PROPAGATION OF WIDE-APERTURE LASER BEAMS THROUGH THE ATMOSPHERE

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This paper presents the results of theoretical studies on the propagation through the atmosphere of wide-aperture laser beams (i.e., those whose diffraction length is much larger than the thickness of the active atmospheric layer with thermal blooming taken into account. The average energy characteristics of the beams in the observation plane are calculated for both partially and completely coherent laser radiation. The results obtained for both of these cases are shown to be in good mutual agreement over a wide range of laser radiation output parameters.

In recent years there has been no lack of interest in the problem of atmospheric long-range transport of laser radiation energy.[1] For lasers operating in the IR the most important effects which determine the fraction of energy transported are molecular absorption, thermal self-action, and eddy blooming.[4] The beam divergence in a laser constructed to transmit energy through the atmosphere exceeds the diffraction limit by a factor of several units. Such a beam divergence is the result of various physical processes occurring within the active laser medium (see, e.g.. Ref. 5), the multimode structure of the outgoing radiation,[6] and other causes.

The diverse nature, the variety, and the statistical independence of the physical mechanisms leading to the deterioration of the divergence characteristics of the laser significantly hinder a deterministic description of the phase parameters of the laser radiation. Therefore statistical approaches seem to be the most promising for describing such characteristics of IR lasers;[4,7] these assume partial coherence of the laser radiation. However, numerical modeling of the propagation of partially coherent laser radiation through the atmosphere meets with additional difficulties, associated with the higher dimensionality of the investigated functions,[4,7] in comparison with completely coherent radiation. This results in a significant increase in the requirements on the computers used in such calculations.

This paper describes the results of numerical simulations of the propagation of coherent and partially coherent radiation with the goal of comparing the two representations of laser energy transport from the Earth's surface to outer space through the nonturbulent atmosphere, with thermal self-action taken into account. A geometrical depiction of the problem is shown in Fig. 1. The assumption of the absence of eddy fluctuations in the atmosphere is usually justified, since the initial divergence of the radiation and the characteristic angles of refraction of the rays corresponding to the thermal density gradients of this medium usually far exceed the angle of eddy blooming of laser beams along vertical atmospheric beam paths.[4]

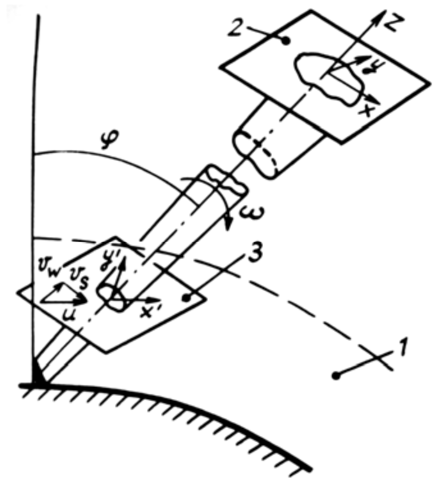

FIG. 1. Geometrical diagram of the problem: 1 — surface atmospheric layer; 2 — observation plane; 3 — intermediate computational plane; $z = z_i$, $v_C = 2\pi\omega z_i/360°$— linear scan rate; φ — zenith angle; $\omega = \partial\varphi/\partial t$ — angular scan rate.

1. MODEL OF PROPAGATION OF COHERENT RADIATION

This model is based on the self-consistent solution of the paraxial equation of wave optics, which accounts for refraction of radiation by the density inhomogeneities of the medium, together with the stationary equation of gas dynamics in the acoustic approximation. The latter takes into account heating of the gats medium by radiation and dissipation of the absorbed energy as the result of forced convection (due to wind and scanning of the laser beam).[4] The system of equations for the model looks as follows:

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$$2ik\frac{\partial\Psi}{\partial z} + \Delta_\perp\Psi + 2k^2 g(z)\rho'(x, y, z)\Psi/\rho_0(z) + ik\kappa(z)\Psi = 0, \quad (1)$$

$$\Delta_\perp = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2},$$

$$u(z)\frac{\partial}{\partial x'}\left[a^2(z)\Delta'_\perp - u^2(z)\frac{\partial^2}{\partial x'^2}\right]\rho'(x', y', z') = (\gamma - 1)\rho_0(z)\, a^2(z)\kappa(z)\,\Delta'_\perp I(x', y', z)/\gamma p_0(z), \quad (2)$$

$$I(x', y', z) = \Psi(x', y', z)\,\Psi^*(x', y', z),$$

where xyz and $x'y'z'$ are the Cartesian coordinate systems. The z axis is directed along the propagating beam; the x axis – along the direction of beam scanning; the x' axis – along the velocity vector $u(z)$ for gas evacuation from the beam channel due to forced convection; it is determined for each section z = const. $\rho_0(z)$ and $p_0(z)$ are the nonperturbed air density and pressure; $a(z)$ is the speed of sound; $g(z)$ is the Gladstone-Dale constant; $\kappa(z)$ is the absorption coefficient; γ is the ratio of specific heats; ρ' is the perturbed gas density; and, finally, Ψ and k are the wave function and wave number. In general, when the scanning is in a direction different from that of wind, the coordinate system $x'y'z'$ does not coincide with the coordinate system xyz.

Since the molecular absorption coefficient decreases with altitude, scanning at a sufficiently high angular velocity leads to such a situation that the principal input to the deterioration of the radiation characteristics associated with thermal self-action is produced by the atmospheric layers closest to the radiation source. Subsonic speeds of forced convection $u(z) < a(z)$ are typical for these layers, so that Eq. (2) remains elliptical. Numerical solution of Eq. (2) was obtained using the cyclic reduction technique. The solution of Eq. (1) over the initial section of the beam path was generated using the decomposition and the Fourier fast-transform techniques, and further up the path – by means of the Fresnel-Kirchhoff integral.

2. MODEL OF PROPAGATION OF PARTIALLY COHERENT RADIATION

Propagation of partially coherent laser beams through the atmosphere was modeled using the self-consistent solution of the transfer equation together with the material equation (2). As was shown in Refs. 10–12, the transfer equation adequately describes the propagation of radiation through the atmosphere if the characteristic time of the intensity fluctuations is low in comparison with the medium response time to these fluctuations, and the coherence radius for radiation ρ_k is considerably less than the effective transverse dimension of the beam. If these conditions are satisfied, the transfer equation assumes the form

$$\frac{\partial J}{\partial z} + \vec{\theta}\,\nabla_{\vec{R}} J + \nabla_{\vec{\theta}} J\,\nabla_{\vec{R}} n = 0, \quad (3)$$

where $J(\vec{R}, \vec{\theta}, z)$ is the Wigner function, which is related to the mutual coherence function $\Gamma(\vec{R}, \vec{\rho}, z)$ of the laser beam by the Fourier transform with respect to the difference coordinate ρ; n is the refractive index of the medium;

$$\Gamma(\vec{R}, \vec{\rho}, z) = \int d^2\vec{\theta}\, J(\vec{R}, \vec{\theta}, z)\exp(ik\vec{\theta}\vec{\rho}).$$

The values of the vector $\vec{R} = (\vec{r}_1 + \vec{r}_2)/2$, $\vec{\rho} = \vec{r}_1 - \vec{r}_2$ depend on the mutual location of the two considered points $\vec{r}_m = \vec{i}x_m + \vec{j}y_m$, $m = 1, 2$ in the plane normal to the beam propagation axis.

Applying the technique of characteristics to the transfer equation (3) we obtain the following system of ordinary differential equations:

$$d\vec{R}/dz = \vec{\theta}, \quad d\vec{\theta}/dz = \nabla_{\vec{R}}\, n(\vec{R}, z). \quad (4)$$

To solve system (4) together with the material equation (2), a special technique was used, based on computing the trajectories of a set of rays emitted from every point of the radiating aperture at various angles θ_0 and passing through a sequence of refracting screens, which model the nonlinear medium. To find the mean intensity in this way (it enters into Eq. (2) as the heat source) the Wigner functions corresponding to the individual rays which arrive along different directions at the given spatial element[13] were integrated over the angular coordinate

$$\langle I(\vec{R}, z)\rangle = \int d\vec{\theta}\, J(\vec{R}, \vec{\theta}, z). \quad (5)$$

To apply this technique we do not need to impose any additional physical restrictions, except for those mentioned above, in contrast with the technique presented in Ref. 14.

3. RESULTS OF NUMERICAL EXPERIMENTS

An intercomparison was made of the results of numerical experiments based on the above-described models for the case of transport of $^{12}C^{16}O_2$ laser radiation through the atmosphere using the following typical atmospheric conditions and radiation parameters:

– atmospheric climatic model – mid-latitude summer, USSR;

– distance to observation point $L = 0.6kR_0^2$, R_0 – the radius of the emitting aperture;

– zenith angle $\varphi = 45°$ (see Fig. 1);

– wind velocity at the Earth's surface along the x axis – 3.9 m/s; along the axis y axis – 0 m/s;

– angular rate of laser beam scanning – $\omega = 0.76$ rad/s;

– intensity distribution at the emitter aperture:

$$I(x, y, 0) = I_0 \exp(-(r^2/R_0^2)^5), \quad r^2 = x^2 + y^2;$$

– angular characteristics of the laser radiation: coherent radiation propagation model - parabolic phase distribution

$$S(x, y, 0) = k\theta_{11}\theta_d r^2/4R_0;$$

partially coherent propagation model – Gaussian distribution of the Wigner function along the angular coordinate:

$$J(\vec{R}, \vec{\theta}, 0) = I(\vec{R}, 0) \exp(-4\vec{\theta}^2/\vec{\theta}_{12}^2).$$

Here θ_{k1} and θ_{k2} are the characteristic angles of laser beam divergence, normalized by the diffraction divergence angle $\theta_d = 1.22\lambda/R_0$.

Note that the radiation divergence angles θ_{11} and treated below exceed the angle of eddy blooming of laser beams in the atmosphere θ_e. the latter varying within the range $4 \cdot 10^{-6}$–$1.5 \cdot 10^{-5}$ rad for radiation at the wavelength $\lambda = 10.6$ μm.

Figure 2 presents the isophotes realized in the observation plane, calculated for coherent (see Fig. 2b) and partially coherent (Fig. 2a) radiation with power $P = 5$ MW, divergent at twice the diffraction limit. The calculated spatial distribution of the radiation intensity appears to be very similar to that obtained as the solution for radiation propagation along horizontal atmospheric beam paths in the presence of forced convection.[3] Its typical features include the formation of a sickle-shaped beam profile and the shift of the beam energy center of gravity in the direction opposite to that of the scanning velocity vector. Comparison of the isophotes presented in Figure 2 demonstrates that a more irregular spatial intensity distribution, due to the nonlinear effect of thermal self-action, is typical of coherent radiation. The levels of the local minima and maxima of the intensity differ by 50% from similar values calculated for partially coherent radiation.

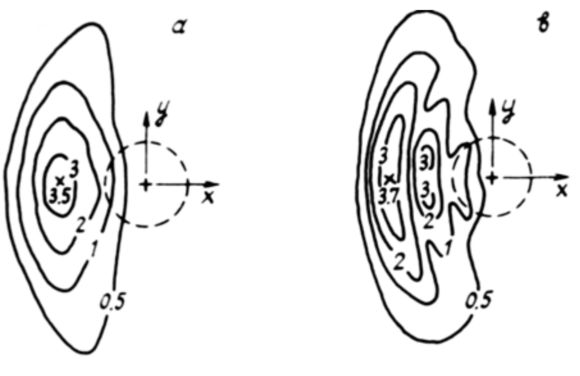

FIG. 2. Isophotes in the observation plane for the cases of partial (a) and total (b) coherence of CO_2-laser radiation (emitted power 5 MW, divergence $\theta_{12} = \theta_{11} = 2\theta_{dl}$). The dashed line indicates the characteristics dimension of the laser beam in the observation plane for the case of no thermal self-action.

In actual fact, the jitter of the guidance systems, atmospheric turbulence, and unpredictable atmospheric conditions lead to spatial "smearing" of the calculated intensity distribution. In this connection one should hardly expect that the models used will enable a detailed description of the local structure of the actual spatial intensity distribution in the observation plane. The data on the average energy parameters of the radiation computed from these models should prove more reliable. We regard the position of the beam energy center of gravity as one such parameter. Its coordinates are given by the following expressions:

$$\vec{r}_c = (x_c, y_c) = \int_{-\infty}^{+\infty} dx \int_{-\infty}^{+\infty} dy \, \vec{r} I(x, y, L) \times \left[\int_{-\infty}^{+\infty} dx \int_{-\infty}^{+\infty} dy \, I(x, y, L) \right]^{-1},$$

where $I(x, y, L)$ is the radiation intensity in the observation plane.

Figure 3 presents the results of calculations of the shift in the position of the beam energy center of gravity, according to each model, as a function of the laser power. The linear dependence of this shift on the emitter power and the good quantitative agreement between the results indicate that such a shift takes place at close distances from the emitter and results from thermal self-action. Due to the low divergence of the laser radiation the spatial intensity distribution remains practically unchanged within this range and does not depend on the model chosen to describe the process of laser beam propagation. It is seen from Fig. 3 that thermal self-action is significant when the emitter power exceeds 2–3 MW. In that case the shift of the beam center of gravity starts to exceed the characteristic size $R_* = \theta_{12}L/2$, which is determined by the initial divergence of the beam.

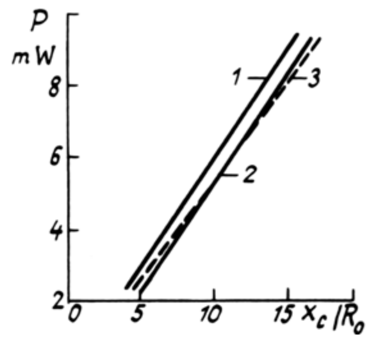

FIG. 3. Dependence of the shift of the beam energy center of gravity along the direction of scanning on the laser emitter power for the totally coherent (solid lines) and partially coherent (dashed line) CO_2-laser radiation with divergence $\theta_{11} = 3\theta_d$ (1); $2\theta_d$ (2); $\theta_{12} = 2\theta_d$ (3).

We regard the power P_a passing through a square of side a, its center coinciding with the energy center of gravity of the beam, as another parameter governing the energy characteristics of radiation:

$$P_a = \int_{-a/2}^{a/2} d(x - x_c) \int_{-a/2}^{a/2} d(y - y_c)\ I(x, y, L).$$

The dependence of the power P_a on the side length of the square a, calculated from both models for lasers of different output power and divergence, is presented in Fig. 4.

The model of coherent radiation propagation satisfactorily describes the energy parameters of the propagated radiation under conditions of strong thermal self-action, even when the initial radiation divergence exceeds the diffraction limit by a factor of 5 (Fig. 4b). The best agreement with the results from the model of partially coherent radiation is obtained when the limiting divergence angle for the totally coherent radiation somewhat exceeds the corresponding angle for the partially coherent radiation. This comparison also demonstrates that the model of the partially coherent radiation describes quite well the propagation of radiation with divergence close to the diffraction limit (Fig. 4a), though the coherence radius in that case becomes comparable to the radius of the laser beam itself.

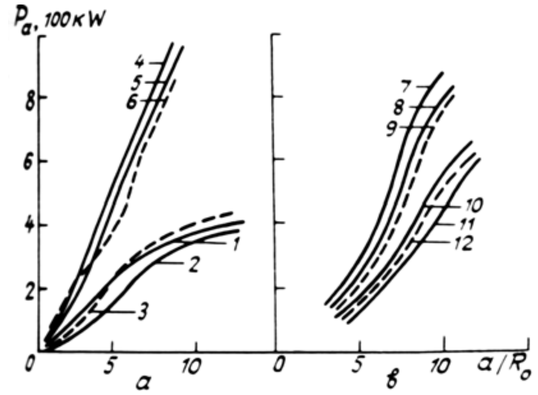

FIG. 4. Power of the radiation passing through a square of side a in the observation plane, its center coinciding with the beam energy center of gravity. Beam divergence $2\theta_d$ (a) and $5\theta_d$ (b). Notation the same as in Fig. 3. $P = 2$ MW, $\theta_{11} = 2.5\theta_d$ *(1)*, $\theta_{11} = 3\theta_d$ *(2)*, $\theta_{12} = 2\theta_d$ *(3)*, $P = 10$ MW, $\theta_{11} = 2.5\theta_d$ *(4)*, $\theta_{11} = 3\theta_d$ *(5)*, $\theta_{12} = 2\theta_d$ *(6)*, $\theta_{11} = 5\theta_d$ *(7)*, $\theta_{11} = 6\theta_d$ *(8)*, $\theta_{12} = 5\theta_d$ *(9)*, $P = 5$MW, $\theta_{11} = 5\theta_d$ *(10)*, $\theta_{11} = 6\theta_d$ *(11)*, $\theta_{12} = 5\theta_d$ *(12)*.

These numerical experiments modeling the propagation of CO_2-laser radiation through the atmosphere, performed over a wide range of output laser parameters (emitter power 1–10 MW, divergence – within 2–5 diffraction limits) demonstrated the following:

1. The considered model of propagation of partially coherent radiation makes it possible, despite the simplifications introduced, to calculate the propagation through the atmosphere of wide-aperture laser beams with divergence exceeding the diffraction limit by a factor of two or more.

2. To describe the average energy characteristics of laser beams propagating through the atmosphere, a model of coherent radiation.

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