PROPAGATION OF A PROBING BEAM IN A RANDOM REFRACTION CHANNEL IN THE ATMOSPHERE

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Received July 29, 1991

An initially coherent probing beam propagating in a randomly inhomogeneous channel formed by powerfull heating radiation is theoretically analyzed. The relation is derived for the modulus of a spatial correlation function allowing one to trace the transformation of a probing beam width and of a correlation radius along the propagation path. The effects of asymmetrical defocusing and stochastic transformating a probing beam nonuniform in the transverse cross section as functions of the initial characteristics of beams and their relative position are analyzed.

INTRODUCTION

Use of the optical methods of probing of the refraction channels formed due to absorption of the intense optical radiation (IOR) in the atmosphere is of great practical interest for optical communication, detection and ranging, measurement of the flow velocities, range finding, as well as for operation of the systems of adaptive correction of the IOR distortions.[1-5] Stochastic character of the intense radiation and turbulent fluctuations of the refractive index of a medium would call for the statistical approach to the description of the transformation of the probing beam in the propagation channel.[1]

Propagation of the narrow partially–coherent beam through the medium, whose random inhomogeneities are described by the quadratic structural functions, was considered in Ref. 1. The structure of the probing beam in the presence of distortions of the IOR due to aberrations was investigated within the geometric optics approximation in Ref. 2. However, in the above–mentioned papers the effect was analyzed solely of natural turbulent fluctuations of the refractive index of the medium on the beam propagation.

Note that the scattering of the probing beam on the random inhomogeneities of the refractive index induced by the intense heating radiation significantly changes the pattern of transformation.

This paper is devoted to the theoretical analysis of propagation of the coherent probing beam in a randomly inhomogeneous channel formed by an intense heating radiation used for clearing up the cloud layers of the atmosphere. The scheme with two parallel beams is considered. It is shown that the transformation of the probing beam degrades its coherence already on the propagation paths before entering into clouds and the beam axis is displaced from the initial direction.

MATHEMATICAL FORMULATION AND METHOD OF SOLUTION

In quasioptical approximation, the propagation of the coherent probing beam with initial amplitude $A_p(x, y, z = 0) = \sqrt{I_0}\cdot\exp[-(x^2 + y^2)/2a_p^2]$ along the Z axis in the channel of intense multimode heating radiation displaced parallel to the probing beam along the X axis at a distance $\mathbf{l}_0 = (l_0, 0, 0)$ with the amplitude $A_h(x, y, z = 0) = \xi(x - l_0, y)\sqrt{I_0}\exp[-((x - l_0)^2 + y^2)/2a_h^2]$ can be described by the equation

$$\left(\frac{\partial}{\partial z} + \frac{i}{2k}\frac{\partial^2}{\partial \mathbf{r}^2} + \frac{\alpha}{2}\right)A_p(\mathbf{r}, z) = -\frac{ik_0}{n_0}n_{nl}(|A_h(\mathbf{r} - \mathbf{l}_0, z)|^2)A_p(\mathbf{r}, z), \quad (1)$$

where $\mathbf{r} = (x, y)$ is the coordinate transverse to the propagation direction (to the Z axis); k_0 is the wave number, $\xi(\mathbf{r})$ is the complex random process with the Gaussian correlation function and the correlation radius r_0 $<\xi(\mathbf{r})\,\xi^*(\mathbf{r} + \Delta\mathbf{r})> = \exp[-(\Delta\mathbf{r}/r_0)^2]$.

Nonlinear deviation of the refractive index n_{nl} from its undisturbed value n_0 is given by the material equation describing heat conduction and is determined by the intensity of heating radiation, because it is much higher than the intensity of the probing beam $I_h \gg I_p$:

$$\left(v_0\frac{\partial}{\partial(x - l_0)} - \chi\frac{\partial^2}{\partial(\mathbf{r} - \mathbf{l}_0)^2}\right)n_{nl}(\mathbf{r} - \mathbf{l}_0) = \frac{\alpha n_t}{\rho c_p}|A_h(\mathbf{r} - \mathbf{l}_0, z)|^2, \quad (2)$$

where α, χ, and n_t are the coefficients of absorption, molecular thermal diffusivity, and thermal nonlinearity, respectively (in the atmosphere $n_t < 0$); ρc_p is the heat capacity per unit volume at constant pressure; the velocity $\mathbf{v}$ is directed along the X axis, but in general the velocity vector lies in the XOY plane (we ignore the longitudinal component of the velocity vector along the Z axis, since it has no effect on the beam transformation[10]).

The system of Eqs. (1)–(2) can be solved by the method of a given nonlinear channel,[8] which determines the distribution of the refractive index n_{nl} over the refraction channel by the initial intensity of the heating light field. In this approximation we have succeeded in obtaining the sought–after solution in the integral form

$$A_p(\mathbf{r}, z) = -\frac{ik_0}{2\pi z}\int_{-\infty}^{\infty}\!\!\int d^2\rho A_p(\rho, z = 0) \times$$

$$\times \exp\left[-\frac{ik_0}{2z}(\mathbf{r} - \rho)^2 - \frac{ik_0}{n_0}\int_0^z n_{nl}(\rho, z')\,dz'\right] \quad (3)$$

It should be noted that this method is applicable only for the paths before entering into the clouds, where the effects accompanying the propagation of the intense laser beam through the ensembles of aerosol particles[7] can still be ignored.

0235-6880/92/01 42-04 $02.00

The regime of thermal blooming depends on the relation between the characteristic transite time of the medium $\tau_v = a_h/v$ and the characteristic time of thermal diffusion $\tau_\chi = a_h^2/\chi$. The effect of the thermal diffusion on the formation of the temperature channel is negligible ($\tau_v \ll \tau_\chi$) in the atmosphere under conditions of even not very strong wind ($v \sim 1$ m/s), and Eq. (2) can be given in the form

$$-v\frac{\partial n_{nl}(\mathbf{r}-\mathbf{l}_0)}{\partial(x-l_0)} = \frac{\alpha n_t}{\rho c_p}|A_h(\mathbf{r}-\mathbf{l}_0, z=0)|^2 . \qquad (4)$$

In this case the solution is

$$n_{nl}(\mathbf{r}) = -\frac{\alpha n_t}{\rho c_p v}\int_{-\infty}^{x}|A_h(\zeta, y)|^2 d\zeta . \qquad (5)$$

The modulus of the spatial correlation function for the probing beam is

$$|\Gamma_p(\mathbf{r}_1, \mathbf{r}_2, z)| = |\langle A_p(\mathbf{r}_1, z)A_p^*(\mathbf{r}_2, z)\rangle| =$$

$$= \left|\left(-\frac{ik_0}{2\pi z}\right)^2\right)\int\int\int\int_{-\infty}^{+\infty} d^2\rho_1 d^2\rho_2 \langle A_p(\rho_1, z=0)A_p^*(\rho_2, z=0)\times$$

$$\times\exp[-iF(\rho_1, \rho_2)]\rangle\exp\left[-\frac{i\kappa_0}{2z}\{(\mathbf{r}_1-\rho_1)^2-(\mathbf{r}_2-\rho_2)^2\}\right]\Big| , \qquad (6)$$

in which

$$F(\rho_1, \rho_2) = \frac{\kappa_0 z}{n}\{n_{nl}(\rho_1) - n_{nl}(\rho_2)\} . \qquad (7)$$

After appropriate calculations Eq. (6) can be reduced to the form

$$|\Gamma_p(\mathbf{r}_1, \mathbf{r}_2, z)| = \sqrt{I(\mathbf{r}_1, z)I(\mathbf{r}_2, z)}\,|\gamma(\mathbf{r}_1, \mathbf{r}_2, z)| , \qquad (8)$$

where $I(\mathbf{r}, z)$ is the average intensity of the probing beam at the point $(\mathbf{r}, z)$, $\gamma(\mathbf{r}_1, \mathbf{r}_2, z)$ is the degree of correlation of the probing beam,

$$I(\mathbf{r}, z) = \frac{I_0 a_p^2}{a_x(z)a_y(z)}\exp\left[-\frac{(x-x(z))^2}{a_x^2(z)} - \frac{y^2}{a_y^2(z)}\right] , \qquad (9)$$

and

$$|\gamma(\mathbf{r}_1, \mathbf{r}_2, z)| = \exp\left[-\frac{(x_1-x_2)^2}{r_x^2(z)} - \frac{(y_1-y_2)^2}{r_y^2(z)}\right] . \qquad (10)$$

In formulas (9) and (10) the values $a_x(z)$ and $a_y(z)$ the mean radii of the beam along the X and Y axes, $r_x(z)$ and $r_y(z)$ are the correlation radii along the X and Y axes, and $x(z)$ is the displacement of the energy axis of the probing beam along the X axis.

DISCUSSION OF THE MAIN RESULTS

Disregarding the intermediate calculations analogous to that carried out in Refs. 8 and 9, we analize the relations for the mean statistical spatial characteristics of the probing beam

$$a_x(z) = a_p\left\{\left(1 + \frac{z^2}{L_{nl}^2}\frac{l_0}{a_h}\exp\left(-\frac{l_0^2}{a_h^2}\right)\right)^2 + \frac{z^2}{L_{df}^2} + \right.$$

$$\left. + 2\frac{z^4}{L_{nl}^4}\frac{a_h^2}{a_p^2}\left(\exp\left(-\frac{2l_0^2}{a_h^2}\right) + \frac{\pi N}{2}\right)\right\}^{1/2} ;$$

$$a_y(z) = a_p\left\{\left(1 + \frac{z^2}{L_{nl}^2}\left[\frac{\sqrt{\pi}}{2} + \frac{l_0}{a_h} + \frac{2l_0^3}{2a_h^3}\right]\right)^2 + \right.$$

$$\left. + \frac{z^2}{L_{df}^2} + \frac{z^2}{L_{nl}^2}\pi N\frac{a_h^2}{a_p^2}\right\}^{1/2} \qquad (11)$$

$$r_x(z) = a_p \times$$

$$\times\left\{\frac{\left(1 + \frac{z^2}{L_{nl}^2}\frac{l_0}{a_h}\exp\left(-\frac{l_0^2}{a_h^2}\right)\right)^2 + \frac{z^2}{L_{df}^2}}{\frac{1}{2}\left(\frac{zL_{df}}{L_{nl}^2}\right)^2\frac{a_h^2}{a_p^2}\left(\exp\left(-\frac{2l_0^2}{a_h^2}\right) + \frac{pN}{2}\right)} + 4\frac{z^2}{L_{nl}^2}\right\}^{1/2} ;$$

$$r_y(z) = a_p\left\{\frac{\left(1 + \frac{z^2}{L_{nl}^2}\left[\frac{\sqrt{\pi}}{2} + \frac{l_0}{a_h^2} + \frac{2l_0^3}{2a_h^3}\right]\right)^2 + \frac{z^2}{L_{df}^2}}{\frac{1}{2}\left(\frac{zL_{df}}{L_{nl}^2}\right)^2\pi N\frac{a_h^2}{a_p^2}} + 4\frac{z^2}{L_{nl}^2}\right\}^{1/2} ;(12)$$

$$x(z) = -\frac{z^2}{L_{nl}^2}a_h\exp\left(-\frac{l_0^2}{a_h^2}\right) . \qquad (13)$$

Here $L_{\rm df} = k_0 a_p^2$ is the diffraction length of the probing beam, $L_{nl} = \left(\frac{n_0\rho c_p v a_h}{|n_t|\alpha I_0}\right)^{1/2}$ is the nonlinear modulation length of the heating beam, and $N = (a_h/r_0)^2$ is the initial number of spatial inhomogeneities in the heating beam.

Applicability of the near–axis aberration–free approximation used in the derivation of formulas (8)– (9) was justified in Ref. 2, where it was shown that for $a_p/a_h \sim 1$ the method yields good results on paths of length $z < 3\,L_{nl}$.

First of all note that the presence of wind results in inhomogeneous distribution of the refractive index over the transverse cross section of the beam that gives rise to the beam asymmetry ($a_x < a_y$) on the initial section of the propagation path. However, for large z ($\sim$ 2–3 L_{nl}), this effect proves to be much weaker than the total nonlinear and diffraction spreading of the beam and the resulting shape of the beam cross section remains practically constant. Figure 1 shows the dependences of the beam eccentricity $\varepsilon = \sqrt{I - (a_x/a_y)^2}$ on the longitudinal coordinate z for different ratios between $L_{\rm df}$ and L_{nl} and for different initial N. It can be seen that with increase of the intensity of heating radiation, the beam asymmetry parameter increases and the maximum value of ε increases with N.

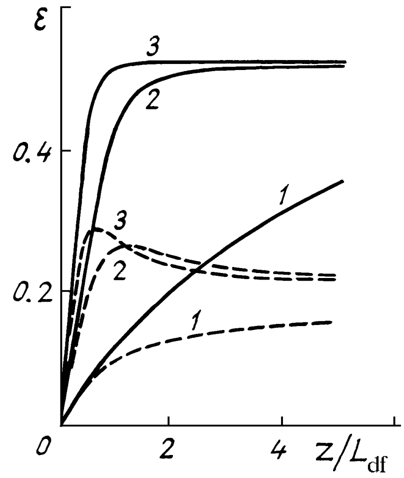

FIG. 1. Dependence of the eccentricity ε of the beam on the normalized longitudinal coordinate z/L_{nl} for $N = 1$ (solid curves) and $N = 0.5$ (dashed curves): $a_p/a_h = 0.1$ and $l_0/a_p = 0.4$ for $L_{df}/L_{nl} = 0.1$ (1), 0.3 (2), and 0.5 (3).

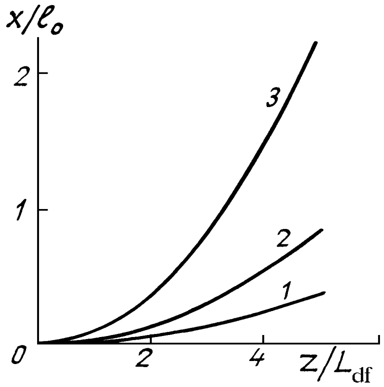

FIG. 2. Displacement of the energy axis of the probing beam x/l_0 as a function of the normalized longitudinal coordinate z/L_{df} for $l_0/a_h = 0.4$ and $L_{df}/L_{nl} = 0.2$ (1), 0.3 (2), and 0.5 (3).

The displacement of the energy axis of the probing beam is independent of the spatial structure of the channel and becomes greater when the intensity of heating radiation increases. Since both the probing and heating beams are displaced in windward direction, the distance between the beams can be greater or smaller depending on their position relative to the wind direction (in contrast to the case of an immobile atmosphere when the beams diverge). The optimum scheme is that in which both beams are in the plane of the wind velocity, in addition, the probing beam is displaced in the windward direction relative to the heating beam. Figure 2 shows the variation of the distance between the axes of the beams as a function of the longitudinal coordinate for this case. It can be seen that for $z = z^* = L_{nl}/\{a_h/l_0(1 - \exp[-(l_0/a_h)^2])\}^{1/2}$ this variation is equal to l_0, i.e., the probing beam falls in the center of the channel and in such a way the optimum conditions for further clearing of the cloud layers are realized.

Let us analyze also the transformation of the spatial structure of the probing beam. The number of spatial inhomogeneities $N_r = \dfrac{a_x(z)\, a_y(z)}{r_x(z)\, r_y(z)}$ increases along the path at a faster rate for a higher heating radiation intensity and larger number of the initial spatial inhomogeneities in the heating beam (Fig. 3).

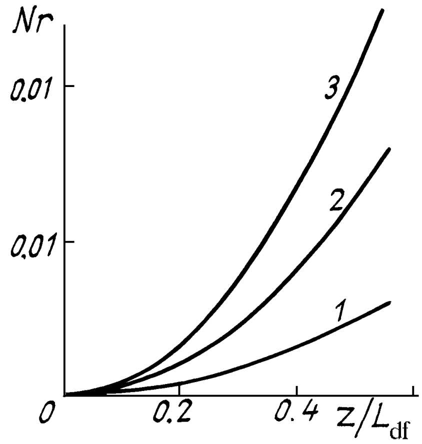

FIG. 3. Dependence of the number of spatial inhomogeneities in the probing beam N_r on the normalized longtudinal coordinate z/L_{df} for $a_p/a_h = 0.1$, $L_{df}/L_{nl} = 0.1$, and $N = 1$ (1), 3 (2), and 5 (3).

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