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TRANSIENT THERMAL LENS FORMED BY SHORT LASER PULSE IN CONDENSED MEDIUM

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The problem of relaxation is solved for a thermal lens which has been formed by a short laser pulse in a condensed medium. An expression is obtained for the focal length of such a lens and the asymptotic trend of the focal length as time increases is determined.

Recent years have witnessed a growing interest in quasioptical structures developing in nonuniformly heated media. Gradients of thermodynamic parameters caused space–time modulation of the refractive index, which alters the optical properties of the medium. It has demonstrated in earlier studies [1, 2] that formation and relaxation of a thermal phase diffraction grating can be successfully used in transient holography as well as for contactless measurements of thermophysical properties of materials. There are also known gaseous lenses used as phase correctors for light guides.

In this communication the results of a study pertaining to a thermal lens formed during passage of a short strong laser pulse through a thin layer of a substance will be presented, whereupon a relation will be established between thermophysical properties of that substance, the space–time variation of the refractive index, and the optical properties of the lens.

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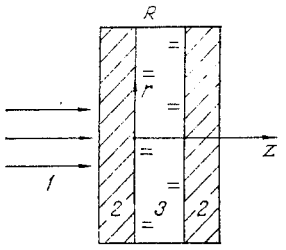

Fig. 1

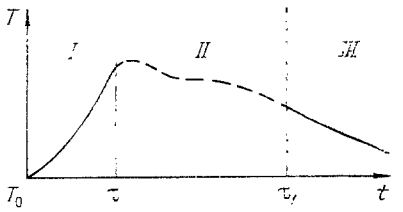

Fig. 2

Fig. 1. Schematic diagram of thermal lens: 1) incident light beam; 2) vessel walls; 3) fluid.

Fig. 2. Schematic representation of the process: I) absorption stage; II) vibration damping stage; III) thermal relaxation stage.

Let us briefly describe the physical situation. On a thin layer of a substance in the from of a cylinder whose height is much smaller than its radius impinges a short but strong light pulse, the axis of the light beam coinciding with the axis of symmetry of the cylinder (Fig. 1). Absorption of luminous energy by the substance causes its temperature to change, which results in space–time variations of its refractive index. Dissipation processes subsequently cause these variations to relax. We will evaluate the changes due to these processes under the following conditions: 1) the vessel with fluid (dimensions d = 100 μm and r_0 = 1 mm so that $d \ll r_0$) is thermally insulated; 2) reflection losses at the glass walls of this vessel do not exceed 10%, such an estimate being also valid for a layer of solid substance in air; 3) the medium absorbs some incident luminous energy (approximately 1%); 4) the power of incident radiation is approximately 10 MW and the duration of a pulse is τ_p = 10 nsec.

The entire process, absorption of radiation and relaxation of thermal nonuniformity, can be tentatively subdivided into three stages (Fig. 2). In the first stage the temperature of the medium rises fast, as a result of absorption. In the second stage a local pressure jump excites thermomechanical vibrations which, not surprisingly, are dampled out fast by the viscosity of the medium. In the third stage the temperature relaxes, rather slowly, as a result of heat conduction.

In the aforementioned configuration with the given values of parameters, the energy absorbed by the layer is on the order of 10^{-3} J and the maximum temperature rise is on the order of 1°K (assuming the substance has a density $\rho = 10^3$ kg/m^3 and a specific heat c_V = 4 kJ/kg·K). We will therefore hypothesize that after lengths of time comparable with the duration of pulse action all processes can be ignored, except temperature changes (consequently also isochoric pressure rise) and absorption of laser radiation. It will also be assumed that the thermal conductivity of the vessel glass is much lower than that of the medium inside. As scales of length and time we select r_0 and $\tau_0 = r_0/c_0$, respectively. All quantities in this study will be treated in dimensionless form.

On the aforementioned layers of a substance with parameters T_0, P_0, ρ_0 let there impinge a light pulse whose space–time structure can be described by a known function $I(r, \tau)$ and whose intensity does not increase from the center to the periphery. The first stage of the process is described by the equation

$$\partial\theta/\partial\tau = \alpha I(r, \tau), \ \rho = \rho_0, \qquad (1)$$

$$v = 0, \ P = P_0 + \alpha_V \theta/\varkappa_T.$$

The resulting temperature field, established by absorption of radiation, is

$$\theta(r, \tau_p) = \alpha \int_0^{\tau_p} I(r, \tau)\, d\tau = \alpha \tilde{I}(r). \qquad (2)$$

The temperature field $\theta(r, 0) \equiv \theta(r, \tau_p)$ and the pressure field after passage of the pulse will be regarded as the initial ones for the second stage, during which a pressure gradient will cause the medium to move. The maximum pressure rise at the beginning of the second stage reaches 1 atm ($\alpha_V \approx 2 \cdot 10^{-4}$ K^{-1} and $\varkappa_T \approx 5 \cdot 10^{-5}$ atm^{-1} for water) so that the maximum velocity can be estimated at 10^{-1} cm/sec, the mass flux contributing much more than the thermal flux and thus not a negligible one (rather the opposite is true), but this motion of the

medium soon decays because of the viscosity (in water the pressure relaxation time is two orders of magnitude shorter than the temperature relaxation time). The mechanical effects will be examined in a separate study. Here we will only assume that they do not noticeably influence the temperature evolution. In other words, the second stage will be regarded as a short one and the temperature field (2) will be regarded as the initial one also for the third stage. During that third period we will disregard all processes except heat conduction.

This situation corresponds to the problem of cooldown of an infinite cylinder according to the equation

$$(1/r)\,\partial/\partial r\,(r\partial\theta/\partial r) = \chi^{-1}\partial\theta/\partial\tau \tag{3}$$

with initial and boundary conditions

$$\theta(r,\ \tau)|_{\tau=0} = \theta(r,\ 0);\ \theta(r,\ \tau)|_{r=1} = 0;\ \theta(r,\ \tau)|_{r=0} < \infty. \tag{4}$$

The solution to Eq. (3) for conditions (4) is [4]

$$\theta(r,\ \tau) = \sum_{m=1}^{\infty} A_m J_0(\mu_m r)\exp(-\mu_m^2\chi\tau), \tag{5}$$

where

$$A_m = \int_0^1 r\theta(r,\ 0)\,J_0(\mu_m r)\,dr \Big/ \frac{1}{2}[J_1(\mu_m)]^2. \tag{6}$$

We will describe the thus formed inhomogeneity with the Lorentz–Lorentz equation [5]

$$(n^2-1)/(n^2+2) = 4\pi\beta/3v. \tag{7}$$

We will assume that the change in volume in this problem is caused solely by a change in temperature, i.e.,

$$v(\theta) = v(1+\alpha_v\theta). \tag{8}$$

Then

$$(n^2-1)/(n^2+2) = B[1+\alpha_V\theta(r,\ \tau)]^{-4};\ B = \frac{n_0^2-1}{n_0^2+2}, \tag{9}$$

and this yields

$$n(r,\ \tau) = [1+2B+\alpha_V\theta(r,\ \tau)]^{1/2}[1-B+\alpha_V\theta(r,\ \tau)]^{-1/2}. \tag{10}$$

The expression for the eikonal of the given system is

$$\Phi(r,\ \tau) = \int_0^d n(r,\ \tau)\,dz = dn(r,\ \tau). \tag{11}$$

The coefficient of r^2 in the expansion of the eikonal into a power series in r^2 is known [5] to be equal to the lens power (reciprocal of the focal length). On the basis of relation (11), (10), and (5) we obtain for the lens power the expression

$$c_2(\tau) = [f(\tau)]^{-1} = \frac{d\alpha_V\,\dfrac{\partial\theta(0,\ \tau)}{\partial(r^2)}\{[1-B+\alpha_V\theta(0,\ \tau)]^{1/2} - [1+2B+\alpha_V\theta(0,\ \tau)]^{1/2}\}}{2[1-B+\alpha_V\theta(0,\ \tau)]^{3/2}[1+2B+\alpha_V\theta(0,\ \tau)]^{1/2}}. \tag{12}$$

Here

$$\theta(0,\ \tau) = \sum_{m=1}^{\infty} A_m\exp(-\mu_m^2\,\chi\tau), \tag{13}$$

$$\partial\theta(0,\ \tau)/\partial(r^2) = -\sum_{m=1}^{\infty} A_m\mu_m^2\exp(-\mu_m^2\,\chi\tau) \tag{14}$$

(we have expanded the Bessel function into a series in r^2).

The obtained expression relates the focal length of a diverging lens to the thermodynamic parameters of the system and to time. It follows from this relation that, for instance, the focal length of such a lens increases boundlessly with time, which is consistent with the physical nature of the given problem.

In conclusion, let us derive the asymptotic expression for the focal length at time $\tau \to \infty$. Because roots μ_m with higher index numbers m are larger, one needs to retain only the first terms in series (13) and (14). Moreover, $\alpha_V\theta(r, \tau) \ll 1+2B, 1-B$.

Linearization of relation (10) with respect to $\alpha_V\theta$ yields

$$|f(\tau)|^{-1} \underset{\tau\to\infty}{\approx} -\frac{3B\alpha_V d\mu_1^2}{2(1-B)^{3/2}(1+2B)^{1/2}} \exp(-\mu_1^2\chi\tau), \tag{15}$$

so that the quantity

$$\ln|f(\tau)| = -\ln\frac{3B\alpha_V d\mu_1^2}{2(1-B)^{3/2}(1+2B)^{1/2}} + \mu_1^2\chi\tau \tag{16}$$

is a linear function of time.

NOTATION

ρ_0, initial density; T_0, initial temperature; P_0, initial pressure; n_0, initial refractive index; r_0, radius of a specimen; d, thickness of a specimen; c_0, acoustic velocity at T_0, P_0; χ, dimensionless thermal diffusivity; $\theta = (T-T_0)/T_0$, dimensionless temperature; J_0 and J_1, Bessel functions; μ_m, roots of the Bessel function J_0; $\tau_0 = r_0/c_0$, characteristic time; τ, dimensionless time; r, dimensionless space coordinate; α_V, coefficient of thermal expansion; v, molecular volume; Φ, eikonal; c_2, lens power; f, focal length; τ_p, pulse duration; α, absorption coefficient for light; and β, polarizability of one molecule.

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