DEFOCUSING OF A LASER BEAM UNDER CONDITIONS OF THERMAL BLOOMING

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In this paper we discuss some results of experimental studies of the laser beam thermal blooming. The influence both an atmospheric path and zone of stagnation between the laser source and the optical system on the beam defocusing are analyzed.

When high power laser radiation propagates through the atmosphere, the energy absorbed by atmospheric gases and aerosols causes a change of refractive index of the air and aerosol particles and, as a result, changes in the parameters of the radiation itself as well as sounding beams propagating through such a refractive channel. Mechanisms of such an interaction are of a great variety and defined by many factors. The principle ones among them are the following: total power, power density, duration and (lasing pulsed, CW or frequency–pulsed) regimes of source generation, geometric form of a beam (dimensions, focusing, and intensity distribution over cross–section), propagation conditions (molecular and aerosol absorption, velocity and direction of the wind, homogeneity of the path, and turbulence strength). Problems concerned with the propagation of radiation under conditions of thermal blooming attract sufficiently much attention in both experimental and theoretical studies.[1–3]

The lowest threshold mechanism of radiation interaction with the atmosphere from the standpoint of the power is the thermal blooming being determined by transfer of the absorbed power into heat and corresponding change in the refractive index. The theory allowing for all the peculiarities of radiation interaction with the real atmosphere have not founded yet. Therefore, the experimental studies especially under conditions of the real atmosphere are of a great importance and of interest for developers of adaptive optics systems.

This paper gives the results of experimental studies of the defocusing of laser beam propagating through the atmosphere under conditions when a principle mechanism of interaction is thermal nonlinearity. It is known that one of the basic factors, which determine the thermal nonlinearity effect on the laser beam parameters, is the condition of heat transfer from the thermal channel created by the radiation.[1–3] Therefore, when analyzing the results of studies, according to the propagation conditions the path was divided into two sections, namely, section of stagnation between the laser source and optical system and atmospheric section of the path extended from the optical system to the target.

The section of stagnation is characterized by the small length, relatively high power density, unchanged beam geometry (small divergence, stability of dimensions), and, in the majority of cases, by absent or very low velocity of heat transfer away from the channel with the air flow. The second section has a greater length above the relatively smooth underlying surface, smaller power density, path–varying geometry (focusing) of the beam, and sufficiently high velocity of heat transfer away from the channel due to the atmospheric wind. An analysis of these sections effects on the thermal blooming of laser beam is presented in this paper. When the studies were carried out, the following parameters were measured: meteorological ones (temperature, wind velocity and wind direction, relative air humidity, and pressure), radiating power at the output of source, and power distribution at the end of atmospheric path.

To calculate the radiation absorption coefficients α_{abs} from the measured values of temperature t, C°, humidity U%, and pressure P for the mean concentration of carbon dioxide (0.033%) the known relationships[4,5] were used

$$\alpha_{H_2O} = 1.76{\cdot}10^{-3}\, e\,(1 + 1.78{\cdot}10^{-3} P) +$$

$$+ 0.42{\cdot}10^{-6}\, e \exp[2273/(273 + t)],$$

$$e = 13.25\, U/(273 + t) \exp[17.58/(241.9 + t)],$$

$$\alpha_{CO_2} = 386\,(273 + t)^{-1.5} \exp\{(2232\,[1/296 - 1/(273 + t)]\},$$

$$\alpha_{abs} = \alpha_{H_2O} + \alpha_{CO_2}, \tag{1}$$

where e is the absolute humidity of air and α_{H_2O} and α_{CO_2} are the absorption coefficients for radiation by the water vapor and carbon dioxide, respectively.

The influence of temperature on thermal defocusing is described by the generalized nonlinearity parameter N_c which takes into account the propagation conditions and beam parameters[1]:

$$N_c = (dn/dt)\,(\alpha_{abs}\, P_0\, L^2 / \rho\, C_p\, V_\perp\, a^3)\, f(a) = N_c^0\, f(a), \tag{2}$$

where dn/dt is the temperature gradient of the refractive index of air; ρ, C_p are the density and heat capacity of air; $V_\perp$ is the perpendicular component of mean wind velocity; a is the beam radius; P_0 is the radiating power; $f(a)$ is the function allowing for the variation of the beam radius along the propagation path; and, L is the path length.

At the initial section of the path (zone of stagnation) the heat transfer away from the channel in the steady–state regime occurs through the convection caused by heating up of air by absorbed radiation. The velocity V_{con} of such convection is determined by the ratio[1]

$$V_{con} = (\alpha_{abs}\, g\, \beta\, P_0 / 2\pi\, \rho\, C_p)^{1/3}, \tag{3}$$

where g is the acceleration due to gravity and β is the thermal expansion coefficient of air.

Therefore the nonlinearity parameter at the section of stagnation is

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$$N_c^{st} = A_1 (\alpha_{abs} P_0)^{2/3} . \quad (4)$$

At the atmospheric section of path the parameter N_c is determined by the relationship[1]

$$N_c^{end} = N_c^0 F [2F/(F - 1)] \{1 - \ln(F)/(F - 1)\} =$$

$$= A_2 (\alpha_{abs} P_0/V_\perp) , \quad (5)$$

where $F = a_1/a_f$, a_1 and a_f are the beam radii at the start and end of the path for $t = 0$; A_1 and A_2 are the constant coefficients for the given beam geometry.

The results of studies were systematized based on two beam parameters: the change in relative power density at the maximum of the beam energy distribution and relative change in the beam radius at the end of measurement path.

Since the propagation path consisted of the two parts which were strongly distinguished by condition of heat transfer in the area of beam localization, the general nonlinearity parameter N_c was set equal to the sum of the nonlinearity parameters, corresponding to these separate parts of the path: $N_c = N_c^{st} + N_c^{end}$.

Figure 1 shows the relative power density $\delta = E_m/(kE_0)$ as a function of the nonlinearity parameter N_c, where E_m is the power density at the maximum and E_0 is the total output power of a source. The coefficient k takes into account the attenuation of radiation by the atmosphere and losses due to optical elements. The points are the experimental data and the solid curve shows the dependence $\delta = 0.22N_c^{-0.36}$ calculated by the least–square technique. The correlation coefficient R equals 0.35.

An analysis of the results of studies shows that in spite of the great spread in the experimental data the pronounced tendency to more than two times decreasing in the power density can be observed when the nonlinearity parameter N_c changes from 0.4 up to 2. The great data spread over the experimental error limits for $N_c < 1$ when the contributions of the atmospheric section and section of stagnation are comparable, shows that the simple arithmetic summation of the parameters N_c^{st} and N_c^{end} is not quite correct to describe the whole path and each section ought to be accounted with its own weight in the sum.

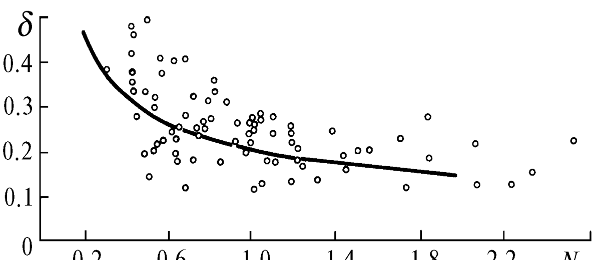

FIG. 1. The relative power density at the maximum δ as a function of the generalized nonlinearity parameter N_c.

When analyzing the results of studies of the beam defocusing the data were divided into two groups according to the propagation conditions at the atmospheric section of the path. These conditions are determined by the mean value of the perpendicular component of mean wind velocity $V_\perp$. The data for $V_\perp > 1$ m/s are referred to the first group (Fig. 2) and the data for $V_\perp \approx 0$ (Fig. 3) – to the second group. The beam radius normalized to the beam radius averaged over all the measurements at the end of the path at the moment $t = 0$ is plotted on the ordinate. The time normalized to the time of heat transfer away from the channel $\tau = 2a/V_\perp$ is plotted along the horizontal axis in Fig. 2 and the time t – in Fig. 3. The averaged experimental dependences of beam radius on time are shown in Figs. 2 and 3 by solid curves.

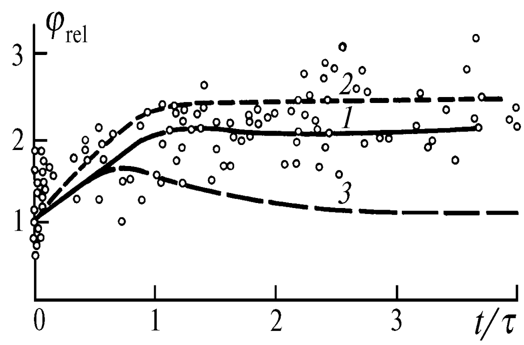

FIG. 2. The change in the relative beam radius $\varphi_{rel} = a(t)/a(0)$ with the time t normalized to $\tau = 2a/V_\perp$ for $V_\perp > 1$ m/s. The points are the experimental data, curve 1 shows the averaged experimental time–dependence. Curves 2 and 3 represent the results of calculation in the case of absence of wind velocity fluctuations in the atmosphere $\sigma_v/V_\perp = 0$ (curve 2) and $\sigma_v/V_\perp = 0.2$ (curve 3).

An analysis of the results presented in Fig. 2 ($V_\perp > 1$) and estimations obtained allow us to draw the following conclusions:

– the changes in the mean beam radius and root–mean–square deviation of this radius at $t = 0$ are determined by the turbulence effect and accuracy of optical system alignment;

– the time of transition to the steady–state regime of defocusing is determined by the perpendicular component of mean wind velocity and is close to $\tau = 2a/V_\perp$;

– the change in the beam radius at the nonsteady regime ($t/\tau < 1$) is approximated by linear function of the form $\varphi_{rel} = 1 + 1.2t/\tau$ with the correlation coefficient $R = 0.65$;

– the beam radius in the steady–state regime ($t/\tau > 1$) is mainly determined by the influence of the section of stagnation. The dependence of the beam radius on the nonlinear parameter at the atmospheric section and total value of N_c is slight as compared with dependence on N_c^{st}.

An analysis of the results presented in Fig. 3 ($V_\perp \approx 0$) and estimation obtained allow us to draw the following conclusions:

– the beam thermal blooming is 1.5 or 2 times as large as than in the presence of the perpendicular component of wind velocity;

– when the time $t < 0.6$ s the beam defocusing is not approximated by the linear function.

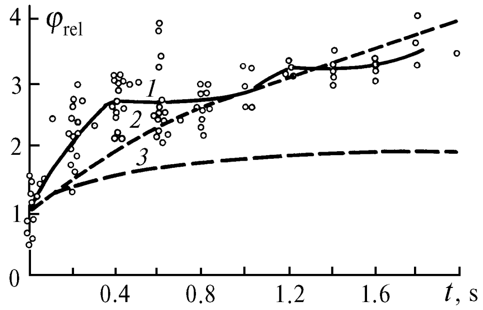

FIG. 3. The change in the relative beam radius $\varphi_{rel} = a(t)/a(0)$ with the time t at $V_{\perp} \approx 0$. The points are the experimental data, curve 1 (solid) shows the averaged experimental time–dependence. Curves 2 and 3 represent the results of calculation in the case of absence of wind velocity fluctuations in the atmosphere $\sigma_V/V_{\perp} = 0$ (curve 2) and $\sigma_V/V_{\perp} = 0.2$ (curve 3).

It is known[5] that the beam thermal blooming sufficiently depends on the fluctuations in the wind velocity and wind direction along the propagation path. The data shown by dashed curves in Figs. 2 and 3 are calculated in the nonaberration approximation under the following conditions: the relative wind velocity fluctuations $\sigma_V/V_{\perp} = 0$ (curve *2*); $\sigma_V/V_{\perp} = 0.2$ (curve *3*) (σ_v is the root–mean–square deviation of the wind velocity); the refractive index fluctuations are ignored ($C_n^2 = 0$), because their contribution into the defocusing is small as compared with thermal blooming; and the nonlinearity parameter is $N_c = 2.2$.

A comparison between the calculated and experimental data confirms qualitatively the conclusions drawn from the theory about the influence of the wind velocity fluctuations on the time of transition to the steady–state regime of thermal blooming. This agreement becomes worse for the small or longitudinal along the path wind velocities (Fig. 3). Probably, that is related to the neglected effect of the section of stagnation where the time of transition to the steady–state regime is comparable or less than at the atmospheric section of the path.

Thus, on the basis of the presented results the following conclusions can be made:

– the parameter N_c can be used to estimate the beam defocusing and maximum intensity in the real atmosphere;

– the path section between the laser source and optical system forming the radiation beam mainly contributes to the beam defocusing whereas the thermal blooming along the atmospheric path is relatively slight. This fact ought to be taken into account in the adaptive systems in which the beam control is carried out at the output of optical system;

– the qualitative experimental confirmation of influence of wind velocity fluctuations on beam defocusing indicates the need of the purposeful experiments intended to find the precise regularities of this influence.

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