VARIATION OF REFRACTIVE INDEX IN A ZONE OF HIGH–POWER LAZER BEAM ACTION

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Received December 30, 1992.

A technique is proposed for determining the integral variation of the refractive index in a zone of action of high–power optical radiation by shifts of an image of a sensing beam source, when the beam crosses the active zone at some angle with respect to its axis. Some experimental data on the refractive index measured at a windless part of a path were obtained and compared with the calculational data. It is shown that under certain meteorological condition a nonlinear thermal lens formed at the input part of the path determines the distortions of a high-power radiation in the focusing region at the far end of the path.

In propagation of the high–power radiation (HPR) through the atmosphere there occurs an absorption of some portion of energy by the atmospheric gases resulting in appearance of an additional gradient of the dielectric constant ε in the active zone.[1,3] Variations in the optical characteristics of the medium cause the distortions of the actuating beams themselves. At present there are neither exact analytical nor numerical methods for solving the problem of the HPR propagation through nonlinear media. The difficulty of obtaining its solution consists in the fact that the structure of the refractive index field in the active zone depends on the spatiotemporal distribution of the radiation intensity and atmospheric conditions at the moment of propagation.[1,2] Data on a structure of the refractive index field in the active zone can be obtained by experimental investigations of distortions of the low–power sensing beams propagating in a zone of the induced temperature gradient. The radiation power of such beams is not absorbed by the medium and, hence, does not induce any changes into the structure of the interaction zone.[4,5]

This paper presents the experimental results on determination of the integral variation in the refractive index Δn in the zone of high–power radiation propagation at the input part of the atmospheric path. It is shown that under certain conditions the nonlinear thermal lens formed at the input part of the path determines the HPR distortions in the focusing region at the far end of the path.

The laser radiation with the wavelength $\lambda_a = 10.6\ \mu m$ was used in the experiment as an actuating signal. The laser operated in a quasicontinuous mode. The atmospheric path was chosen in an open terrain above a smooth underlying surface at an altitude of 3–4 m. Proceeding from the fundamental theorems of the heat transfer in the zone of interaction of radiation with the atmosphere the path used in the experiment can be divided into two parts. An initial part – from an emitter to a forming optical system – can be characterized by the high–energy density, short length, and heat transfer in a channel due to the convective motion appearing when the medium is heated in the active zone. Such parts – zones of rest[2] – are responsible for the considerable defocusing and displacement of radiation caused by the heat of the medium. The focal length of the negative thermal lens forming in this case can reach up to tens of meters. An external atmospheric part – from the forming optical system to a target – can be characterized by the lower energy density, long length, beam focusing in the target plane, and carrying the heat out of the active zone caused by the perpendicular component of the wind velocity. The wind available on this part of the path prevents the formation of thermal lens and defocusing of radiation affects here to a less degree. The ratio of the input part of the path to the atmospheric part was 1:50.

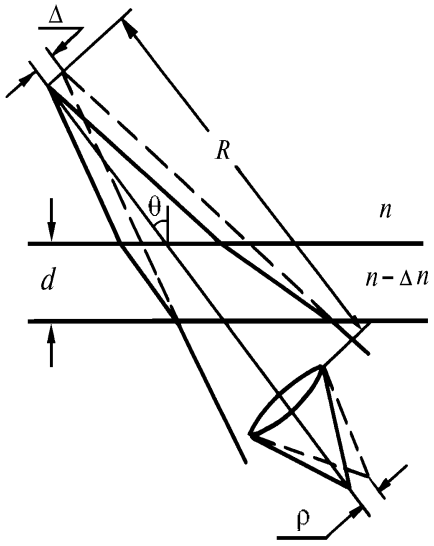

FIG. 1. Diagram for determining the variation in the refractive index.

The technique for investigating the refractive index variation in the zone of rest on the path consisted in scanning over the region of the HPR action by a divergent sensing laser beam ($\lambda_s = 0.63\ \mu m$) propagating at some angle with respect to an actuating beam and in measuring the shift of a center of gravity of the image of the sensing beam source.[5] This technique makes it possible to obtain the data on integral variation of the refractive index in the region of beam intersection without structure disarrangement of the action region. The diagram of experimental arrangement is illustrated in Fig. 1. The angle between axes of the actuating beam and sensing beam (SB) was about 4–8° (the angle of the SB incidence on the action region θ was equal to 82–86°). The HPR channel in a cross section was the rectangle whose vertical size was twice as much as its horizontal size and power density distribution

0235-6880/93/03 238-03 $02.00

was practically uniform. Over the entire intersection region of the beams the size of the SB cross section did not exceed the size of the HPR channel.

At the windless path the process of carrying the heat out of the channel and, hence, the variation in the channel form have to happen in this zone on the path due to two phenomena, namely, the molecular thermal conductivity and natural convection resulting from the temperature difference inside and outside the channel. A characteristic time of the convection appearance τ_c can be determined by the formula[3]

$$\tau_c = a\left(\frac{\alpha\, a^2 I\, \beta\, g}{\rho\, C_p}\right)^{-1/3},$$

where a is the radius of the HPR beam, α is the atmospheric absorption coefficient, I is the radiation power density, β is the thermal coefficient of the air expansion, g is the acceleration of gravity, and ρ and C_p are the density and the specific heat of air. For $\alpha = (1–3)\cdot 10^{-6}$ cm^{-1} and parameters of actuating radiation realized during experiment the values of τ_c lies within the limits of ~1 s, and the thermal conductivity time $\tau_v = a^2/4\chi > \tau_c$ ($\chi = 0.2$ cm^2 s^{-1} is the thermal conductivity of the medium). Hence, the effect of thermal diffusion on the process of setting the temperature in the channel can be neglected. In this case for the time of action ≤ 1 s the channel will not be destructed and it can be considered as a flat plate with the refractive index less by Δn than the refractive index of the ambient medium. According to the principles of geometrical optics the ray incident on such a plate must be shifted by the value of Δ depending on Δn (Ref. 6)

$$\Delta = d \sin\theta\left(1 - \sqrt{\frac{1 - \sin^2\theta}{n_1 - \sin^2\theta}}\right),$$

where Δ is the ray shift at the channel output, d is the transverse size of the channel, and $n_1 = n - \Delta n$ is the refractive index of the medium in the channel.

The image of the SB source will be displaced by the value of

$$\rho = \Delta(l/R)\,,$$

where l is the distance from the receiving lens to the plane of the source image and R is the radius of the wave–front curvature of the sensing beam at the receiving lens.

This technique makes it possible to obtain the integral variation in the refractive index in the channel as a function of two coordinates simultaneously when using the sensing and actuating beams propagating in different planes. In the experiment the position of the center of gravity of the source image ρ was measured by a tracking system at the dissector,[7] (whose photocathode plane was coincided with the source image plane) with an accuracy of $\pm$ 5 μm within the frequency range 0–100 Hz. In converting to the refractive index variations this error in determing ρ makes it possible to obtain Δn correct to the seventh decimal place. Prior to action the SB source image was placed at the center of the dissector photocathode that was considered as a zero count of the measuring system. The SB image started to shift as soon as the HPR was switched on. The signals from the HPR system proportional to the shifts were recorded on the photographic paper by an oscillograph and then they were processed. The initial and final points of action were also recorded. From recorded sequences of experimental data we obtained the maximum value of a signal, the time needed for reaching the maximum value, the time required for setting the stationary state, the rate of the signal build–up during different periods of action, and the time and rate of the channel destruction after completion of action.

We measured simultaneously the refractive index in the zone of rest on the path and the energy distribution over the HPR beam at the far end of the atmospheric path by the square matrix of the receivers. The signals obtained from the matrix elements were processed by a computer, they determined the size of incident radiation and its shifts. The power of actuating beam was determined at the emitter output. All measurements were accompanied by measuring the meteorological parameters along the path, namely, temperature, humidity, speed, and direction of wind.

Figure 2 shows the compared results of measurements of relative integral variation in the refractive index $\Delta n/\Delta n_{max}$ at the input part of the path (the zone of rest) as a function of variation in the relative angular size φ/φ_0 of the HPR beam at the matrix of receivers at the wind velocity $V_\perp > 2$ ms^{-1} (where φ_0 is the angular size of the beam at $t = 0$). The time t varies along the horizontal axis. The vertical lines show the spread of the measured parameters in the individual experimental realizations. From the figure one can see the correlation between variations Δn and size of the HPR beam that verifies an assumption on influence of the zone of rest on the HPR broadening. According to the estimations, the HPR beam size φ_0 at the first instant of action ($t = 0$) can be determined by the diffraction at the elements of optical system for the beam formation and by the turbulence effect on the atmospheric path. For the weak or longitudinal wind ($V_\perp < 1$ ms^{-1}) such a correlation is not observed because of a significant effect of the atmospheric path on the beam distortions.

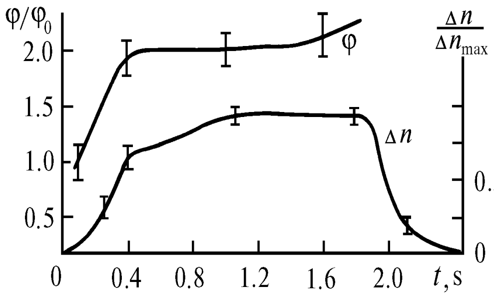

FIG. 2. A comparison between the angular size of the HPR beam at the far end of the path and variation in Δn inside the active channel.

The mode of temperature stabilization on the zone of rest on the path can be divided into three sections depending on the time. On the first section the temperature increases with the rate ≥ 5 deg/s. Duration of this section is about 0.3–0.4 s and, proceeding from estimations, is the same as the time of developing the convective motion on this section. Supplemental investigations which were carried out showed that the time of achieving the stable operation for the emitter is about 0.05 s from the beginning of action and during the process of lasing the power varies less than 5%. On the second section the temperature grows slowly (~1 deg/s), and after (1.5–1.6) s from the beginning of action one can observe a stabilized operating mode. In the experiment the action lasted less than 2 s and the stabilized operating mode was observed for only a few realizations. The signal fluctuations can be observed on this section with slight increase in temperature and with stabilized mode of operation. The probable causes of fluctuations can be the following: the power variation during the action, appearance of nonuniformities of a medium in the channel in developing the convection, fluctuations in the beam as a whole, and variation in the beam divergence. Gradual dissipation of the temperature in the channel (the third section) up to the level e^{-1} occurs for the time ~ 0.1 s and depends slightly on the radiation energy. In contrast to the results of Ref. 5 in which the beams with a Gaussian distribution of the actuating radiation intensity were used and fluctuating mode was observed in transition to the stabilized condition in this experiment the mode of transition to the stabilized condition can be characterized as monotonic.

The measured values of Δn make it possible to determine the parameter of nonlinearity[3] N_c in the zone of rest with the help of which it is easy to characterize the thermal blooming of the HPR

$$N_c = -\frac{dn}{dT}\frac{\alpha I L^2}{\rho C_p V_\perp a} = \Delta n \frac{L^2}{a} = \frac{L^2}{L_t^2},$$

where L is the length of an action zone, $dn/dT = 10^{-6}$ deg^{-1} is the temperature gradient of the refractive index, and L_t is the characteristic length of the thermal blooming.[2]

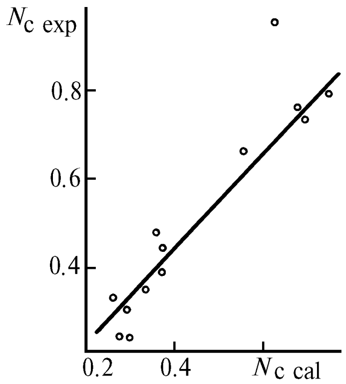

FIG. 3. A comparison of the experimental values of the nonlinear parameter N_c with the calculated results.

Figure 3 shows the results of comparisons between $N_{c\ exp}$ and $N_{c\ cal}$. The values of $N_{c\ exp}$ were determined by the value of maximum deflection of the sensing beam. To obtain the values of $N_{c\ cal}$ we calculated the absorption coefficient α, km^{-1} using the measured values of the wind velocity, temperature, and humidity as well as the technique presented in Ref. 8. The velocity of an appearing convective flow $V_c = d/\tau_c$ was considered as the perpendicular component of the averaged wind velocity. As can be seen from the figure, the measured and calculated values of the nonlinearity parameter agree well taking into account the errors in experiment.

Thus, the obtained results make it possible to conclude that the zone of rest being short in length at the input part of the path affects significantly the HPR beam distortions at the far end of the path at the wind velocity more than 2 m/s.

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