STATISTICAL PROPERTIES OP A CO_2-LASER PULSE TRANSMITTED THROUGH AN AERODISPERSIVE DROPLET LAYER

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Results are reported of a theoretical investigation of variations of the variance of fluctuations in the hole-boring and probing beam intensity in an aerodispersive droplet layer, cleared by pulsed radiation. The nonlinear interaction between the laser radiation and the cloud medium is shown to result in a considerable increase in the initial intensity fluctuations.

The interaction between laser radiation and the medium is known to be a nonlinear process if the beam intensity exceeds a certain threshold value. This means that the propagation of the beam through the medium causes the medium to change its properties. In other words, the latter become dependent on the laser intensity while the extent and nature of the response of the medium to the irradiation are, in turn, essentially different from the linear case. This nonlinear interaction leads to heating of the medium, phase-state transformations of the components of the medium, formation of plasma regions, etc., as well as to beam attenuation, beam energy redistribution, and wave-front distortion[1,2]. The statistical properties of the medium and the radiation are also changed. The laser-induced fluctuations of the medium parameters are superimposed on temperature and permittivity oscillations already present as a result of turbulence. One of the mechanisms responsible for the laser-induced variations of the medium parameters is connected with the transformation of the initial beam intensity fluctuations during the course of the nonlinear interaction. The changes in the statistical properties of the initially stable aerosol-droplet medium subject to laser radiation with spatial intensity fluctuations were first investigated by Almaev and Svirkunov[3] who derived expressions for the variances of the laser-induced temperature and water-content variance in a regular vaporization regime. Investigations of the effect of an intense laser pulse on clouds and fogs, including the case of explosive destruction of the condensation phase, are of current interest. Definite progress has been made in the study of the clearing of a droplet aerosol by pulsed radiation with stable parameters, whereas the exposure of the cloud medium to pulsed fluctuating intensity radiation has not yet been discussed in the literature. However, the solution to this problem is important because under real conditions the radiation experiences fluctuations that occur both in the laser source and during propagating through the turbulent part of the atmosphere below the cloud layer. The present work deals with a theoretical investigation of the changes in the initial intensity fluctuations of the hole-boring beam during the course of its nonlinear interaction with the medium. In addition, the intensity fluctuations of a low-intensity probing beam passing through a cleared medium are evaluated.

Consider the following problem. A pulsed CO_2 laser beam with a radiant intensity fluctuating at every point on its cross-section propagates in the positive direction of the axis through a cloud medium occupying the half-space $z \geq 0$. The microstructure of the cloud medium and its optical characteristics are affected by the radiation. The fluctuation parameters of the hole-boring and probing beams at the end of the pathlength z with initial optical thickness τ_0 are to be determined. Examined below are situations in which the pulse duration is short enough so that wind-blurring of the boring zone can be neglected and the propagation pathlength through a typical cloud is less than typical diffraction and refraction pathlengths.

Under these assumptions the system of simultaneous equations[4] for laser pulse propagation is written as

$$\frac{\partial I}{\partial z} = -I \left\{ \int_0^\infty \sigma(R)\, f(R,r,t)\, dR + \alpha \right\} \tag{1}$$

$$\frac{\partial f}{\partial t} + \frac{\partial}{\partial R}(\dot{R} f) = \int_{R_k(I)}^{\infty} \varphi(R',R)\, f(R',r,t)\, \delta(t-t_b(R',I)]\,dR' - f(R,r,t)\, \theta(R-R_k(I))\, \delta(t-t_b), \tag{2}$$

$$\dot{R} = -\frac{\beta_T K_n(R) I}{4\rho_b L}, \tag{3}$$

$$I\, K_n(R_k)\, R_k = C, \tag{4}$$

$$\int_0^{t_b} \frac{3K_n(R)I}{4R}\,dt = (T_b - T_0)\,\rho_b\,C_b \quad (5)$$

with the boundary and initial conditions

$$I(r,t)\big|_{z=0} = I_0(\rho,t),$$
$$f(r,R,t)\big|_{t=0} = f_0(r), \quad (6)$$
$$R\big|_{t=0} = R_0,$$

where I is the radiation intensity, $f(R, r, t)$ is the droplet size distribution function (R = the droplet radius) at the point $r = (x, y, z)$, t is time, α is the air absorption coefficient, $\sigma(R)$, and $K_n(R)$ are the attenuation cross-section and droplet absorption efficiency factors, respectively, $\varphi(R', R)$ is the size distribution function of the droplet fragments of radius R' due to explosion, $T_b = 578$ K is the explosive vaporization temperature, t_b is the time it takes the droplet to reach T_b, R_k is the droplet threshold radius. For incident intensity I, $C = 33$ W/cm is constant obtained from fitting the experimental data, $\delta(u)$ is the Dirac delta function, $\theta(u)$ is the unit step function ρ_b, C_b, L are the density, specific heat, and water evaporation heat, respectively, β_t is the vaporization efficiency factor derived from the droplet mass-energy balance relations[1], T_0 is the ambient temperature, ρ is the transverse radius vector, $I_0(\rho, t)$ is the fluctuating radiation intensity upon entry to the droplet medium.

Note that Eq. (2) for droplet-size distribution dynamics accounts for the possibility of droplet explosive fragmentation (non-zero right-hand side) and relations (4) and (5) define droplet-explosion conditions.

Consider first a simplified model of the clearing of an aerosol droplet medium by a pulsed beam that will enable us to derive analytical relations with which we can estimate the time-dependent intensity fluctuations which take place during the laser-medium interaction. The intensity of the hole-boring beam is assumed to be insufficient for droplet explosion to occur. To be more exact, random intensity excursions which exceed the explosive threshold I_{th} are unlikely to take place. In this case clearing of the medium will have a regular pattern and Eqs. (1)–(6) are reduced to Eqs. (1) and (2) with zero right-hand side, and Eq. (3) with boundary and initial conditions (6). Then the water-content approximation and the assumption of that β_t is constant yield the following expression for the boring-beam intensity at the end of the path with optical thickness τ_0:

$$I(\rho,z,t) = \frac{I_0(\rho,t)}{\left[1+(\exp(\tau_0)-1)\exp(-\mu\int_0^t dt'\,I_0(\rho,t')\right]}, \quad (7)$$

where $\mu = \frac{3\beta_\tau A_n}{4\rho L}$, $A_n = 10^3$ cm^{-1} is the water-content approximation parameter.

Assumin gaussian intensity fluctuations with[1] dispersive power $\sigma_0^2 = \frac{D_0^2}{\bar{I}_0^2} = \frac{\overline{I_0^2} - \bar{I}_0^2}{\bar{I}_0^2}$ at every point on the cross-section of the beam upon entranceinto the medium layer (the bars denote ensemble averaging over realizations), we have

$$\bar{I}(\rho,z,t) = \frac{1}{\sqrt{2\pi}D_0} \times$$
$$\times \int_{-\infty}^{\infty} \frac{I_0 \exp\left[-\frac{(I_0-\bar{I}_0)^2}{2D_0^2}\right] dI_0}{\left[1+(\exp(\tau_0)-1)\exp(-\mu\int_0^t dt'\,I_0(\rho,t')\right]} \quad (8)$$

$$\overline{I^2}(\rho,z,t) = \frac{1}{\sqrt{2\pi}D_0} \times$$
$$\times \int_{-\infty}^{\infty} \frac{I_0^2 \exp\left[-\frac{(I_0-\bar{I}_0)^2}{2D_0^2}\right] dI_0}{\left[1+(\exp(\tau_0)-1)\exp(-\mu\int_0^t dt'\,I_0(\rho,t')\right]^2} \quad (9)$$

It should be noted at this point that this kind of representation is only valid with the proviso that $\bar{I}_0^2 / 2D_0^2 \gg 1$.

Let us calculate now the dispersive power of the intensity fluctuations $\sigma_I^2 = \frac{\overline{I^2} - \bar{I}^2}{\bar{I}^2}$. It is clear from Eqs. (8) and (9) and from physical considerations that at the initial moment of the interaction and after a period of time $t \gg \tau_0/\mu I_0$ exceeding the characteristic time of clearing of a medium with an optical thickness τ_0 the dispersive power σ_I^2 should approach σ_0^2. Therefore it would be of interest to calculate σ_I^2 at intermediate times when the medium is not entirely cleared. This kind of treatment corresponds to the case in which the inequality $(\exp(\tau)-1)\exp\left(-\mu\int_0^t dt' I_0(\rho,t')\right) \gg 1$ holds and Eq. (7) for $I(\rho, z, t)$ is recast in the following form

$$I(\rho,z,t) \approx I_0(\rho,t)(\exp(\tau_0)-1)\exp(-\mu\int_0^t dt'\,I_0(\rho,t')) \quad (10)$$

Assuming further that the hole-boring is rectangular and making use of expression (10), we obtain for the intensity and dispersive power of into the medium layer (the bars denote ensemble the intensity fluctuations

$$\bar{I}(r,t) \approx \bar{I}_0(1+\sigma_0^2\bar{q}_0)\exp(-\tau_0+\bar{q}_0(\rho,t))\times$$
$$\times\exp(\sigma_0^2 q_0^2/2) \tag{11}$$

$$\sigma_I^2 = \sigma_0^2\exp(\sigma_0^2\bar{q}_0^2(\rho,t))\times$$
$$\times\left[\frac{1+\sigma_0^2(1-\exp(-\sigma_0^2\bar{q}_0^2)+4\bar{q}_0(1-1/2\exp(-\sigma_0^2\bar{q}_0^2)}{1+2\sigma_0^2\bar{q}_0 \quad +\sigma_0^4\bar{q}_0^2}+\right.$$
$$\left.+\frac{4\sigma_0^2\bar{q}_0^2(1-\exp(\sigma_0^2\bar{q}_0^2))}{1+2\sigma_0^2\bar{q}_0 \quad +\sigma_0^4\bar{q}_0^2}\right], \tag{12}$$

where $\bar{q}_0(\rho, z, t) = \mu\bar{I}_0(\rho)t$ is the thermal-effect function. It can be seen from Eq. (11) that, as a result of droplet vaporization, the mean intensity at the end of the path, which at the initial instant of time is equal to $\bar{I}_0 e^{-\tau_0}$, monotonically increases as the interaction time t (or q_0) is increased. In so doing, the greater is σ_0 at the time satisfying the relation $\sigma_0^2 < 1$, the higher is $\bar{I}(r,t)$ at any arbitrary instant of time. It follows from Eq. (12) that $\sigma_I^2 = \sigma_0^2$ at $t = 0$ ($q_0 = 0$) will subsequently increase with increasing interaction time and for $\sigma_0 q_0 > 1$ the temporal dependence of σ_I^2 becomes exponential

$$\sigma_0^2 \approx \sigma_0^2\exp(\sigma_0^2\bar{q}_0^2(\rho,t) >> \sigma_0^2 \tag{13}$$

The value of σ_I^2 may significantly exceed the initial dispersive power of the intensity fluctuations σ_0^2 due to the nonlinear interaction of the radiation with the medium. Note that relative intensity fluctuations grow in time (for $(\exp(\tau_0) - 1)\exp(-\bar{q}_0) > 1$) in spite of the increase in the intensity. This is due to enhanced intensity fluctuations and a deeper optical thickness in the time interval in which the process of medium clearing is most active.

Representative curves describing the behavior thermal effect of σ_I^2 as a function of $\bar{q}_0$ (or of time) over a wide range of the thermal-effect function S, obtained by numerical calculations based Eqs. (8) and (9), are plotted in Fig. 1. The calculations were carried for clearing of an aerosol droplet medium of initial optical thickness τ_0 = 5, 10, and 15 by fluctuating radiation with σ_0^2 = 0.25. The maximum relative intensity fluctuations are seen to occur in those situations in which the medium (for a given optical thickness) is not completely cleared. It is in such cases that intensity fluctuations of the hole-boring radiation lead to significant fluctuations of the optical thickness and the response of the medium to the radiation appears to be most pronounced. It also follows from Fig. 1 that as the interaction time is increased ($\bar{q}_0 > \tau_0$) and the medium becomes optically transparent, σ_I^2 tends to σ_0^2 at the end of the path.

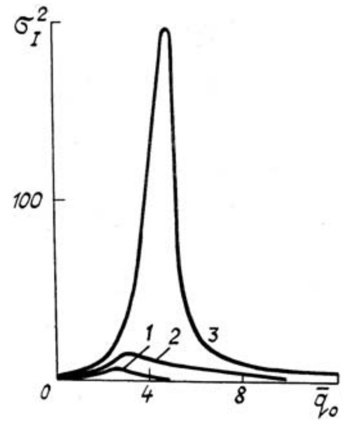

FIG. 1. Dispersive power σ_I^2 of the hole-boring beam intensity fluctuations vs the thermal-effect function.

Aerosol droplet medium stochastization in the course of penetration of the medium by radiation of fluctuating intensity causes considerable fluctuations of the probing beam that follows its hole-boring counterpart along the cleared path. The maximum dispersive power of the relative intensity fluctuations of the probing radiation in the visible dramatically exceeds that of the hole-boring beam because aerosol media with typical cloud-microstructure parameters are most optically active at the probing wavelength. Calculations of σ_p^2 confirm this fact.

Consider now a situation where both the mean and the instantaneous intensity of the hole-boring beam exceed the threshold value I_{th} for explosive droplet fragmentation. It is no longer possible to obtain simple relationships for the purpose of estimating the variations of the radiation intensity fluctuations in the nonlinear interaction, wherefore the problem is solved numerically using the full system of equations (1)–(5). Again it is assumed that the initial intensity fluctuation distribution is Gaussian. System of equations (1)–(6) was solved for each random realization of the initial intensity distribution and thereupon the statistical characteristics of the beam were obtained by averaging over the ensemble of realizations. The medium parameters used in the calculations were as follows: initial water content $W_0 = 3.10^{-7}$ g/cm^3, modal droplet radius R_m = 5 μm, droplet fragment radius r_m = 0.5 μm, gamma distribution parameters for droplets and their fragments μ = 3 and μ′ = 3, respectively. The calculations were carried out for hole-boring CO_2laser beams with mean intensities $\bar{I}_0(0) = 10^5$ W/cm^2 and

10^3 W/cm^2. The latter value, which was taken for comparison, produces clearing in the regular droplet vaporization regime.

Note that, unlike the situation treated in the first part of this work, the problem of regular clearing is here given a more rigorous consideration. First, the dependence of β_T on the radiation intensity and droplet size R is taken into account; second, more precise tabular data on scattering and absorption factors are used here instead of the linear dependence of these coefficients on R typically adopted in the water-content approximation.

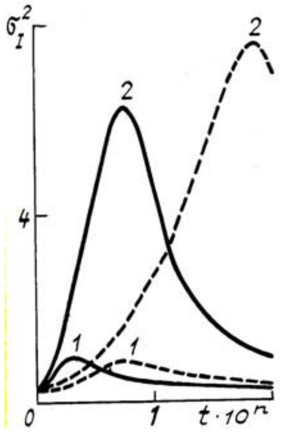

FIG. 2. σ_I^2 as a function time, $\tau_0 = 3(1)$, $\tau_0 = 10(2)$. Solid lines (——) denote the case for $\bar{I}_0(0) = 10^5$ W/cm^2, n =4; dashed lines (------) denote the case for $\bar{I}_0(0) = 10^3$ W/cm^2, n = 2.

The results of our calculations are presented in the form of plots of the time dependence of the dispersive power fluctuations of the hole-boring (σ_I^2) and probing ($\sigma_{I_p}^2$) beams in Figs. 2 and 3, respectively. It is clearly evident from Fig. 2 that the time dependence of σ_I^2 is analogous to that shown in Fig. 1. Both figures exhibit a characteristic maximum associated with the times at which a partial clearing of the medium is found to occur. It is also seen that in other words, move this phrase to the end of the sentence the maximum is attained within much shorter time intervals for the case of explosive aerosol clearing. This is quite natural because in this case the clearing efficiency increases both as a result of decreasing scattering losses due to fractionation of large droplets and also as a result of the realization of energetically more advantageous regimes of vaporization of the condensation phase. For this reason the maximum value of σ_I^2 is smaller for explosive clearing than for regular clearing conditions.

It also follows from the results obtained that the dependence of the mean hole-boring beam intensity is analogous to that cited for regular droplet destruction.

A different picture is observed for the fluctuation behavior of the probing beam (see Fig. 3). While $\sigma_{I_p}^2$ does increase and decrease much faster for explosive clearing than the regular clearing, the maximum value of $\sigma_{I_p}^2$ is much higher in the former case. This is due to the optical activity of a great number of small fragments produced by the explosion of large droplets at the hole-boring wavelength. Pulsations of the hole-boring radiation give rise to considerable variations of optical thickness at the probing wavelength. For $\bar{I}_0(0) = 10^5$ W/cm^2, the dynamics of the probing beam fluctuations is characterized by the presence of two extremes on the $\sigma_{I_p}^2$ curve. The latter is related to the fact that droplets explode layer by layer. The process involves first the front-layer droplets ($I > I_{th}$) and then, as the medium gets cleared, extends to the more deep-seated layers.

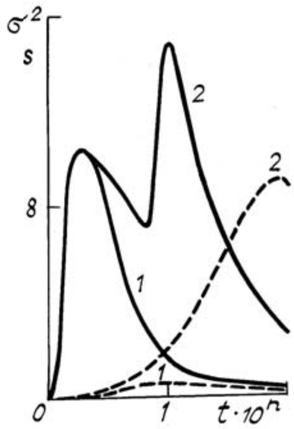

FIG. 3. Dispersive power of the intensity fluctuations of the probing beam as a function of clearing time, $\tau_0 = 3(1)$, $\tau_0 = 10(2)$. Solid lines (———) denote the case $\bar{I}_0(0) = 10^5$ W/cm^2, n = 4; dashed lines (-------) denote the case $\bar{I}_0(0) = 10^3$ W/cm^2, n = 2.

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