Influence of the atmosphere on power density distribution and divergence of a wide-aperture beam of a cw CO_2 laser

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We present the experimental results on studying characteristics of high-power radiation of a continuous-wave CO_2 laser propagated along near-ground atmospheric paths. The results obtained are analyzed with the allowance made for thermal defocusing, phase distortions of radiation at the laser output and in the beam formation system, diffraction, and regular divergence. The influence of the "input" section on the beam divergence is analyzed, and some methods to decrease this influence are discussed.

Nonlinear interaction of high-power laser beams propagating along long atmospheric paths is determined by the beam power and geometry as well as by the conditions of propagation and heat transfer along the path. The study of this interaction is a rather complicated experimental problem, because the experiment is normally conducted with the interference of the background of random processes of turbulent broadening, radiation extinction due to atmospheric gases and aerosols, and wave front distortions introduced by an optical-mechanical channel.

Additional difficulties arise in such experiments because the measurement paths are, as a rule, inhomogeneous in regarding the manifestations of the effects of thermal nonlinearity. Usually the propagation paths include the initial "inner" section from a laser to an exit aperture, where the beam is formed, and the atmospheric section, where the beam is most often focused. The initial section is characterized by a short length, low speed of air motion, and relatively high radiation energy density. For this reason, the manifestation of nonlinear effects is most strong here. A long length and the presence of wind are characteristic of the atmospheric section. In this section of the path the radiation is focused by large apertures, hence, the density of the transmitted energy is low, as compared with the initial section, and therefore the nonlinear effects are less pronounced. The influence of the atmosphere on the radiation characteristics at the end of the path is determined by the joint effect of both sections.

Thermal blooming of a laser beam on atmospheric paths is measured by use of specialized techniques to analyze the experimental data. Few papers devoted to experimental studies of the efficiency of concentrating the energy of high-power technological lasers on the near-ground paths$^{1–5}$ describe possible approaches to solution of this problem and present the results and estimates of the influence of thermal nonlinearity on the efficiency of laser beam focusing in the atmosphere.

This paper presents the results of experimental studies with a continuous-wave CO_2 laser under atmospheric conditions.

For the atmospheric section of the path, the equation was derived in Ref. 3 for estimating the beam diameter d_f at the distance L for radiation with the Gaussian intensity distribution with the allowance made for distorting factors such as thermal defocusing, phase distortions, and the initial divergence at the output of an optical system, diffraction, and distortions due to atmospheric turbulence.

The phase distribution at the exit aperture can be presented, in the first approximation, as a sum of two components. The first one is a regular component (the mean phase front) determining the regular divergence of a beam θ_r, which includes the divergence at the output of the laser itself and additional divergence caused by thermal defocusing occurring in the inner section. The second component is the deviation of the phase front from the mean value, that is, distortions introduced by the optical system and distortions inherent in high-power laser radiation. This irregular divergence component φ_{ir} can be characterized by the variance σ_0^2 and the correlation length l_0.

For a wide-aperture beam the parameter $\Omega = k_0 a_0^2/2L$ is usually far larger than unity ($k_0 = 2\pi/\lambda$; λ is the radiation wavelength; a_0 is the beam radius at the output of the optical system). At small optical depth $\alpha L < 1$ (α is the absorption coefficient), which is typical of the clean atmosphere for a CO_2 laser at low humidity on the path of up to 1 km length, the equation for beam diameter at the end of the path d_f can be written as

$$d_f^2 = [d_{f0}(1 + N)]^2 + (2a_0 Q)^2; \quad (1)$$

$$N = N_c\, a_0/a_{f0} = N_c\, a_0/L\theta_r, \quad (2)$$

where $N_c = \frac{dn}{dT}\frac{\alpha I_0 L^2}{n_0 \rho c_p a_0 V_\perp}$ is the parameter of nonlinearity for a collimated beam[4]; N is the parameter of nonlinearity with the allowance for regular divergence of the beam θ_r; I_0 is the intensity at the beam axis at the output of the transmitting optical system; n_0, ρ, and c_p are the mean refractive index, density, and specific heat of the medium; $V_\perp$ is the wind velocity component normal to the beam axis; $Q = [\sigma_0^2 + D_s(l_0) + l_0^2/a_0^2](k_0 l_0^2/2L)^{-1}$; $D_s(l_0) = 3.2\, C_n^2\, k_0\, L\, l_m^{-1/3}\, l_0^2$ is the structure function of phase fluctuations; $\sigma_0^2 = (2\pi l_0 \varphi_{ir}/2\lambda)^2$ is the variance of the irregular divergence φ_{ir}; l_0 is the correlation length of the irregular divergence component at the output of the optical-mechanical channel; $d_{f0} = 2a_{f0} = 2\theta_r L$ is the beam diameter due to regular divergence; C_n^2 is the structure function of fluctuations of the atmospheric refractive index; $l_m \approx 0.1$ cm is the inner scale of atmospheric turbulence.

As is seen from Eq. (1), the beam size d_f is determined by two components. The first one takes into account the regular divergence component d_{f0} and thermal broadening of the beam determined by the parameter of nonlinearity N, which is proportional to the absorbed energy and inversely proportional to the regular divergence θ_r. It is assumed that the regular divergence component determined by the averaged wave front surface, in the first approximation, can be compensated for by cylindrical or spherical optical systems. The second component takes into account phase fluctuations at the exit aperture and turbulent and diffraction broadening of the beam.

As shown by estimates made using experimental data for atmospheric paths and typical parameters of a cw CO_2 laser radiation, thermal broadening of the beam can exceed broadening due to the second component. In this case, the mean intensity at the axis of the beam focused at the distance L is determined by the following equation[4]:

$$I = I_0 \exp(-\alpha L - N) \approx I_0 \exp(-N). \tag{3}$$

Measurement technique

In our experiments we used a setup including a fast-flow CO_2 laser with self-maintained discharge and a beam formation system with the magnification factor $\Gamma = 4.4$. The radiation characteristics on the measurement path were determined by the methods described in Ref. 3.

Experiments were conducted along 900 and 2500-m long paths at the altitude of several meters above a smooth terrain. The path was mostly closed on both sides, so the heat transfer due to wind motion of air masses was limited, and air humidity was rather high in many cases. This provided the possibility of making measurements at high values of the nonlinearity parameter N of the atmospheric part of the path and its dominating role in nonlinear distortions of the beam, as compared with those occurring in the inner section of the path.

The power characteristics of the output laser radiation were measured with a scanning wattmeter (SW) and 1×1 m grid meters (GMs) both at the laser output and at the input of the optical-mechanical channel. At the end of the path, the power was measured with a grid meter of the same size, and the power density distribution over the beam cross section was retrieved using a computer processing of data measured with an array of closely packed sensors. The grid meters were calibrated and energy transfer ratios at different sections were determined by comparing the data of the scanning wattmeter, array of receivers, and grid meters.

The studies were accompanied by measurements of the following meteorological parameters: temperature, temperature lapse rate, humidity, and wind velocity. These parameters were used to calculate the absorption coefficient α, the generalized parameter of nonlinearity N, and distortions due to turbulence.

The total extinction of CO_2 laser radiation at 10.6 μm in the atmosphere is determined by absorption by water vapor $\alpha(H_2O)$ and carbon dioxide $\alpha(CO_2)$ as well as by scattering on aerosols α_e, that is, the total extinction coefficient α consists of three components

$$\alpha = \alpha(H_2O) + \alpha(CO_2) + \alpha_e. \tag{4}$$

The equation used in the experiment for estimating $\alpha(H_2O)$ at the wavelength $\lambda = 10.6$ μm has the form[6]:

$$\alpha(H_2O) = 1.76 \cdot 10^{-3}\, a\, (1 + 1.78 \cdot 10^{-3}\, p) + 0.42 \times 10^{-6}\, a^2 \exp(2273/T), \tag{5}$$

where $a = 13.25(e/T)\exp[17.58/(T - 31.3)]$ is the absolute air humidity (in g/m^3) calculated from measured values of the relative humidity e (%), temperature T (K), and pressure p (mbar).

The absorption coefficient $\alpha(CO_2)$ was calculated for the mean volume concentration of carbon dioxide in the atmosphere (0.033%) (Ref. 7):

$$\alpha(CO_2) = 386\, T^{1.5} \exp[2232(1/296 - 1/T)]. \tag{6}$$

The coefficient of radiation extinction by aerosol $\alpha_e(10.6)$ was calculated using the results of measurement of the extinction coefficient in the visible spectral region $\alpha_e(\lambda)$ ($\lambda = 0.63$ μm) with the use of the specialized equations.[8]

To minimize the influence of the inner section on the radiation divergence, the absorption coefficient at this section should be reduced to minimum. Purging the input section with a weakly absorbing air can do this. The corresponding air blowing system was a part of the experimental setup.

Measurement results

The variance of the irregular divergence component $\sigma_0^2 = 2$ and the correlation length $l_0 = 11.2$ mm were determined from independent measurements.

The atmospheric absorption coefficient ($\lambda = 10.6$ μm) calculated for the measurement site based on the data of atmospheric monitoring by Eq. (4) varies from 0.1 to 0.6 km^{-1}, what agrees with the data of direct measurements with a low-power CO_2 laser.

Analysis of monthly variations of the ratio $\alpha/V_\perp$, whose value determines variations of the nonlinearity parameter N_c at a constant output beam characteristics and path length, showed that atmospheric conditions are best suited for ground measurements during the fall season (values $N_c < 1$ form about 65%), being the worst suited in summer (values $N_c > 1$ account for almost 90%), while the value of $\alpha/V_\perp$ varies from 0.02 in April to 2 in August.

The structure constant of fluctuations of the refractive index C_n^2 varied from 10^{-14} to 10^{-15} m$^{2/3}$.

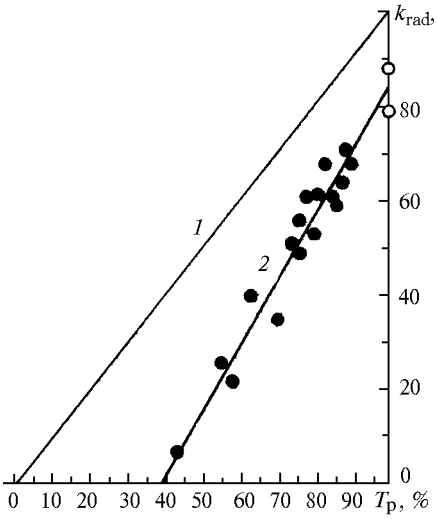

Fig. 1. Radiation transfer ratio k_{rad} vs. atmospheric transmission coefficient T_p.

Figure 1 shows measurement data on the ratio of radiation transfer k_{rad} from the laser to the aperture of the grid meters ($k_{rad} = P_{GM}/P_{SW}$ is the ratio of the power at the end of the path to the laser output power) placed at 900 m distance as a function of atmospheric transmission coefficient T_p.

The straight line *1* in Fig. 1 corresponds to the equation $k_{rad} = T_p$, and the straight line *2* is calculated by the method of least squares $k_{rad} = -49.5 + 1.33\ T_p$. The intersection of the straight line *2* with the ordinate at $T_p = 100\%$ determines the transfer ratio of the optical-mechanical channel. The transfer ratio of the optical-mechanical channel measured by the grid meters at the output of the laser and the channel and shown in Fig. 1 (open circles) at $T_p = 100\%$ supports this fact. The slope of the experimental straight line equal to 1.33 and not to unity is indicative of the nonlinear character of radiation interaction during propagation of the cw CO_2 laser radiation through the atmosphere.

Figure 2 shows the experimentally measured dependence of the maximum energy E_{max} on the diffraction parameter of nonlinear distortions $N_d = N_c\, a_0/a_d = \dfrac{dn}{dT}\dfrac{\alpha I_0 L^2}{n_0 \rho c_p a_d V_\perp}$, i.e., in the parameter N [Eq. (2)] the regular divergence $a_{f0} = \theta_r L$ is replaced by the limiting diffraction $a_d = \theta_d L$.

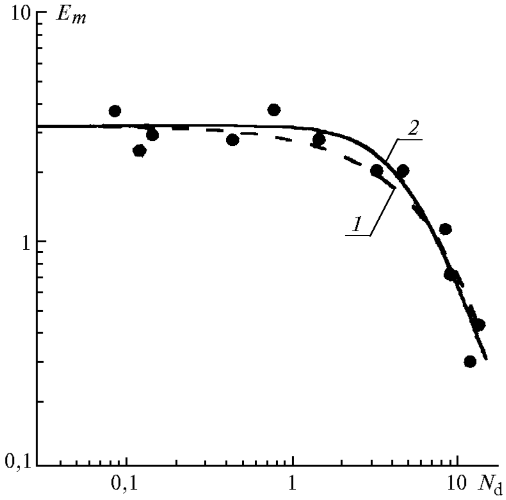

Fig. 2. Maximum energy E_{max} measured with the array of receivers vs. diffraction parameter of nonlinearity N_d.

The solid curve *2* in the figure shows the dependence described by the approximating equation $E_{max} = 3.2(1 + 0.025\, N_d^{2.2})$ proposed in Ref. 4, the dashed curve *1* shows the dependence $E_{max} = 3.2 \exp(-0.14\ N_d)$ obtained using the least-squares fit. It is seen that the energy E_{max} as a function of N_d is well described by both the complex power function and the simpler exponential one.

The obtained experimental data on E_{max} allow one to estimate the regular divergence θ_r. Actually, the parameter N_d is related to $N = N_c(a_0/a_{f0})$ as $N_d = N_c(a_{f0}/a_d)$. As the estimates show, the parameter of nonlinearity N in the experiments took the values $N \approx 1$, and $Q^2 \approx 0.16$ and thermal distortions of the beam prevailed. Then, from Eq. (3) it follows that the intensity at the beam axis must fall down to $e^{-1}I_0$ level at $N \approx 1$. It is seen from Fig. 2 that $E_{max}(N_d) = e^{-1}E_{max}(0)$ roughly at $N = 8$. From that it follows that $a_{f0}/a_d \approx 8$, i.e., the regular divergence at radiation focusing is $\theta_r = 8\theta_d$. This result is in a good agreement with the experimental results from Ref. 3. The estimation of radiation divergence from the size of a spot on the array in the case of minimal atmospheric distortions of the high-power beam, i.e., $N_c \approx 0$, gives the same value.

One of the possible ways to decrease the regular divergence, enhanced by the thermal interaction in the inner section of the path, is optimal focusing with the beam formation system, at small values of N on the atmospheric section of the path. Focusing of radiation at the distance ~ 0.5 L allows the area of the focal spot to be decreased by three times, what corresponds to the 1.7 times decrease in the regular divergence.

The thermal blooming in the inner section can be decreased by minimizing the air absorption coefficient and forcing the air to move across this section. The system for purging with dry air was made and tested. Dry air with the flow rate of 2.5 m^3/s, temperature $T \approx 20°C$, absorption coefficient $\alpha = 0.07\ km^{-1}$ (determined by CO_2 absorption) was blown through the distribution system in the path of the high-power radiation (7 m long section) normally to the beam axis. Thus, we have managed to decrease the ratio $\alpha/V_\perp$ by ten times. The measurements showed that the use of the air blowing through system resulted in the almost three times decrease of the regular divergence at the output of the beam formation system.

Conclusion

As is seen from the results, the contribution of the input section proves to be significant at weak influence of thermal interaction along the atmospheric section of the path.

Use of purging with dry air of this section of the system decreases the divergence down to the values determined by the laser divergence and thermoelastic distortions of the cooled mirrors of the beam formation system. This allows to more efficiently decrease the radiation divergence as compared with the compensation for thermal distortions using spherical optical systems (by a factor of two in our experiment).

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