Nonlinear defocusing of a focused beam: a fine beam from the focus

G. A. Askar'yan and M. A. Mukhamadzhanov
P. N. Lebedev Physics Institute, USSR Academy of Sciences

(Submitted 27 November 1980)

Pis'ma Zh. Eksp. Teor. Fiz. **33**, No. 1, 48–51 (5 January 1981)

This paper describes experiments on the focusing of a laser beam in a weakly absorbing nonlinear defocusing medium: a fine beam, which comes from the focus zone, is observed. Its formation dynamics are investigated as a function of time. The explanation of this effect in other experiments with a light spark in terms of light defocusing in the spark plasma is rejected. Simple explanations of these effects, such as the light defocusing in a spark plasma, are given.

PACS numbers: 42.60.He, 52.35.Mw, 52.80.Mg

Thermal nonlinear refraction causes beam defocusing in most media. We have investigated the possibility of using nonlinear defocusing to produce fine, directional rays from the beam focus in a layer of the medium.

The experimental setup is shown in Fig. 1. The beam from the laser (1) was focused by the lens (5) with a focal length $F = 10$ cm in the layer (6) of a nonlinear medium (water, alcohol, or Plexiglas), and the intensity distribution of transmitted light was observed visually or photographically on a screeen, recorded directly on the film (7,8), or investigated by using a photomultiplier (PMT) (9), which detected the light passing through a small hole in the screen (7) at different power and location of the focus.

We used a single-mode, unmodulated neodymium laser with an energy of $1J$ and with a millisecond pulse and a YAG-Nd laser in operating single and high-frequency millisecond-pulse repetition modes. The radiation of these lasers, which was absorbed noticeably in water and alcohol (absorption coefficients $\kappa \approx 0.1$ cm^{-1}), produced strong thermal nonlinear effects. To visualize the invisible neodymium-laser beam, we added to it in some cases a green radiation of its second harmonic or the continuous radiation of an He-Ne laser (3), so that we could study the process and its consequences for a longer period of time.

0021-3640/81/01044-05$00.60

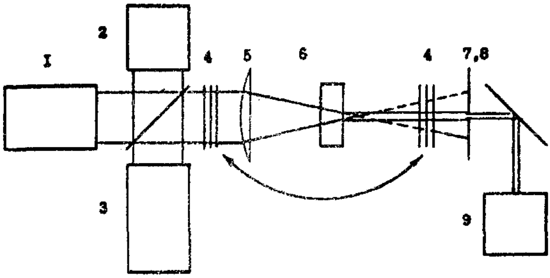

FIG. 1. Schematic of the setup: 1, YAG-Nd or neodymium-glass laser; 2, photodiode for recording incident power and triggering oscilloscope; 3, auxiliary He-Ne laser; 4, calibrated neutral-density filters; 5, lens; 6, cells with a nonlinear medium; 7, screen with a hole; 8, film or screen; 9, FEU-62 photomultiplier.

The filters (4), which attenuate the intensity by a factor of 300, were moved to different locations for comparison. The filters eliminated the nonlinear refraction when they were placed in front of the nonlinear medium and did not eliminate it when they were placed beyond the medium; however, the detectable power was reduced to the same level.

We immediately noticed that the nonlinear refraction increases significantly the radiation concentration on the axis even at a distance of 50 cm from the focal point. A bright, high-intensity spot, in which the light intensity was many times greater than the light intensity in the absence of nonlinear refraction, was detected on the axis.

Figure 2 shows a photograph of the beam striking the film directly: (a) without nonlinear refraction (filters are in front of the nonlinear medium) and (b) with nonlinear refraction. The formation of a narrow beam with dimensions of tenths of a mm (the photography produces a magnification of 6×) can be seen. In this case, the lens focus was at a distance of 1 cm (inside the nonlinear medium).

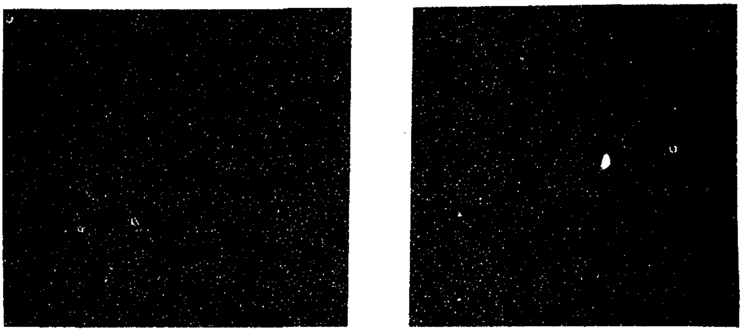
a b

FIG. 2. Photograph of a beam on film: a, filters (4) in front of nonlinear medium, the exposure was not show the spot because of low intensity; b, filters (4) behind the nonlinear medium. Photograph is for one pulse.

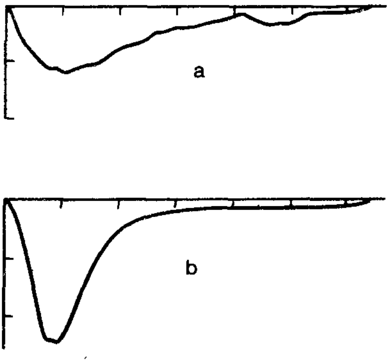

FIG. 3 Oscillogram of the radiation transmitted through the hole in screen: a, filters in front of the cell. The sensitivity is 0.1 V/div; b, filters behind the cell. The sensitivity is 0.5 V/div. The sweep is 200 μsec/div.

Figure 3 shows oscillograms of the signals from the PMT that recorded the light passing through a 300-μm-diam hole in the screen (7). Figure 3a is without nonlinear refraction and Fig. 3b is with nonlinear refraction (in this case, the oscilloscope gain was reduced by a factor of 5). A 12-fold increase in intensity was observed, which demonstrated the strong concentration of light at a distance. We can see that the intensity increases at the beginning of the pulse, and then it decreases; this is attributable to too much refraction. These measurements were made while recording the fundamental radiation (the films and detectors used were sensitive to light with a wavelength of 1 μm).

When the process was examined in color by the He-Ne laser, we observed a long-term beam-compression aftereffect, which is due to the large inertia of the thermal negative lens. The beam-contraction time lasted for fractions of a second.

The conditions for the appearance of the observed processes were determined. For the focusing angle $\theta_0 = a_0/F$ the condition for the beam "flattening" is $\theta_0^2 \approx \Delta n$, where the change in the refractive index is

$$\Delta n = n'_T \Delta T \approx n'_\rho \rho'_T \kappa \int_0^t P dt / \pi a^2 \rho C = n'_\rho \alpha \kappa Q(t) / \pi a^2 C = A_1(t)/a^2,$$

where α is the thermal expansion coefficient, κ is the light absorption coefficient, C is the specific heat of the medium, ρ is its density, and $P(t)$ is the total beam power. The radius of the flattening front is $a(t) = \sqrt{A(t)}/\theta_0$. After substitution of the pulse energy $Q(t) \approx \int_0^t P dt \sim 0.1\text{–}1\ J$, we obtain the flattening radius $a \approx 10^{-2}\text{–}3 \times 10^{-2}$ cm for the production of $\Delta n \sim \theta_0^2 \sim 10^{-4}$, consistent with the data of the experiment.

A more detailed estimate can be obtained from the aberration-free equation for the beam behavior in a medium with small absorption $a''_{zz} = A(t)/a^3$, where $A(t) = A_1(t) + \lambda^2/\pi$, if the diffraction is taken into account. After multiplication by a'_z and integration, we obtain $(a'_z)^2 = A(1/a^2{}_0 - 1/\alpha^2) + \theta_0^2$, $(a'_z(0) = -\tan\theta_0 \approx -\theta_0$. From this we immediately obtain (assuming that $a'_z = 0$) the minimum size $a^2_{\min} = A a_0^2/(A + \theta_0^2 a_0^2)$. Integrating once more, we obtain $(\sqrt{a_0^2 - a^2_{\min}})(t) - (\sqrt{a^2 - a^2_{\min}}) = z\sqrt{A}/a_{\min}$; for $z < z_m$ (and the " + " in front of the square root for $z > z_m$), where z_m is the coordinate of the minimum cross section (which coincides with the flattening front)

$z_m = (a_{\min}/\sqrt{A})(\sqrt{a_0^2 - a_{\min}^2}) = (a_0/\theta_0)\,[\theta_0^2 a_0^2/(A + \theta_0^2 a_0^2)]$, i.e., the flattening front moves toward the radiation along the focusing cone, and the maximum value of $a_{\min}$ is determined by the pulse duration. If the layer of medium has a thickness of $z = 1$, we obtain $a(1)$ and $a'_z(1)$ at the exit boundary, which define the beam propagation outside the medium. For example, for small $a'_z \gtrsim -\theta_D \sim \lambda/a$ the expansion length of the beam is of the order of the Fresnel length $L_F \approx \pi a^2/\lambda$, i.e., it can be quite large (for $a \sim 0.1$ cm, $L_F \approx 3$ m).

Such cumulative flattening of the focused beam can facilitate its locking in the waveguide, self-focusing mode.[4]

We note that the effects observed by us are entirely due to defocusing, since the durations of the pulses (and of the spikes) were much greater than the typical acoustic times, which excluded the influence of acoustic non-steady-state processes.[8] The observed process had an increasing, cumulative nature characteristic of thermal defocusing.

These experiments make it possible to understand correctly the work reported in Refs. 1–3 on the so-called "observation of self-focusing" during light breakdown in a gas at the focus of a laser beam. The observed fine beams from the focus were erroneously interpreted in these papers as the result of light self-focusing in the breakdown plasma. A much simpler and more jusitifiable explanation is that the plasma of the occurring breakdown is a defocusing lens, which produces $\Delta n \approx -\omega_0^2/2\omega^2 = -N/2N_{\mathrm{cr}}$. For a neodymium beam $N_{\mathrm{cr}} \approx 10^{21}$ cm^{-3} and a density $N \approx 10^{17}$–10^{18} cm^{-3} is sufficiently to produce $\Delta n \approx 10^{-3}$–10^{-4}; the latter is easily attainable in the initial breakdown stage (when the narrow beams were observed).

We use this opportunity to correct the wrong citations in Refs. 2 and 3: self-focusing in a plasma was first analyzed in Ref. 4, rather than in Ref. 5, and self-focusing with the appearance of excited atoms and molecules was first analyzed in Ref. 6 rather than in Ref. 7.

We note that similar focused-radiation flattening due to formation of a pre-breakdown and breakdown plasma must be observed in microwave beams; to observe this effect, it is sufficient to produce a plasma with a low density $N \sim N_{\mathrm{cr}}\theta^2 \ll N_{\mathrm{cr}} \approx 10^{13}/\lambda^2$.

We can estimate directly from the given expression for a_m^2 the expansion of the focus area $s_f = s_{f_0}\{1 + n'_p \alpha\kappa Q(t)/C\lambda^2\}$ in a weakly absorbing medium. A small value $\lambda^2 \sim 3\times 10^{-9}$ cm^2 shows that we can obtain $s_f \gg s_{f_0}$ for $\kappa \approx 10^{-4}$ cm^{-1}, $\alpha \approx 10^{-4}$ deg^{-1}, and $Q/C \sim 1$ g·deg. Therefore, it is impossible to correctly estimate the thresholds of nonlinear effects (disintegration, breakdown, or scattering) without taking into account this decrease of the flux density at the focus. Nonlinear amplification of the absorption can enhance this effect (these estimates can be extended to the case of nonlinear absorption).

[1] A. J. Alcock and V. V. Korobkin, Phys. Rev. Lett. **21**, 1433 (1968).
[2] J. S. Bakos, I. B. Földes, and Zsuzsa Sörlei, Phys. Lett. A **75**, 208 (1980).
[3] J. S. Bakos, I. B. Földes, and Zsuzsa Sörlei, Preprint Centr. Inst. for Phys., KFKI-1980-30, Budapest.
[4] G. A. Askar'yan, Zh. Eksp. Teor. Fiz. **42**, 1567 (1962) [Sov. Phys. JETP **15**, 1088 (1962)]; Usp. Fiz. Nauk

111, 249 (1973) [Sov. Phys. Usp. **16**, 680 (1973–74)].
[5]M. S. Sodha *et al.*, Progress in Optics, Vol. XIII, Ed. E. Wolf, Amsterdam, 1976.
[6]G. A. Askar'yan, Pis'ma Zh. Eksp. Teor. Fiz. **4**, 400 (1966) [JETP Lett. **4**, 270 (1966)].
[7]F. V. Bunkin, I. K. Krasyuk, V. M. Marchenko, P. P. Pashinin, and A. M. Prokhorov, Zh. Eksp. Teor. Fiz. **60**, 1326 (1971) [Sov. Phys. JETP **33**, 717 (1971)].
[8]Yu. P. Raĭzer, Zh. Eksp. Teor. Fiz. **52**, 470 (1967) [Sov. Phys. JETP **25**, 308 (1967)].

Translated by Eugene R. Heath
Edited by S. J. Amoretty