INVESTIGATION OF THE REFRACTION CHANNEL BY A PROBING BEAM

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The results of experimental investigation of distortions of the probing beams propagating in the channel formed by the heating laser beam in an absorbing medium under conditions of the self–induced convection are given. The characteristic relaxation time of the medium and the magnitudes of distortions are determined in the case in which the power of a heating beam and the geometry of the experiment changes.

The region with constant gradient of the dielectric constant ε which is called the refraction channel[1,2] is formed in the process of propagation of high–energy laser beams in the atmosphere. The propagating radiation changes the optical properties of the medium which, in turn, results in the additional (to atmospheric) distortions of heating beams. The steady–state spatial structure of the refractive index field of the medium in the refraction channel is established after a time from the start of the laser action. It is a function of the intensity distribution of a heating beam, of the shape and duration of pulses in a pulsed regime of radiation, and of the propagation conditions.[3–5]

The maximum overheating of the medium in the channel occurs in the so–called calm regions,[4] where the heat is removed from the channel by a light–induced convective flow and by thermal conductivity. The nonlinear thermal lens is formed which redistributes the radiation intensity in the cross section of the beam. For the prediction of the resulting distortions and for operation of the systems of correction of the adaptive distortions, the operative information about the channel characteristics must be available. This problem can be solved with the use of probing beams, which do not distort the spatial structure of the channel and provide the information about the distribution field of the refractive index in the channel.

The paper studies the shift of the centroid of a probing beam which crosses the channel at an angle to its axis because in practice the alignment of axes is impossible or inexpedient since alignment and separation of the beams is accompanied by the large energy losses. In addition, slant sensing and the technique employed make it possible to obtain the data on the integral characteristics of the channel in the region being sounded.

It is well known that the centroid of the image of a source of radiation transmitted through the inhomogeneous medium without the amplitude fluctuations is given by the formula[6]

$$\mathbf{r}_c = -\frac{F}{k\,\Sigma}\int\!\!\int_{\Sigma} \Delta S\,(\rho_0)\,\mathrm{d}^2\rho_0\ ,$$

where $\nabla S\,(\rho_0)$ is the phase gradient of the wave on the surface of the objective, F is the focal length of the objective, and $k = 2\pi/\lambda$ is the wave number. When the laser beam is completely subtended by the lens aperture the integration is performed over the illuminated part of the objective Σ.

For the beams with the intensities being distributed symmetrically about the objective axis in the absence of phase distortions $\mathbf{r}_c \equiv 0$.

We assume that the probing beam upon entering the medium which absorbs the radiation with wavelength λ_1 (heating radiation) and does not absorb the radiation with wavelength λ_2 (probing radiation), has the initial distribution of the radiation field

$$U\,(0,\ \rho_0) = U_0\,\exp\left(-\frac{\rho_0^2}{2a_p^{\,2}} - \frac{ik\,\rho_0^2}{2R}\right),$$

where a_p is the effective radius of the beam, U_0 is the axial field intensity, R is the curvature radius of the wavefront at the exit from the source and the heating beam with the plane wavefront and the Gaussian distribution of the radiation intensity.

In the absence of the heating radiation, the medium is homogeneous and the probing beam (PB) propagates through the medium keeping the symmetry and experiencing the phase shift due to the refraction in the medium. Alignment of the axis of the receiving system with the centroid of the source image determines the zeroth reading of the system. When the heating radiation is switched on, the medium is heated and its refractive index changes, but since heating is nonuniform due to the convection and to the nonuniform distribution of the intensity, the resulting phase shift of the PB $\Delta S \sim kL\,\dfrac{\partial n}{\partial T}\,T\,(x,\ y,\ z)$ (where L is the path length, n is the refractive index of the medium, and $T\,(x,\ y,\ z)$ is the temperature distribution in the cross section of the PB) leads to the shift of the centroid of the source image $r_c \neq 0$. In general, r_c is a function of the medium properties, of the parameters of heating and probing beams, and of the time over which the pulse acts. Measuring the coordinates of the centroid of the PB as a function of time, one can study the behavior of the refractive index in the channel and determine the characteristic time of the channel relaxation.

THE EXPERIMENTAL SETUP

The radiation of an LGN–503 laser with wavelength $\lambda_1 = 0.488\ \mu$m and power $P \sim 1$ W passes through the lens system which forms the collimated beam with the effective radius $a_\mathrm{m} = 0.3$ cm and entered the cell filled with

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fuchsine–dyed distilled water. The coefficient of absorption of liquid α is equal to 0.03 cm^{-1}. The faces of the cell are made of the plane–parallel glass plates. The cell length is 35 cm and its cross section is 25×25 cm^2. The probing beam of a single–mode helium–neon laser with wavelength $\lambda_2 = 0.63$ μm and with radius $a_p = 0.15\,a_{\rm m}$ enters the cell at the angle θ with respect to the probing beam in the horizontal plane with the help of mirrors. The image of the source of the probing beam is formed with the lens behind the cavity in the plane of a photocathode of the dissector receiving system which allows us to record the shift of the source image along two perpendicular directions.[7] The electric signals Ux and Uy, proportional to the shifts along the x and y axes, are recorded by the N–702 x–t plotters. Simultaneously, the changes in the axial intensity of the probing beam are recorded. The output radiation of the LGN–503 laser was modulated with an electric mechanical chopper blocking the beam in the focus of the collimated optical system. The power of the heating radiation is measured by a commercial OSISM device in every 15 minutes with the help of the mirror inserted into the beam. The distribution of the radiation intensity in the cross section of the beam is measured upon entering the cell with the help of the photomultiplier with the aperture 0.5 mm in diameter by way of vertical and horizontal scanning. In the case of a low–power radiation the distribution is close to the Gaussian, while in the case of a high–power radiation (0.3–0.4 W) the flat top of the distribution occupies ~ 1/5 part of the cross–sectional area of the beam. During measurements the power of the heating radiation upon entering the cell was 0.14, 0.2, 0.3, and 0.4 W and the angle between the axes of the heating and probing beams varied from 10 to 55 μrad, in addition, the PB propagates along the diagonal of the cylinder with different radius, being inside the refraction channel near its axis or in the channel with the surrounding medium which is also involved into the process of heat exchange.

THE RESULTS AND THEIR DISCUSSION

The nonlinear thermal lens, which is formed due to the interaction between the laser radiation and the absorbing medium is usually described by the characteristic amount of thermal blooming[4]

$$L_{\rm T} = \left(-\frac{\partial n}{\partial T}\frac{\alpha P}{\pi\rho\, c_p V_c a_{\rm m}^3}\right)^{-1/2},$$

by the parameter of heat release[8]

$$q = \frac{\alpha P\,\beta g a_{\rm m}^3}{\pi\nu^3\rho c_p}$$

and by the convection speed[3]

$$V_c = \left(\frac{\beta g\,\alpha P a_{\rm m}}{\rho c_p\,16\nu}\right)^{1/2}.$$

In the given equations P is the power of the heating beam, ρ and c_p are the density and the specific heat of the medium, respectively, β is the thermal coefficient of volume expansion of the medium, g is the acceleration of centroid, and ν is the viscosity of the medium.

The estimates of these parameters for the conditions of our experiment are given in Table I. They indicate that the experiment was carried out under conditions of "moderate" convection,[8] the diffraction divergence of the beam was small and had no effect on the distribution of the radiation intensity in the cross section of the beam, and the thermal lens formed due to the interaction between the radiation and medium was "thin".[9]

TABLE I.

P, W	$\lvert L_T\rvert$, cm	q	V_c, cm·s^{-1}
0.4	81	127	$3.24\cdot10^{-2}$
0.3	87	95	$2.81\cdot10^{-2}$
0.2	96	63	$2.29\cdot10^{-2}$
0.14	105	45	$1.91\cdot10^{-2}$

The experimental results can be devided into two groups, one of which describes the temporal processes of forming of the nonlinear thermal lens and of its relaxation and another describes the shift of the PB image as a function of the parameters of heating radiation and the geometry of the experiment. The typical record of the shift of the centroid of the image of probing source along the coordinates and of the changes in the axial intensity of the heating beam is shown in Fig. 1. The record was made with the use of heating radiation with a power of 0.3 W.

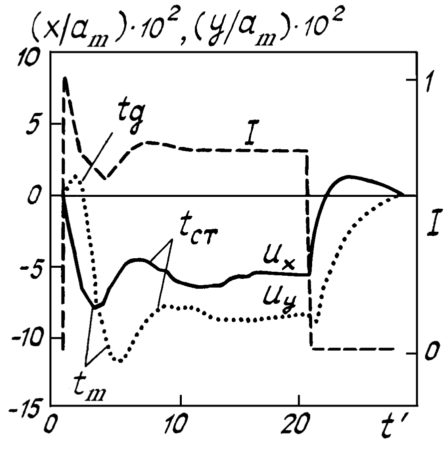

FIG. 1. Record of the shifts of the probing beam Ux and Uy and changes of the axial radiation intensity I of a heating beam.

Time $t' = t/t_0$, where $t_0 = \dfrac{a_{\rm m}}{V_c}$ is laid off as abscissa, and the shifts of the PB at the exit face of the cell, converted from the shifts of the source image and scaled by the radius of the heating beam, is laid off as ordinate. In the study of the results, the time of defocusing t_d was determined from the start of the shift of the vertical component in the downward direction, the time for the shift to reach its maximum value was $t_{{\rm m}x,y}$, and the relaxation time $t_{rx,y}$, was defined as the time of termination of the first oscillation.

It follows from the obtained results that the process of the refractive index field relaxation in the refraction channel for our experimental conditions has the character of decaying oscillations with 1–2 periods. The number of oscillations increases and their period decreases with the power of heating radiation. The period $0 - t_d$, – the period of defocusing of the heating beam – was determined from the start of the shift of the PB counter to the convective flux. In the curve showing the change of the axial intensity of the heating beam this period is determined from the change of the rate of the intensity decay. Its duration changes slightly in the experiment (10–12 s) and to within the order of magnitude agrees with the period of establishing of the convection speed in liquid $t_c \frac{a_m}{\nu^2}$ (Ref. 8).

Next period $t_d - t_m$ is the period of maximum speed of a light–induced flow. At the start of heating the speed of the convective flow is small and, as a result, the flow is insufficient for eliminating the heat released in the process of absorption of the energy in the central region of the beam. The medium is overheated, buoyancy accelerates the liquid up to the maximum speed, the heat is eliminated from the central region of the beam, the air temperature falls, and the convection speed decreases. The decaying free oscillations are excited[8] and the process is stabilized.

The results of experimental measurements of time for the shift to reach its maximum and of relaxation time in the horizontal (Fig. 2*a*) and vertical (Fig. 2*b*) directions as functions of the angle between the heating and probing beams for different powers of heating radiation are shown in Fig. 2. The time is scaled by the time t_0. Two values are laid off as abscissa, that is, the angle between the beams (lower scale) and the separation of the beam axes upon entering the cell a is scaled by the heating beam radius a_m (upper scale), which correspond to this angle.

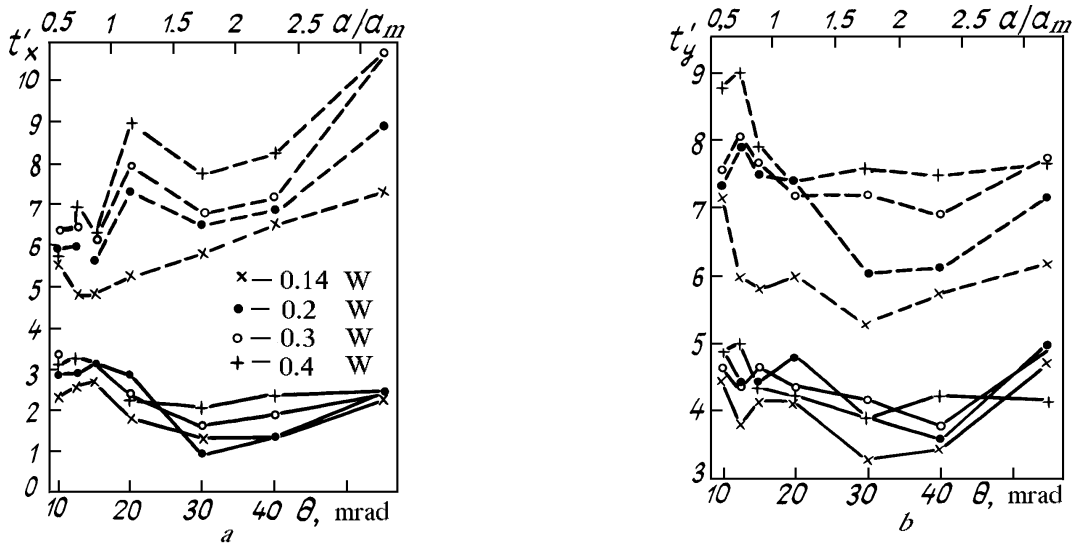

FIG. 2. The time for shift to reach its maximum (solid curves) and the relaxation time (dashed curves) in the horizontal (a) and vertical (b) directions.

As can be seen from Fig. 2, the shift in the horizontal direction reaches its maximum, on the average, 2–3 times faster than in the vertical direction, that is, $t_{mx} \sim (1-3)t_0$ and $t_{my} \sim (3-5)t_0$. In this period the probing beams passing through the region of the channel, whose radius is $\lesssim 2a_m$, have the shortest time for the shift to reach its maximum. The relaxation time scaled by t_0 for vertical and horizontal shifts is $t_{ry} = (5-8)\,t_0$ and $t_{rx} = (5-10)\,t_0$. It increases with the radiation power. In addition, t_{rx} increases from $(4.5-7)\,t_0$ up to $(7-10)\,t_0$ as the angle between the beams increases, while t_{ry} is practically independent of the angle between the beams. It should be noted that the real time for shift to reach its maximum and the relaxation time in the channel decreases with the radiation power. This obviously results from the necessity of taking into account the contribution of the thermal conductivity to the elimination of heat from the channel, since the characteristic time $t_0 = \frac{a_m}{V_c}$ in the experiment to within the order of magnitude agrees with that of the heat conductivity.

Analyzing the amplitudes of shift of the PB along the two directions, one can see that in all realizations the shifts in the vertical plane occur counter the convective flow with the exception of the start of heating from 0 to t_d during which the source image of the PB remained unchanged or shifted in the upward direction, i.e., in the direction of the convective flow. In our opinion, this fact can be explained by the uncertainties in the alignment of the beam axes and by the local deviations of the intensity distribution of the heating beam from the normal distribution. In the horizontal plane the sign of the shift of the probing beam depends on the angle θ between the beam axes. The results of measurements of the PB shifts in the horizontal plane in the steady–state regime of heating are shown in Fig. 3*a*.

It can be seen from Fig. 3*a* that when the angles between the beam axes $\theta \lesssim \arctan\frac{2a_m}{L}$, corresponding to the separation beam axes upon entering the cell $a \lesssim a_m$, the shifts of the PB result in the decrease of θ (the sign of shift is negative), while for $\theta > \arctan\frac{2a_m}{L}$ (i.e., for $a > a_m$) the PB shifts increase the angle θ. One possible reason of this phenomenon may be the deviation of the distribution of the radiation intensity in the cross section of the heating beam from the Gaussian distribution, however, the sign modification was observed in the case of the low–power heating beam, in which the distribution of the radiation intensity in the cross section of the beam was the Gaussian. The analogous dependence on the angle between the beam axes was found for the maximum shift in the horizontal plane. The vertical shifts in the steady–state regime of heating as functions of the radiation power are illustrated by Fig. 3*b* for the angles $\theta > \arctan\frac{2a_m}{L}$. In the same figure the dependence $\Delta\theta_y \sim P^{1/2}$ is denoted by a dashed curve. It can be seen from the figure that these shifts depend weakly on the angle between the beam axes. For the probing beams propagating inside the channel ($\theta \le \arctan\frac{2a_m}{L}$), the shifts increase by a factor of 2.5 – 3 as the radiation power increases from 0.14 to 0.4 W.

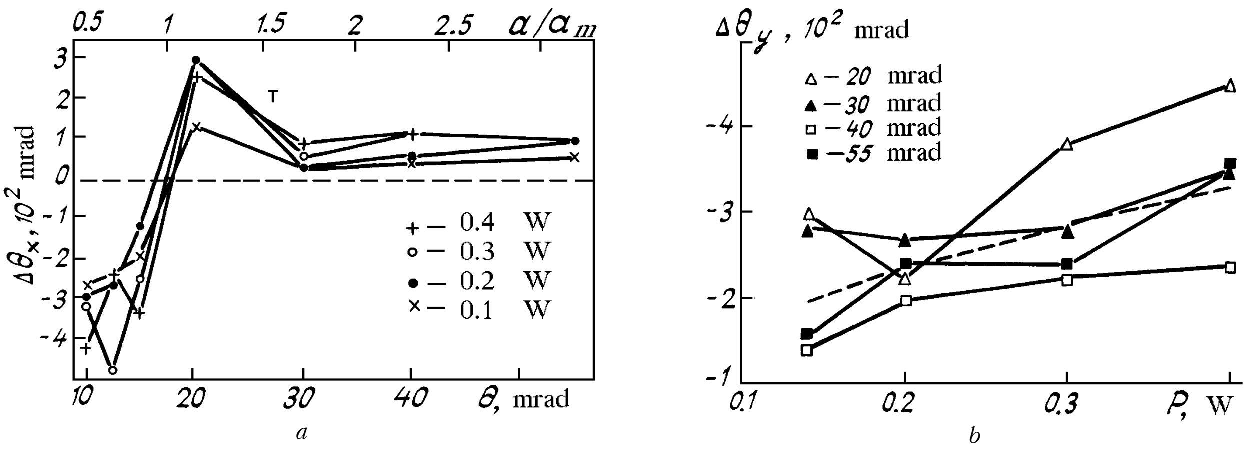

FIG. 3. The shifts of a probing beam in the steady–state regime of heating in the horizontal plane as functions of the angle between the beam axes (a) and in the vertical plane as functions of the radiation power (b).

The maximum shifts of the probing beam in the vertical direction observed during forming of the refraction channel are 1.2 – 1.5 times larger than that in the steady–state regime, while for the shifts in the horizontal direction this ratio varies within the limits 1.1 – 1.3.

The results of comparison of the experimental data and calculated dependence of the shifts of the PB in the incidence plane (perpendicular to the wind flow) obtained in Ref. 10 on the basis of numerical solution of the transfer equation for the radiation brightness, are illustrated by Fig. 4. The experimental conditions and the calculation parameters are identical. It can be seen from Fig. 4, that the experimental values are 2.5–3 times larger than the calculated. This discrepancy can be explained both by the errors in conversion of the shift of the beam in the image plane of the source on the shift at the angle plane of the cell and by the assumptions made in calculations in Ref. 10.

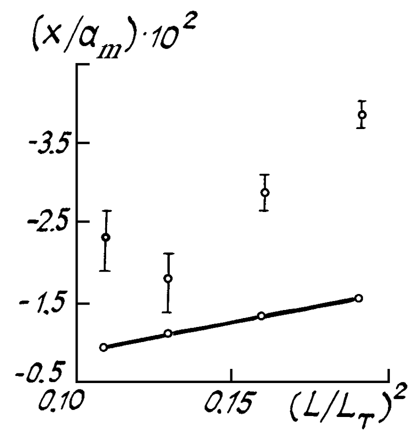

FIG. 4. Intercomparison of the experimental values of shifts of the probing beam and the calculated values presented in Ref. 10.

Summarizing the results, the following conclusions can be drawn:

– the process of relaxation of the refraction channel has the character of decaying oscillations, with the characteristic relaxation time being much longer than the time of heat transfer across the channel by the light–induced convective flow and

– the distortions of the probing beams in the case of slant sensing are functions of the sensing angle, of the power of heating radiation, and of the convective flow direction.

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