerosol significantly reduced the energy losses as compared with a single pulse with the same energy.[10] This is connected with the laser radiation clears of the beam channel by vaporizing and removing solid particles, which initiate breakdown under conditions of high effective power densities. At lower intensities the transmission is also observed to increase for a sequence of laser pulses in droplet media in the presence of a solid fraction. This is evident from the numerical calculations of the dependence $T_e(\omega_f)$ for fog ($\tau_0 = 1.6$), presented in Fig. 4. Two types of action on the medium were studied: an isolated pulse with peak intensity $I_{max} = 2 \cdot 10^7$ W/cm^2 (curve 1) and doubled pulses with $I_{max1} = I_{max2} = 6 \cdot 10^6$ W/cm^2 (curve 2). In the focal plane the focal length $\bar{F}$ in a nonattenuating medium was chosen to be equal to 0.07. The number density of the course fraction N_{cf} was equal to 10^{-3} cm^{-3}. In this case, however, the transmission of the fog for doubled pulses is higher than fore single pulse with the same total energy because the energy of each separate pulse in the series ii not high enough to maintain optical breakdown ii the medium, while the single pulse activates all centers of plasma formation.

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