NONLINEAR SCATTERING AND SELF-FOCUSING OF INTENSE LIGHT BY PERTURBATIONS OF THE MEDIUM NEAR ABSORBING INHOMOGENEITIES

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Refraction of intense light by the halo around an absorbing inhomogeneity in a transparent medium is investigated. A new effect, self-focusing of light by inhomogeneities in the medium, is discovered. Experiments are performed in the beam of a cw yttrium-garnet (YAG-Nd) laser. A red beam from a helium-neon laser is added to the invisible beam to make the process visible. Scattering and shuttering of the beam increasing with time and due to absorbing particles in water and Plexiglas and self-focusing in various optical glasses are observed. The dynamics of the process is investigated by means of color motion pictures. The practical significance of the observed effects of nonlinear scattering of light in halos near inhomogeneities in natural media (water, air) and in optical and laser components (platinum particles in neodymium glass, carbon particles in ruby, particles in liquid media, etc.) limiting the transmission of large powers is discussed. The observed effects can be used for pulsed scattering, reflection, and modulation of high-power light.

INTRODUCTION

ABSORBING particles present in transparent media transmitting intense light can cause local changes of the refraction index of the medium, or "halos" around the absorbing particles, and a nonlinear scattering of light that depends on the intensity of light and time. This effect was first observed and investigated experimentally in[1] involving liquids with inhomogeneities surrounded by micro-bubbles upon the passage of intense light (these halos of the new phase have maximum gradients of the refraction index). The next paper[2] reported on such a nonlinear scattering in a more general case of arbitrary media (solid, liquid, and gaseous) due to the formation of thermal and acoustic perturbations of the medium near inhomogeneities.

Subsequent papers reported on experimental research of nonlinear scattering by inhomogeneities in a liquid[3,4] (colloidal dye solution) and in a solid with microscopic impurities[5]. The authors of[5] interpreted the observed nonlinear scattering as a result of local heating and acoustic waves and cited[6]; that paper however considered neither thermal nor acoustic perturbations but merely discussed the possible variations of the scattering capability due to striction and the optical Kerr effect.

In the present paper we investigate nonlinear scattering and shuttering of intense light flux by the halo near an absorbing inhomogeneity, a macroscopic particle. We have discovered a new effect: self-focusing of light by the halo from the absorbing particle.

INVESTIGATION OF NONLINEAR REFRACTION OF INTENSE LIGHT NEAR AN ABSORBING INHOMOGENEITY IN THE MEDIUM

These processes were investigated in the beam of a cw infrared ($\lambda = 1.06\ \mu$) yttrium-aluminum garnet (YAG-Nd) laser at the power level of 1–10 W. The beam passed through a transparent medium containing

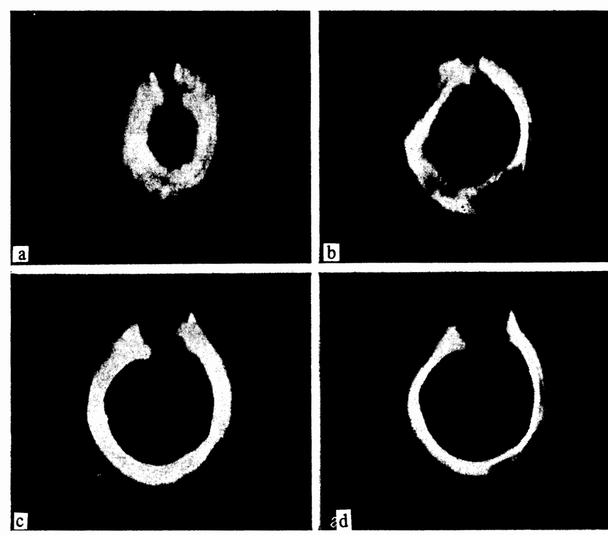

FIG. 1. Expansion of shadow from a small body in water (beam passed horizontally) at various times: a–t = 0, b–t = 3 sec, c–t = 5 sec, d–t = 10 sec.

a small absorbing body in the form of a metal disc 1–1.5 mm in radius simulating the inhomogeneity in the medium. The profile of the perturbed beam was observed through an infrared binocular on a screen 2 m away from the inhomogeneity. To facilitate observation and to record nonlinear effect a red beam from a helium-neon laser was added to the infrared invisible beam; the red beam was given the same direction by means of an inclined plate.

The media were represented by water, Plexiglas, and various optical glasses. The particle was suspended in the liquid or placed in surface depressions, or else it was pressed to the surface or pressed between two specimens of the material.

Figures 1 and 2 show the profile images of the red auxiliary beam taken at indicated intervals for the case of particles in water and in Plexiglas. Since

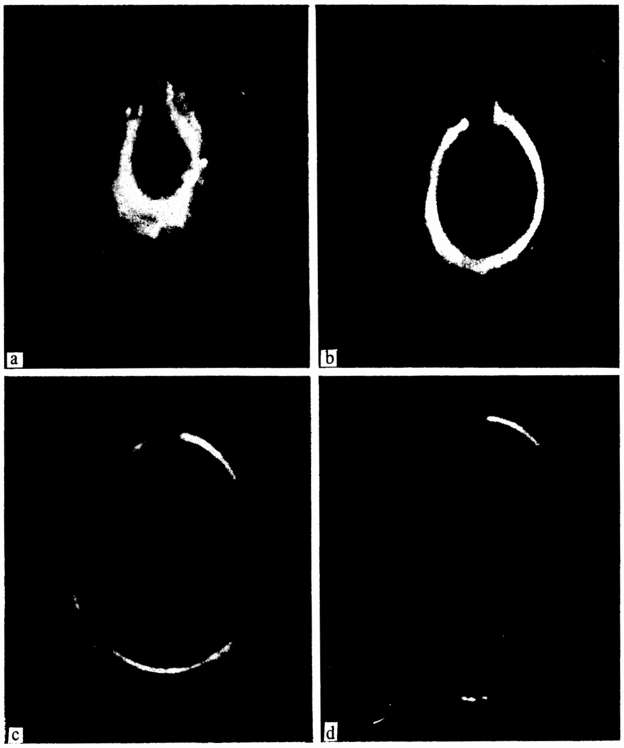

FIG. 2. Expansion of shadow and scattering of light by a halo from a small body in plexiglas. Strong nonlinear refraction due to the large value of dn/dT for plexiglas; a—t = 0, b—t = 3 sec, c—t = 5 sec, d—t = 10 sec.

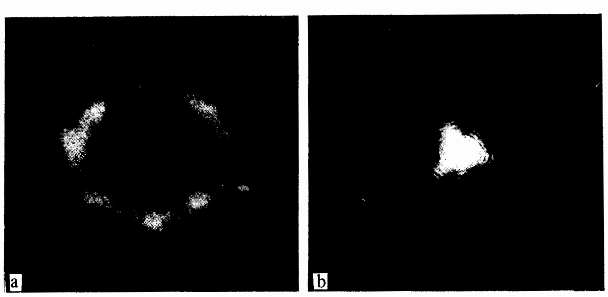

FIG. 3. Self-focusing of light by a halo around an absorbing particle in glass. a—initial beam profile, shadow of particle is visible in the center; b—profile after stabilization, a bright spot is visible in the center.

these media slightly absorb infrared light (coefficient of absorption $\sim 0.1\ cm^{-1}$) thin layers of the medium ($\sim$1 cm) and low power levels ($\sim$1—3 W) were used to eliminate defocusing of the beam; the beam profile near the inhomogeneity was checked continuously.

We observed that the inhomogeneity becomes surrounded by a focusing halo in some glasses that increase the refraction coefficient on local heating. Figure 3 shows the auxiliary beam profile right after the high-power beam was turned on (a) and then after the self-focusing pattern was established (b). We see a bright spot in the center that appeared 3 sec after the main beam was turned on and vanished 10 sec after the beam was cut off.

A small absorbing inhomogeneity a_0 in size can become surrounded in the medium by a lens of much larger dimensions. For example the temperature distribution about a small particle continuously absorbing heat in a medium of usual thermal conductivity is

$$\delta T(r,t)=\frac{a_0^2 I}{4k}\frac{1}{r}\{1-\Phi(r/2\sqrt{\chi t})\},$$

where I is the density of incident light constant in time, $k = C\rho\chi$ is the thermal conductivity coefficient of the medium, and Φ is a function of the error integral. For $r \ll 2\sqrt{\chi t}$ the quantity $\Phi \ll 1$ and $\delta T(r) \sim 1/r$; for $r \gtrsim 2\sqrt{\chi t}$, $\Phi \approx 1$ and $\delta T \to 0$, i.e., the region involved in thermal perturbation continues to increase, but within the boundary of the region the temperature hardly changes in time and rapidly increases in space towards the center. Such a local temperature increase changes the index of refraction of the medium due to a change in density with the attendant stress in the solid. (In a solid

$$\frac{\delta\rho}{\rho}=-\alpha\frac{(1+\sigma)}{3(1-\sigma)}\delta T(r),$$

where α is the coefficient of thermal expansion and σ is the Poisson coefficient).

The formation of a region of size a characterized by a change in the index of refraction leads to a redistribution of intensity that is significant at a distance $L \approx a/\theta$, where θ is the angle of refraction of light by the halo; $\theta \approx l\partial n/\partial r \approx l\delta n/a \sim \delta n$. Therefore we should expect the appearance of shadow or intensification of brightness (depending on the sign of dn/dT) at a distance of $L \approx a/\delta n$. For this reason we recorded beam deviations of $\theta \sim 10^{-2} - 10^{-3}$ rad for a beam with a diameter 2—3 times larger than the diameter of the inhomogeneity. We recorded the shuttering of the entire beam by the halo from a small inhomogeneity that cast a large shadow zone.

The above processes of scattering by halos surrounding inhomogeneities can be widely encountered in practice since real media always contain inhomogeneities such as impurities, sol, dislocations, etc. Therefore the transparency and scattering capability of media depend on intensity of light and time (thus a barely perceptible haze or a slightly scattering cloud can turn out to be opaque and very turbid to high-intensity light flash). The short halo formation time ($\tau \sim a/c_{S,T}$, where $c_{S,T}$ is the speed of sound or of thermal wave, $\tau \approx 10^{-9}$—10^{-10} sec for $a \sim 10^{-4}$—10^{-5} cm and $c_S \approx 10^5$ cm/sec) renders these processes suitable for use as modulators with variable transmission or reflection.

The practical value of these effects of nonlinear scattering of light by halos near inhomogeneities is particularly high in natural media (water, air) and in optical and laser components (particles of platinum in neodymium glass, particles of carbon in ruby, particles in liquid media, etc.) where they appear as factors limiting the transmission of high power.

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137