FOCUSING OF A PARTIALLY COHERENT BEAM PROPAGATING ALONG A VERTICAL PATH INTO THE ATMOSPHERE

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The propagation of a partially coherent focused beam along the vertical path in the atmosphere is investigated. An algorithm for retrieving the focusing parameters of a beam is proposed which allows one to obtain the angular beam width close to minimum.

It is shown that even for optimal focusing of a beam the efficiency of radiation transfer can be increased for only a limited range of variations of the energy parameters of a beam.

Investigations of propagation of the high-power laser radiation in the atmosphere have revealed different nonlinear effects that distort the spatial and temporal characteristics of the radiation.[1] Phase correction of the radiation at the radiating aperture makes it possible to compensate for these distortions.[2,3]

As was shown in Ref. 4 in aberration-free approximation, phase correction makes it possible to minimize the distortions of a beam. However, this advantage can be realized for only limited range of variations of the energy parameters of a beam.

Let us consider the propagation of high-power optical radiation which enters a nonlinear medium along the vertical path. We can vary the initial foci of a beam in the transmitter plane along the two perpendicular axes. The problem is to minimize the angular divergence of a beam in the far diffraction zone after the beam has passed through a layer of a nonlinear medium. In the calculations we shall use the seasonal models of the atmosphere, in particular, the model of the summer atmosphere with the temperature profile taken from the standard model of the atmosphere. The continuous radiation that propagates along these paths is mostly affected by a thermal wind nonlinearity.

We shall calculate the parameters of the optical radiation on the basis of the solution of the radiation transfer equation in the small-angle approximation. In evolution coordinates normalized to the refraction length

$$L_{\mathbf{R}}^2 = \frac{\pi^{1/2} n_0 \rho c_p v a_0^3}{\alpha \dfrac{dn}{dT} P}$$

has the form

$$\left(\frac{\partial}{\partial z} + \kappa\nabla_R + \frac{1}{2}\nabla_R\tilde{\varepsilon}(z, \mathbf{R}, t)\nabla\right)J(z, \mathbf{R}, \kappa, t) = 0 \qquad (1)$$

where $\tilde{\varepsilon}(z, \mathbf{R}, t)$ is the relative perturbation of the dielectric constant of the medium upon exposure to the incident radiation, $J(z, \mathbf{R}, \kappa, t)$ is the brightness (the intensity) of radiation, a_0 is the initial radius of the beam, α is the coefficient of volume absorption, ρ is the density of the medium, c_p is the specific heat of the medium, P is the radiation power, n_0 is the refractive index of the medium, and v is the wind velocity.

The numerical scheme for calculation of this equation was described in detail in Ref. 6.

A similar problem was considered in Ref. 7 for coherent radiation propagating under conditions of wind nonlinearity when the wind direction does not rotate at distances shorter than the diffraction length. The problem of maximization of the radiation intensity in the focal spot was then solved.

In this paper we discuss the problem of minimization of the angular divergence of a partially coherent beam propagating over a distance much longer than the diffraction length under conditions of wind nonlinearity taking into account the rotation of wind direction on the propagation path.

It appears quite irrational to determine the optimal focusing conditions for minimization of the divergence by the gradient method or the method of sorting the foci. It is more convenient to start from some physical premises. We propose an algorithm for retrieving the parameters of the initial focusing of the beam that yields the foci close to optimal and, consequently, the angular divergence close to minimum.

It is easy to derive the angular divergence (width) of the beam γ_{xy}^2 along the OX and OY axes in the far diffraction zone from simple formulas. The shift of the beam center $\boldsymbol{R}_c$ in the evolution plane z is determined as follows:

$$\boldsymbol{R}_c(z) = P_0^{-1}\int\!\!\int_{-\infty}^{\infty} d\mathbf{R}\mathbf{R}W(z, \mathbf{R}), \qquad (2)$$

where $W(z, \mathbf{R})$ is the intensity of the beam. The formula for the beam width then has the form

$$a_{0_\Sigma}^2(z) = P_0^{-1}\int\!\!\int_{-\infty}^{\infty} d\mathbf{R}R^2W(z, \mathbf{R}) - \boldsymbol{R}_c^2(z). \qquad (3)$$

Beam intensity is related to the radiation brightness by the well-known relation

$$W(z, \mathbf{R}) = \int\!\!\int_{-\infty}^{\infty} d\mathbf{k}J_0(z, \mathbf{R}, \mathbf{k}) =$$

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$$= \int_{-\infty}^{\infty}\int d\mathbf{k} J_0\left(z_R, \mathbf{R} - \frac{}{k}(z - z_R), \quad \right), \qquad (4)$$

where k is the wave number. In the far diffraction zone where $(z - z_R) \gg L_D$ the center shift and the diameter of the beam along the 0X axis are then determined in the following way:

$$x_c(z) = \frac{(z - z_R)}{P_0} \int_{-\infty}^{\infty}\int d\mathbf{R} \int_{-\infty}^{\infty}\int d\mathbf{k} \mathbf{k}_X J\left(z_R, \mathbf{R} - \frac{\mathbf{k}}{k}(z - z_R), \mathbf{k}\right);$$

$$a_X^2(z) = \frac{2(z - z_R)^2}{P_0} \int_{-\infty}^{\infty}\int d\mathbf{k}\mathbf{k}_X^2 J\left(z_R, \mathbf{R} - \frac{\boldsymbol{\kappa}}{k}(z - z_R), \boldsymbol{\kappa}\right) - 2x_c^2(z), \qquad (5)$$

where z_R is the thickness of the effective nonlinear layer beyond which the self-action of a beam is not observed and further propagation of a beam is determined solely by diffraction. The parameters along the OY axis are determined in a similar way. Thus it follows from Eq. (5) that the angular center shift of the beam in the far diffraction zone is given by the weighted mean tilts of the phase front in the initial plane of diffraction. The intensity distribution in this plane is used for the weighting function.

The formula of the angular shift of the beam center has the form

$$\varphi_{X,Y}(z_R) = P_0^{-1} \int_{-\infty}^{\infty}\int d\mathbf{R} \kappa_{c_{X,Y}}(z_R, \mathbf{R}) W(z_R, \mathbf{R}), \qquad (6)$$

where $\kappa_c(z_R, \boldsymbol{R}) = \{\kappa_{c_x}(z_R, \mathbf{R}), \ \kappa_{c_y}(z_R, \mathbf{R})\}$ is the vector whose direction coincides with the direction toward the brightness distribution centroid at point $\mathbf{R}$ of the initial plane of diffraction. This vector is perpendicular to the phase front of radiation at that point

$$\kappa_c(z_R, \mathbf{R}) = W^{-1}(z_R, \mathbf{R}) \int_{-\infty}^{\infty}\int d\boldsymbol{\kappa}\boldsymbol{\kappa} J(z_R, \mathbf{R}, \boldsymbol{\kappa}).$$

We shall define the angular width of the brightness distribution over the axes OX and OY at the given point of the initial plane of diffraction as follows:

$$Q_{X,Y}^2(z_R, \mathbf{R}) = 2 \int_{-\infty}^{\infty}\int d\boldsymbol{\kappa}(\kappa_{X,Y} - \kappa_{c_{X,Y}}(z_R, \mathbf{R}))^2 J(z_R, \mathbf{R}, \boldsymbol{\kappa}). \quad (7)$$

The angular width of the beam in the far diffraction zone can then be written in the form

$$\gamma_{X,Y}^2(z) = P_0^{-1} \int_{-\infty}^{\infty}\int d\mathbf{R}(0.5 Q_{X,Y}^2(z_R, \mathbf{R}) + \infty_k^2(z_R, \mathbf{R})) W(z_R, \mathbf{R}), \qquad (8)$$

where $\varphi_k(z_R, \mathbf{R}) = \kappa_{c_{X,Y}}(z_R, \mathbf{R}) - \varphi_{X,Y}(z_R)$.

Phase correction in the radiating plane makes it possible to minimize the angular width at a distance z. Prescribing phase correction in the form

$$\Psi_0 = \boldsymbol{i}\frac{x^2}{2F_X} + \boldsymbol{j}\frac{y^2}{2F_Y} = \frac{\boldsymbol{i}}{2} K_X x^2 + \frac{\boldsymbol{j}}{2} K_Y y^2,$$

where $K_{x,y}$ is the minimization coefficient, we obtain the shift φ_F additional to the shift φ_k in the z_R plane. At the same time we assume that $\varphi_{Fx} = K_x x$ and $\varphi_{Fy} = K_y y$. To minimize the angular width on account of this assumption, we must minimize with respect to K_{xy} the following integral:

$$\int_{-\infty}^{\infty}\int d\mathbf{R}(\kappa_{c_{X,Y}}(z_R, \mathbf{R}) - \varphi_{X,Y}(z_R) - K_{X,Y}\eta_{X,Y})^2 W(z_R, \mathbf{R}), \quad (9)$$

where $\eta_x = x$, $\eta_y = y$.

Solving this equation, we derive

$$K_X = \frac{A(\mathrm{k}_{c_X}(z_R, \mathbf{R})x) - \varphi_X(z_R)A(x)}{A(x^2)};$$

$$K_Y = \frac{A(\kappa_{c_y}(z_R, \mathbf{R})y) - \varphi_y(z_R)A(y)}{A(y^2)},$$

where

$$A(t) = \int_{-\infty}^{\infty}\int d\mathbf{R} W(z_R, \mathbf{R}) t. \qquad (10)$$

Now the situation has arisen when the refraction length exceeds the thickness of the thin layer of the nonlinear medium (this effective layer is up to 3 km thick in the real atmosphere[3]). Focusing the beam with the foci F_X and F_Y in the initial plane based on formulas (10) derived on the basis of the proposed algorithm gives a value of $\gamma_{X,Y}$ that is close to minimum. Moreover, the larger L_R, the closer is $\gamma_{X,Y}$ to the minimum angular width. When L_R becomes comparable to the thickness of the layer, focusing results in an angular width somewhat larger than the minimum width. However, if $L_R \le 3$ km, the angular width of a beam with initial foci F_x and F_y, given by Eq. (10), already significantly exceeds the width of a collimated beam.

The angular width $\gamma_{\text{eff}} = \sqrt{(\gamma_X^2 + \gamma_Y^2)/2}$ is plotted in Figs. 1a and 1b vs the refraction length L_R. The angular divergence of a collimated beam is shown by the dotted curve, and the angular divergence of a collimated beam corrected on the basis of the proposed algorithm is shown by the dashed curve. The solid curve shows the minimum angular divergence.

As can be seen from the figures, the conclusions drawn in Ref. 4 concerning the description of beam propagation in aberration-free approximation remain true for actual beams. As was indicated above, focusing makes the energy transfer more effective than in the case with a a collimated beam for a definite range of the energy parameters of the beam. However, beyond this range focusing results only in a deterioration of the efficiency of energy transfer.

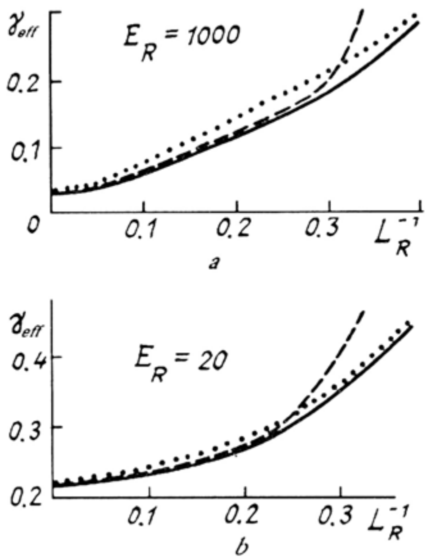

FIG. 1. Angular width γ_{eff} vs the refraction length.

The parameter of nonlinear refraction of a beam E_R is related here with the refraction length L_R via the relation

$$E_R = (L_D/L_R)^2,$$

where L_D is the diffraction length, $L_D^2 = \kappa^2 a_0^4/(1 + a_0^2/a_{coh}^2)$, where a_{coh} is the coherence radius and κ is the wave number.

Optionally choosing $E_R = 1000$, the gain nearly 20% was obtained. The gain was less for $E_R = 20$ in agreement with the results of the previous works obtained in the aberrational–free approximation. In comparison with a collimated beam, the gain was nearly 20 and 10% for $E_R = 10000$ and $E_R = 100$.

Thus, a simple algorithm for minimization of the angular divergence of a beam propagating along the vertical atmospheric path is proposed here which takes a thermal wind nonlinearity into account. It is shown that there exists a range of the energy parameters of a beam, in which focusing on the basis of the algorithm makes it possible to obtain the angular width of a beam close to minimum. Note that the algorithm operates in that range L_R, where optimal focusing gives a large gain in comparison with a collimated beam. At the same time the efficiency of energy transfer deteriorates in that range of the energy parameters of the beam where even optimal focusing is of little importance.

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