MINIMIZING THE ANGULAR DIVERGENCE OF A PARTIALLY COHERENT BEAM PROPAGATING ALONG A VERTICAL ATMOSPHERIC PATH

V.V. Kolosov, M.F. Kuznetsov, and S.I. Sysoev

Institute of Atmospheric Optics,
Siberian Branch of the Russian Academy of Sciences, Tomsk
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The possibility of optimizing the energy transfer of a laser beam propagating along a vertical path through the atmosphere to the far–diffraction zone is analyzed.

On the basis of numerical calculations according to the small–angle radiative transfer equation performed for a wide range of beam energy parameters including the beam focusing along the two perpendicular axes, the range of values of these parameters is identified which provides for the optimal radiation transfer. The use of this approach and the obtained results enables one to assess the potential possibilities of real laser systems intended to transfer the energy through the atmosphere.

Analysis of propagation of laser radiation revealed many factors which engendered variations in the spatial and temporal characteristics of radiation.[1]

The most typical scheme of the energy transfer along a vertical path comprises an energy source, a layer of a nonlinear medium, and, at a fixed distance from the source, a receiving object. The energy transfer of partially coherent radiation through the layer of the nonlinear medium to remote objects was analyzed, in particular, by Zemlyanov and Sinev[2] and Babaev et al.[3] In the process of transfer it is necessary to compensate for the nonlinear effects, which result in broadening of the angular divergence (width) of a beam. Several authors study this subject in their papers considering either the quasioptical approach for coherent beams[4] or the aberration–free approach.[5]

Let us consider the propagation of high–power partially coherent optical radiation, which enters a nonlinear medium, along the vertical path to the far zone. We can vary both beam's energy parameters and initial focusing of the beam in the radiation plane along the two perpendicular axes.

The problem is to maximize the effective power density of radiation in the receiving plane

$$W_{\text{eff}}(z_r) = P/S_{\text{eff}}(z_r) , \quad (1)$$

where P and S_{eff} are the total power and effective cross section of the beam in the receiving plane z_r, determined as

$$S_{\text{eff}}(z_r) = P^{-1}\int\limits_{-\infty}^{\infty}\!\!\int R^2 \mathrm{d}\mathbf{R}\, W(z_r, \mathbf{R}) . \quad (2)$$

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

$$L_R^2 = \frac{\pi^{1/2} n_0 \rho c_p v a_0^3}{\alpha \left|\frac{\mathrm{d}n}{\mathrm{d}T}\right| P}, \quad (3)$$

this equation has the form

$$\left(\frac{\partial}{\partial Z} + \kappa\nabla_R + \frac{1}{2}\nabla_R\tilde{\varepsilon}(z, \mathbf{R}, t)\nabla_\kappa\right) J(z, \mathbf{R}, \kappa, t) = 0 , \quad (4)$$

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 ray intensity) of radiation, a_0 is the initial radius of the beam, α is the volume coefficient of absorption, ρ is the density of the medium, c_p is the specific heat of the medium, n_0 is the refractive index of the medium, and v is the wind velocity. The height dependence of the characteristics of the medium (absorption coefficient, temperature, and direction and velocity of wind) is accounted for by using in calculations the seasonal atmospheric models developed in the Institute of Atmospheric Optics.

In the process of calculations we obtain the angular width of a beam passed through the nonlinear medium in the far–diffraction zone

$$\theta_\Sigma^2 = S_{\text{eff}}/z_r^2 . \quad (5)$$

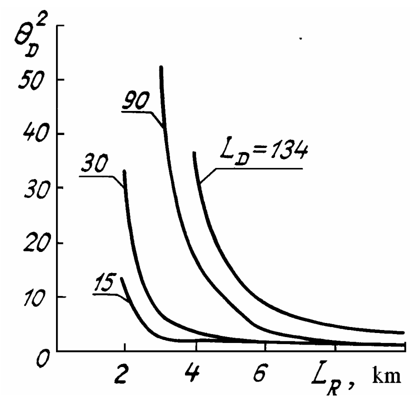

FIG. 1. The angular width $\theta_D^2 = \theta_\Sigma^2/(a_0/L_D)^2$ vs the diffraction length.

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Figure 1 shows the dependence of the quantity $\theta_D^2 = \theta_\Sigma^2/(a_0/L_D)^2$ on the diffraction length for a model of summer atmosphere, where $L_D^2 = \kappa^2 a_0^4 \Big/ \left(1 + a_0^2/a_c^2\right)$ is the diffraction length, a_c is the coherence radius of radiation, and κ is the wave number.

As can be seen from Fig. 1, for the values of L_R greater than the effective thickness of the atmosphere ($\approx$ 3 km), the value θ_D^2 is close to the diffraction limited, but as the power increases the sharp broadening of the beam occurs at $L_R \approx 3$ km.

In practice the energy is incident, as a rule, upon a bounded surface element, whose size can be much smaller than S_{eff}. Then the problem is to maximize the effective power density in the receiving plane

$$W_{\text{eff}}(z_r) = P/S_{\text{eff}}(z_r), \qquad (6)$$

in order to provide for the optimal energy transfer from the transmitter to the receiver. Taking into account the validity of the relation

$$\theta_R^2 = \theta_\Sigma^2/(a_0/L_R)^2, \qquad (7)$$

it is easy to be convinced that the proportionality

$$W_{\text{eff}} \sim \theta_R^{-2}, \qquad (8)$$

follows from Eqs. (3), (6), and (7). In physical sense it means that θ_R^2 is an angular width of the beam determining the effective power density received within S_{eff}.

The dependence of θ_R^2 on L_R is shown in Fig. 2. The solid curve corresponds to the collimated beam. As can be seen from the figure, the optimal value of L_R, minimizing θ_R^2, exists. In other words, there exists such a value of the initial power P, that its exceeding results in a decrease of W_{eff}, i.e., the less amount of energy will be incident on the receiving aperture than that for smaller values of the initial power.

Let us now consider the results of beam focusing along the two perpendicular axes (Fig. 2, dotted curve). We used the values of initial foci calculated on the basis of a simple algorithm described in detail in Ref. 6.

As can be seen, focusing enables one to increase the effective power density. It should be noted that the minimum value of $\theta_R^2 = f(L_R)$ is shifted in comparison with the collimated beam toward the region of larger initial power of the beam. At the same time W_{eff} increases from 10% ($L_D = 30$ km) to 20% ($L_D = 150$ km).

It is evident that the region in Fig. 2, in which θ_R^2 reaches its minimum is of practical interest. Let us denote by θ_m^2 the minimum angular width of the beam. The corresponding value of the diffraction length L_R, at which the angular width reaches its minimum, we denote by $L_{R,\text{m}}$. Then from Fig. 2 it follows that for $L_D > 50$ nearly linear dependence of $L_{R,\text{m}}$, at which θ_m^2 is reached, on the refraction length takes place, namely $L_{R,\text{m}}^2 \approx 0.83\, L_D$. Hence, it follows that $P_{\text{opt}} \sim \theta_D$, where P_{opt} is the optimal initial power of the beam at which the maximum effective power density is transmitted for the given beam with the diffraction length L_D.

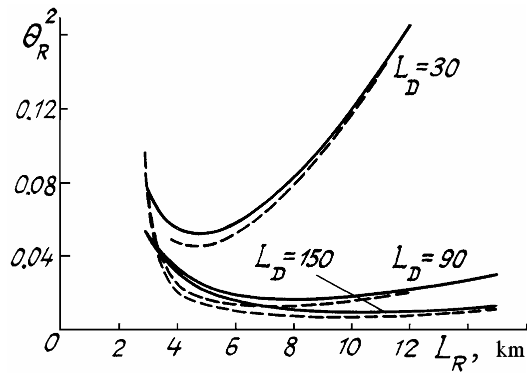

FIG. 2. The angular width $\theta_D^2 = \theta_\Sigma^2/(a_0/L_D)^2$ vs the refraction length. The solid curve stands for the collimated beam, dotted one for the focused beam.

The dependence of θ_m^2 on L_D for a collimated beam is plotted in Fig. 3 from which the proportionality $\theta_R^{-2} \sim L_D^{-1}$ can be seen.

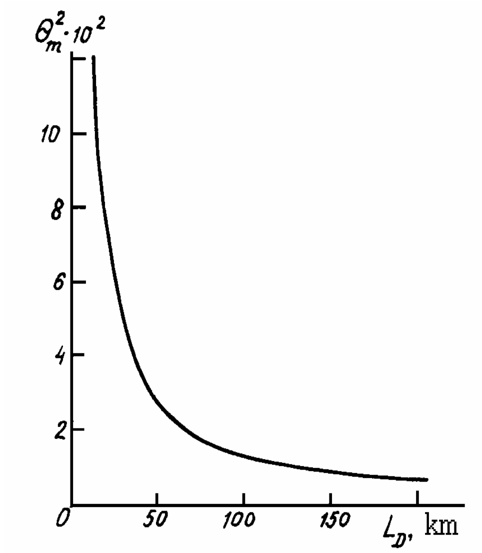

FIG. 3. The minimum angular divergence θ_m^2 vs the diffraction length.

Thus, from the data shown in Fig. 2 the following regularities are determined

$$P_{\text{opt}} \sim \theta_D, \qquad W_{\text{eff,opt}} \sim \theta_D^{-1}. \qquad (9)$$

From which it follows that by improving the coherent properties of a beam (i.e., decreasing the value of θ_D), the increase in the power density of radiation proportional to θ_D^{-1} can be obtained. But it should be noted that such an increase can be obtained only with consistent decrease of the initial power of the beam. Otherwise, the decrease of θ_D has no marked effect on the radiation power density, while the variations of the initial power of a beam without consistent variations of θ_D may even degrade the efficiency of energy transfer.

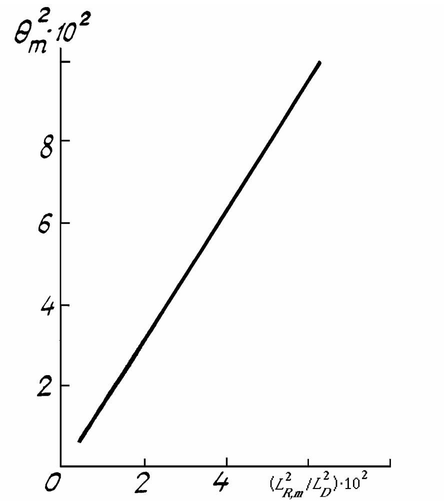

FIG. 4. The minimum angular divergence θ_m^2 vs the ratio of the square refraction length to the square diffraction length.

The above–obtained results can be represented in the other form. Figure 4 shows the dependence of θ_m on the ratio of the square refraction length to the square diffraction length. The linear dependence between these values can be seen. From this dependence it follows that for optimal conditions of energy transfer through the atmosphere the relation

$$\theta_\Sigma^2 \approx 1.6\theta_D^2$$

is valid.

It means that under optimal conditions of energy transfer the contribution of nonlinear effects to broadening of the beam becomes comparable, but still less than the diffraction broadening.

Thus, the conditions of the effective transfer of the energy of continuous powerful partially coherent radiation through the atmosphere have been analyzed in this paper. The obtained results can be used to assess the possibilities of specific laser systems intended to transfer the energy through the atmosphere.

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