A simple demonstration experiment in nonlinear optics (Thermal defocusing of laser radiation)

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Nonlinear optics, which is still referred to as a promising new branch of physics, is in fact older than the current crop of young physicists, most of them graduating from university without having seen a single nonlinear optical effect. This problem was noted, for example, in a recent publication in Uspekhi Fizicheskikh Nauk.[1] The powerful lasers that are usually employed to excite nonlinear optical effects are still rare, expensive, and are used in stationary installations that are ill-adapted for laboratory exercises by large numbers of students or for lecture demonstrations.

On the other hand, there also exist nonthreshold nonlinear optical effects: in particular, the thermal defocusing of intense radiation in absorbing solutions.[2] This thermal defocusing must be taken into account, usually as an undesirable secondary effect, in many studies involving intense radiation, and it has been specifically discussed in many reports (see, for instance, Refs. 3, 4). The elementary theory of thermal defocusing is presented in Ref. 5.

The thermal defocusing effect may be observed in the broadening of the light spot produced by a continuous laser beam on a distant screen when the beam passes through a cell with plane parallel walls containing an absorbing solution. In a steady state radial temperature and density gradients are set up in the solution, which lead to a refractive index gradient. The liquid becomes optically inhomogenous.

As is well known, the rectilinear propagation of light is distorted by inhomogenous media. A simple calculation shows[6] that the radius of curvature R of the ray and the refractive index gradient are connected by the expression:

$$R^{-1} = \frac{\sin i \cdot \operatorname{grad} n}{n}, \qquad (1)$$

where i is the angle the ray makes with the normal to surfaces of constant n. In most liquids $(\partial n/\partial T)_p < 0$ and consequently the function $n(r)$ has a minimum on the axis of the light beam. According to (1) such a distribution of $n(r)$ leads to defocusing of light; if this thermal self-effect is significant the plane-parallel cell containing an absorbing solution acts on the beam as a concave lens. At relatively low beam power the change in angular divergence of the beam depends on its power P and its radius just before entering the absorbing layer a_0 as follows:

$$\vartheta - \vartheta_0 = \frac{(\partial n/\partial T)_p P}{\pi n a_0 k}(1 - e^{-\alpha l}); \qquad (2)$$

where θ_0 is the initial beam divergence, l is the absorbing layer's thickness, α is the absorption coefficient, and k is the thermal conductivity of the solution. In this case the thermal lens acts as a thin lens, i.e., only wavefront distortion is significant, whereas the broadening of the beam inside the cell is negligible.

The radiation-induced thermal lens produces spherical aberrations. Indeed, grad$n = 0$ both on the beam axis and as $r \to \infty$, peaking at some distance r_m from the axis. Given an arbitrary, for example Gaussian, distribution of cross-sectional intensity of the beam as it enters the absorbing layer, rays with the initial coordinate $r_0 \approx r_m$ are deflected the most, and consequently the focal length of the thermal lens is dependent on r_0.[4]

In order to arrive at a correct understanding of the nature of the distribution of cross-sectional intensity of the beam as it leaves the solution one must take into account the coherence of laser radiation.[6,7] The mutually intersecting rays, variously deflected by the absorbing solution interfere and form a system of concentric dark and light rings on the screen. In the thin lens approximation, the phase change of rays within the cell follows the spatial behavior of grad n, having its minimum on the beam axis S_0 and approaching a constant value S_∞ at $r_0 \approx a_0$. This determines the maximum number of aberrational rings, which does not exceed $N = (S_0 - S_\infty)/2\pi$ and increases with radiation intensity.

From expression (2) an increase in radiation intensity leads to a proportional increase in beam divergence. It was found, however, that the effect can be significantly enhanced also at constant intensity by focusing the beam with a convex lens before it enters the absorbing solution, i.e., by reducing a_0. Nonetheless also in subsequent studies of thermal defocusing lasers were employed with output power of 0.1 W and more—in accordance with the custom of looking for nonlinear effects at the greatest possible radiation intensities. At the same time, the additional means of enhancing the effect by tailoring the parameters of the absorbing layer were insufficiently utilized.

We have determined the conditions in which a strong defocusing effect increasing the angular divergence of the radiation by approximately 5° may be obtained with a helium-neon laser of only 6 mW power, which makes the effect suitable for lecture demonstrations for all university and even high school audiences. The proposed demonstration experiment is based on focusing the radiation before it enters the cell with a relatively short-focus lens and using thin cells of high optical density containing an appropriate absorbing solution.

By focusing the beam we increase the power density of the radiation and reduce the volume of the intensely heated solution, which markedly reduces the distorting effects of convection that draws off the excess heat and reduces the vertical diameter of the light spot.[4] The effects of convection are also reduced by using thin cells. At the same time, as is apparent from (2), the absorption coefficient α of the solution must be sufficiently large to fulfill the condition

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$\exp(-\alpha l) \ll 1$. In practice, the upper limit on the optical density of the cell is imposed by the need to have sufficient light on the screen for a demonstration in front of a large audience. Let us note, that if $\theta \gg \theta_0$ and other conditions being equal, high power lasers only reduce the illumination E of the screen by the defocused beam, since from (2) $E \sim P^{-1}$.

At low concentrations the effect of the absorbing substance on the thermophysical properties of the solution is negligible; it suffices to find an absorber that dissolves easily in the chosen solvent, does not dissociate, and does not luminesce when irradiated by a laser. The solvent itself must satisfy more stringent conditions. The physics of the effect and expression (2) stipulate that for strong defocusing the liquid must have low specific heat and thermal conductivity, and a highly temperature dependent index of refraction. From reference book data it follows that water—used in many studies of thermal defocusing—is the least effective solvent; nor is alcohol, the solvent of choice in most studies, the best candidate. Keeping in mind the obvious conditions of availability and low toxicity appropriate for lecture demonstrations we recommend solutions based on chloroform or acetone.

The apparatus for the demonstration of the thermal lens effect consists of: a He-Ne laser of 5–10 mW power, a convex lens of 45 mm focal length, and a plane-parallel cell 1–4 mm thick containing the absorbing solution, positioned in that order on an optical bench in front of a distant screen. A solution of brilliant green dye in chloroform was used. When demonstrating the effect in a hall holding 200 people, a cell with optical density $\alpha l = 0.6$ was used: the resulting pattern on a screen 4 m away was about 50 cm in diameter and sufficiently bright for viewing with the curtains drawn. When demonstrating to a group of 25–30 people it makes sense to increase the optical density to 0.8 and bring the screen closer, yielding a sharper aberration pattern without significantly reducing its size.

In Fig. 1 we present photographs of the light spot produced by an LG-79-2 laser of ~ 6 mW power on a screen 2 m away from the focusing lens, using the aforesaid solution of optical density 0.6 (corresponding to a concentration of about 10^{-3}% by weight) in a cell 1 mm thick. Figure 1,a and b correspond to placing the cell near the crossover point of a Gaussian beam produced by the focusing lens: a–a diverging beam enters the cell, b–a converging beam (virtual focusing) enters the cell; in Fig. 1,c the cell is placed far away from the lens and no nonlinear effects are observed. The demonstration of the thermal radiation effect consists of producing the patterns *c*, *a*, and *b* in order on the screen by moving the cell along the optical work-bench.

The proposed demonstration experiment is technically simple in the extreme and can be accomplished with available cw gas lasers (compare with an analogous demonstration described in Ref. 5); it is visual, easy to explain and to prepare, and takes up little time.

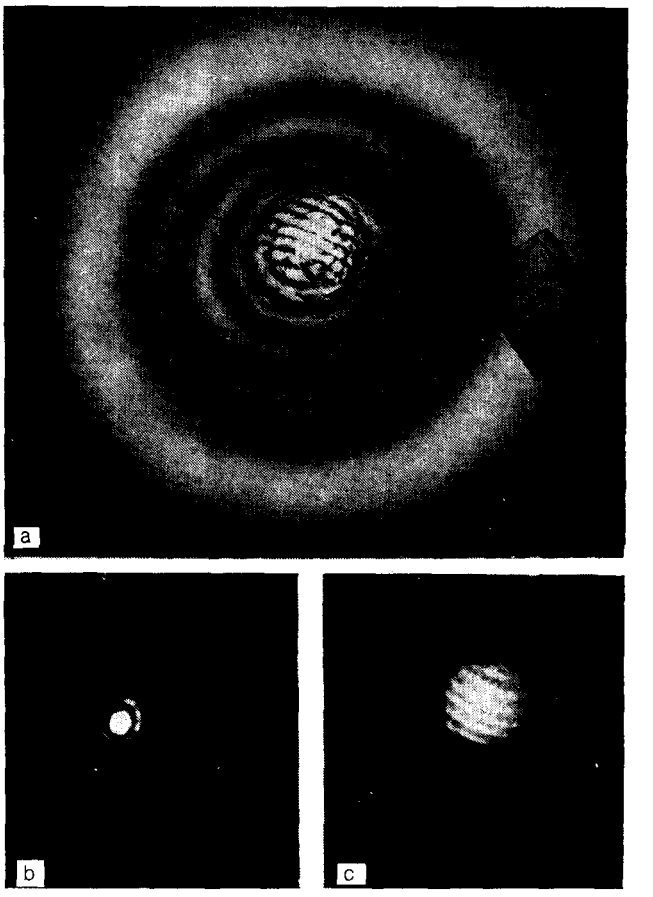

FIG. 1. The pattern produced on the screen by a 6 mW He-Ne laser: defocusing by a thermal lens of a diverging beam (a); converging beam (b); no thermal defocusing (c).

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