INVESTIGATIONS OF DISPLACEMENTS OF THE LASER BEAM ENERGY CENTERS UNDER CONDITIONS OF THERMAL BLOOMING

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In this paper we present some results of experimental studies of displacements of the energy centers of source images of laser radiation which makes up a refraction channel in an absorbing medium, and of sounding beams that propagate through this channel. This particular study concerns the nonstationary (transient) phase of the interaction. In our study we have varied the distance between the beam axes, as a result, we show that most accurate (adequate) information about the amplitude of the displacement process (for the case of a source of high–power radiation) can be obtained with a sounding beam propagating along a path in a windward portion of the beam while the information about the temporal behavior of the displacement process is more accurate if obtained with a sounding beam propagating along a path in the central portion of the beam. It is also shown that for the Reynolds number exceeding two the formation process is similar to damped oscillations.

When propagating laser radiation for long distances through the atmosphere, it is necessary to take into consideration a number of factors that lead to losses in energy portion and to distortion of the transverse structure of a laser beam. These factors include: radiation absorption by atmospheric gasses, scattering by the aerosol, amplitude and phase distortions caused by the turbulent inhomogeneities, nonlinear effects occurring in the case of high powerful wave propagation.[1–3]

The efficiency of operation of the systems intended to transfer the energy of laser radiation can be increased by means of adaptive optics that makes it possible to reduce the influence of atmospheric factors due to distortions *a priori* introduced into the initial field. These distortions account for instantaneous distribution of inhomogeneities over the propagation channel.[4,5] To obtain the information about the field structure of the refractive index, the reference (sounding) beams passing inside the propagation channel of the basic wave are used. These can be either beams of an additional source or portion of the main radiation separated to analyze the distortions and to control the adaptive system.

Because of uniformity of intensity distribution over cross section of an acting beam, distortions of a sounding beam depend on its position in the propagation channel. Thus there is a problem to choose a propagation zone of a sounding beam that can characterize the channel more adequately as a whole. In this paper we present the results of simultaneous measurements of energy center displacement of the image of the sources of high–power radiation and sounding beams in the process of establishment of steady state of the field of refraction index in the aimed refraction channel for different arrangement of the beam axes.

The absorption of radiation along the propagation path results in channel heating and therefore, in defocusing of the beam, and the presence of the wind results in change of intensity distribution and beam shape in a cross section and displacement of the beam energy center from the opposite direction to the wind.[3] These aberrations of the simplest form make the greatest contribution into the beam distortions, but they can be effectively corrected by means of controllable optics.[6] In the medium with homogeneous transverse wind, there is the rotation of the wave–front phase through the angle[2]

$$\theta = \frac{\mathrm{d}n}{\mathrm{d}T} \frac{\alpha\, I_0\, Z}{n\, \rho\, C_\mathrm{p}\, V},$$

where I_0 is the characteristic density of the power at the entrance into medium; α is the coefficient of molecular absorption; Z is the propagation path length; ρ and C_p are the density and thermal capacity of a medium, respectively; V is the wind velocity; $\mathrm{d}n/\mathrm{d}T$ is the temperature gradient of the refractive index of the air. It is too hard to separate a component corresponding to the tilt of the phase front from the total number of the distortions, because for that it is necessary to measure the spatial distortions of the phase front over entire aperture of the receiver in the real time scale. As is shown in Ref. 4, correction of the tilt of phase front of a beam can be carried out by measuring the displacement vector of the center of gravity in the image of reference source formed with the lens.

$$\rho_{cF} = -\frac{F}{k\,\Sigma} \int\limits_{\Sigma}\!\!\int d^{\,2}\rho\, \nabla_\rho\, S(Z, \rho),$$

where F is the focal length of the receiving lens, $k = 2\pi/\lambda$ is the wave number, $\Sigma = \pi R^2$ is the square of lens R in radius, and $S(\rho, Z)$ is the phase fluctuations on the aperture of the optical system. Displacements ρ_{cF} related to the focal length determine the slope angle of phase front of the wave. It is easier to measure displacements of the image of the source than to measure displacement of the beam as a whole.

EXPERIMENTAL SETUP

Investigations of Displacements of the energy centers of the images from the sources of high–power radiation and sounding beams were carried out using the model setup simultaneously. The beam of a LGN–503 laser at the wavelength 0.488 μm and power P up to 1 W (high–power radiation) was converted into the collimated beam of the effective radius a_{ac} = 0.4 cm by means of the lens system. It passed through the cell filled with the distilled water, tinted with water solvable dye. The absorption coefficient for the liquid was $\alpha \sim 0.06$ cm, the length of the cavity was 35 cm, and transverse size was 25×25 cm^2.

Intensity distribution over a beam cross section was defined at the intrance into the cavity by means of scanning over the horizontal and vertical planes with a point receiver. Distribution was bell–shaped and it differed from Gaussian one in more flat vertex. The power of high–power radiation was periodically measured with IMO–2 serial gauge. In addition, an permanent control over the power was carried out with photodiode mounted in the beam reflected by wedge. An electromagnetic shutter for beam break was mounted onto the focus of the first lens of the collimating system.

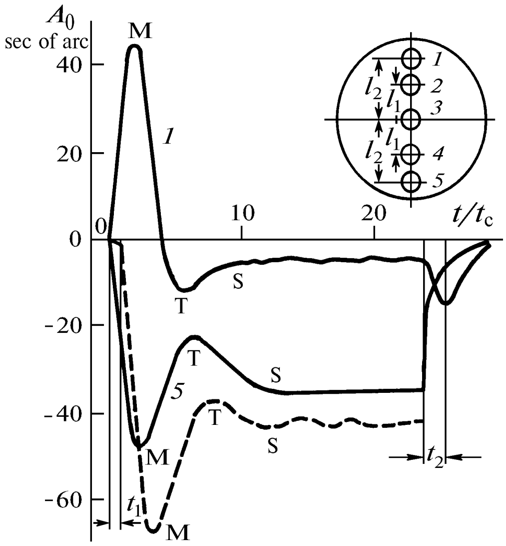

FIG. 1. Record of displacements of high–power radiation (dashed lines) and sounding beams (solid lines). Positioning of sounding beams at cross section of high–power radiation is shown at the top of the figure, the distance l_1 = 2.8 mm *and* l_2 = 4 mm.

The beam of the single–mode laser with λ_s = 0.63 μm and $a_s = 0.1\, a_{ac}$ was used as the sounding beam. It was introduced into the cavity in parallel with high–power radiation by means of the optical wedge. A distance between the beam axes varied from $+a_{ac}$ to $-a_{ac}$. The position of sounding beam at a cross section of high–power radiation is shown in Fig. 1. Behind the cavity the beams were spaced with the help of the plane–parallel plate and filters generating the radiation at the same wavelength. The image of each source was separately created by means of objective lenses 1 m in the focal radius. Photocathodes of dissector systems were mounted onto the plane of the image (focal plane) they kept track of displacements of the focal spot in two mutually – perpendicular coordinates in the plane perpendicular to the direction of the beam propagation. Electric signals proportional to displacements were analyzed with C9–8.

To describe the state of a medium in the aimed refraction channel the following parameters were used:

– heat release parameter[7] $q = \dfrac{\alpha\, P\, \beta\, g\, a_{ac}^3}{\pi \nu^3 \rho\, C_p} \simeq (4\text{–}70)$;

– rate of the convective flow determined by equilibrium between the viscosity and floatability forces in the viscous media[3]

$$V_c = \left(\frac{\beta\, g\, \alpha\, P\, a_{ac}}{16\, \rho\, C_p\, \nu^3}\right)^{1/2} \simeq (0.22\text{–}0.92)\cdot 10^{-2}\ \text{cm}\cdot\text{s}^{-1}\ ;$$

– the Reynolds number (Re) characterizing the relationship between the forces of viscosity and floatability and the Peclet number (Pe) – between the forces of floatability and thermodiffusion

$$\text{Re} = \frac{a_{ac}\, V_c}{\nu} \simeq (0.87\text{–}3.7)\ ;\ \text{Pe} = \frac{a_{ac}\, V_c}{c} \simeq (6.2\text{–}26.4)\ ;$$

– the characteristic length of the thermal lens[2] L_T = (180–87) cm; where β is the temperature coefficient of the expansion of the medium, g is the acceleration due to gravity, ν is the viscosity of medium, χ is the temperature conductivity of medium.

EXPERIMENTAL RESULTS

It is seen from the parameter estimations of the state of medium that under experimental conditions the forces of floatability exceed those of viscosity and thermal thermodiffusion. Under these conditions the presence of temporal changes between the aimed temperature field and convection resulted from such a presence leads to an unstable nature in the process of setting the steady state in the channel.[7] An example of the oscillogram records obtained from the experiment is shown in Fig. 1. The displacement of the center of gravity of the image of high–power radiation source is shown by the dashed curve (hereafter for brevity, we will refer the displacement of the center of gravity to the word "displacement"). The displacement of a sounding beam passing in extremely upper position above the axis of the acting beam is shown by solid curve (*1*), and the sounding beam passing above the acting beam axis is shown by solid curve (*5*).

To remain unchanged the structure of the beam in adaptive systems using the phase correction, it is necessary to know not only the features of the process dynamics, but also the times of setting. Thus, when analyzing the results the values of displacements and the times of achieving the typical points of the process were determined, as is given in Ref. 8. Such points are: the maximum displacement of the signal (M) A_m, t_m; the point of transfer to the steady state (T) A_t, t_t; the steady – state displacement (S) A_s, t_s ; the time from the beginning to the end of the convective motion t_1, and the time from the end of the action to the time of transfer of the region of the maximum heating with the convective beam through a sounding beam t_2. The values of displacements are given in sec of arc in all the figures, the times of setting are normalized to the time of convection $t_c = a_{ac}/V_c$.

The results obtained, confirm a conclusion[8] on the oscillating nature of the process of the establishment of the steady state of the refractive index field in the formed refraction channel. This is true of the whole channel (displacement of high–power radiation) as well as of the separate sections of the channel which are analyzed by sounding beams. Practically instantaneous displacement of sounding beams with the shutter opening was observed in all the experiments while displacement of the high–

power radiation occurs in the certain time t_1 being the time of defocusing. The processes of the beam defocusing play a leading role during that time and contribution from the developing convective flow resulting in refraction displacements is negligible. This time decreases from the values t_1/t_c from 1 to 0.4 with increase in the Pe number from 6 to 26 in our experiments.

Figure 2 shows the values of displacements of high–power radiation at three above–discussed typical points of the process. As is seen from the figure at the low power of the acting beam (Re ~ 1) the process of transition to the steady state is smooth (all three points have approximately close values of displacement), but when Re > 2 the spread between the maximum displacement and that at the transient point is already noticeable and grows with increase in the Re number. The ratio of the value of maximum displacement A_m to the steady–state value of displacement A_s (dashed curve in the Fig. 2) tends to the constant value of 1.6 when Re is > 3.

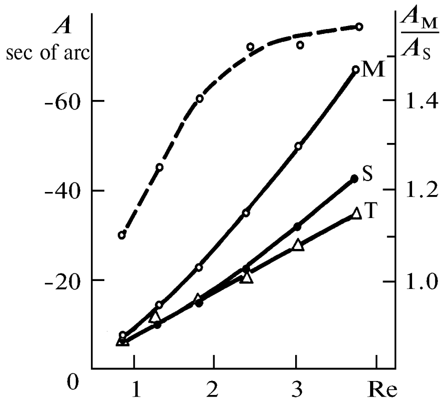

FIG. 2. Amplitude of displacement of high–power radiation at the maximum (M, empty circles), at the transient point of the process (T, triangles), and at the steady state (S, full circles). Dashed curve is A_m/A_s ratio.

Figures 3*a* and *b* show dependences of the values of maximum (*a*) and steady–state (*b*) displacements of a sounding beam propagating through different zones of high–power radiation. These figures show displacements of high–power radiation (dashed line), for comparison. As is seen from the figure, the nature of displacement of sounding beams passing above (leeward side) and below (windward side) the axis of high–power radiation radically differ from each other in the process of setting the steady state. If the direction of the displacement change for the windward beams is identical to that for the acting beam, then the sounding beams passing from the leeward side of the channel are first displaced to the direction of convective flow motion, achieve the maximum, and then change their direction of notion to opposite, i.e., towards the flow. In the steady state (Fig. 3*b*) the sign of displacement of such sounding beams depends on their position in the channel and the power of acting beam. The sign can be positive (in the direction of the convective flow) for the beams well away from the axis.

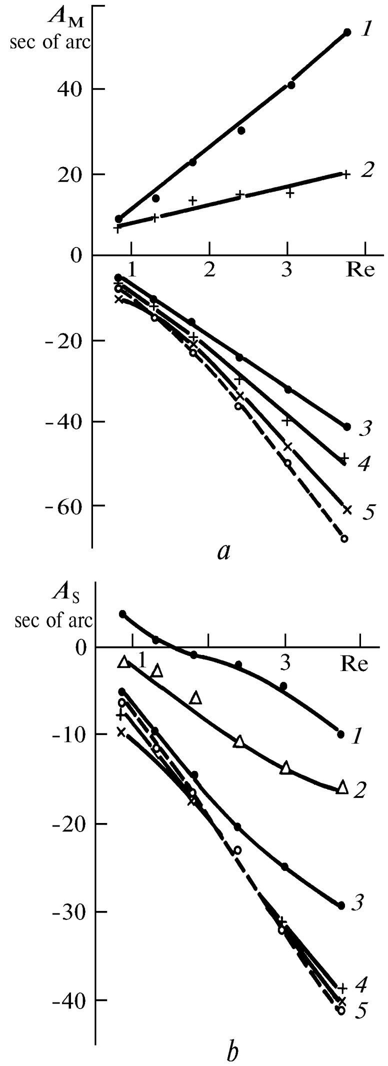

FIG. 3. Displacements of sounding beam (solid line) and high–power radiation (dashed line) at the maximum (a) and in steady state of the process (b). The figures adjacent to the solid curve indicate the position of sounding beams at cross section of high–power radiation (see Fig. 1).

The sounding beam passing at a distance of 0.7 a_{ac} from the center of the channel from windward side is more identical to the acting beam according to the values of displacements at maximum. Displacements at the maximum of sounding beam whose axis is aligned with that of the acting beam are by 40% less than that of the latter. The axis of sounding beam is of the same direction with the axis of high–power radiation. These discrepancies are smoothed in the steady–state mode.

The situation is different for the instants of time for achieving the characteristic points. Figure 4 shows the Re– and Pe numbers depending on the time of establishment of maximum displacement (M) and transient point (T) for high–power radiation (dashed line) and three positions of sounding beam. The time, normalized to the period of the convective transfer $t_c = a_{ac}/V_c$ is plotted along the vertical axis. It is obvious from the figure that the time of the transient process of the setting the temperature gradients is extremely different in the different zones of the sounding beam propagation. The process of establishment occurs much more faster at the periphery of the channel while the coaxial sounding beam has the best correlation with high–power radiation. The maximum deviation of high–power radiation when the Re > 2 is reached at $t \sim 3\,t_c$ and when Re < 2 this time decreases moderately with decrease in Re.

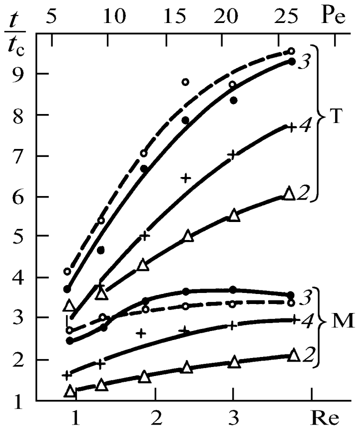

FIG. 4. The time of achieving the maximum displacement (M) and the transient point (T) by the acting beam (dashed lines) and by sounding beam (solid lines). Sounding beam position at a cross section of high–power radiation is the same as in Fig. 3.

The time of establishment of the steady state in the channel depends strongly on the power of the acting beam. This time coincides with the time of establishment of maximum displacement under conditions of lower power (Re < 1.5, Pe < 10) and smooth transient process. The pronounced oscillating nature of the transient process is observed at the powers corresponding to Re > 2 and Pe > 15, the second period of oscillations appears, and the steady state is established at $t > 10\,t_c$. Besides, low–amplitude oscillations caused apparently by the channel instability are observed at low (Re < 1.5; Pe < 10) and high (Re > 2; Pe > 15) powers at the steady state.

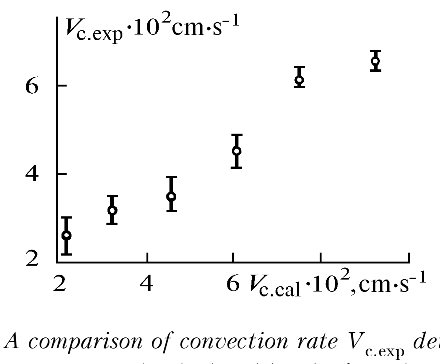

FIG. 5. A comparison of convection rate $V_{c.exp}$ determined in the experiment and calculated by the formula $V_{c.cal}$.

Sounding beams regain their original position upon completion of the action. The time of heat release in this mode is determined by the rate of the convective flow and its relaxation with time. By assuming that the time t_2 (Fig. 1) is in agreement with the time of transfer of maximum heated region through the sounding beam by the undamped convective flow, we estimate the rate of the convective flow according to displacement of a sounding beam at the leeward side of the channel (beam *2*). The distance between maximum heated region and sounding beam is determined from the distance between the axes allowing for their displacements. Figure 5 shows the results of comparison of the calculated rate with the rate of convection flow $V_{c,cal}$ calculated by the above formula.

The investigations carried out allows us to make the following conclusions:

– The transient process of image displacement of high–power radiation and sounding beams has the features of oscillating damped process at the powers of acting beam corresponding to Re > 2. The parameters of such a process depends on absorbed energy and properties of the medium. Maximum amplitude of displacements normalized to steady state tends to a certain constant value.

– The process of establishment of steady state in the channel is "smooth" when Re < 1.5, because viscosity forces are comparable with the forces of floatability of heated liquid, the time of achieving of a steady state is about $3\,t_c$.

– The time of achieving the maximum displacement of high–power radiation is about $3\,t_c$ when Re > 2, the time of achieving a steady state increases with the power increase and reaches the values of about $10\,t_c$ when Re > 3 with the occurrence of the second maximum.

– The field of refraction index in cross section of the channel is inhomogeneous on both the time of establishment and integral value of gradient. A nature of displacement of sounding beam at the windward side of the channel is identical to high–power radiation. Establishment of a steady–state mode of displacements of the beams at the leeward side of the channel occurs in antiphase with high power radiation.

– The process of amplitude and time displacements of high–power radiation is most closely described by sounding beams at the windward side and at the central part of the channel, respectively.

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