Nonlinear high-resolution subsurface imaging: new application of self-focusing

G. A. Askar'yan and A. V. Yurkin
Institute of General Physics, Academy of Sciences of the USSR

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The possibility of utilizing the self-focusing of radiation for subsurface imaging is proposed. A study of this possibility is reported. It is possible to increase the efficiency (to intensify the backward transport of the acoustic and optical responses) and to increase the imaging resolution by virtue of a contraction of the beam spot.

In the detection, observation, and study[1] of objects by means of light beams, one usually makes use of the optical or acoustic response which arises when the object falls in the beam spot. In this approach, one can estimate the distance to the object (from the delay of the response), the position of the object (by virtue of the fact that it falls in the beam spot), its dimensions and velocity (from the time it takes to cross the spot), and its structure (from the recorded image).

In this letter we report a study of the possibility of using self-focusing (see the review in Ref. 2) to increase the resolution and efficiency of subsurface imaging.

Self-focusing is known to cause a contraction of a light beam, and the increase in the intensity of the light acting on an object leads to an intensification of the optical and acoustic responses. The contraction of the beam also leads to an increase in the resolution at which the position of the object is determined. There is yet a third, and extremely important, factor involved here which can significantly improve the backward transport of the response and improve the direction of the reflection.

The point is that during self-focusing a light beam changes the properties of the medium. The changes may persist for a fairly long time and might be utilized for the backward transport of the response.

For the Kerr orientational nonlinearity, the minimum time required for the production of the waveguide is $\lesssim 10^{-11}$ s, and the waveguide exists over the duration of the giant pulse ($\approx 3\times 10^{-8}$ s) at distances $L\approx 10^3$ cm. For the strictive nonlinearity, the time required for the production of the waveguide and the duration of the waveguide are determined by the so-called acoustic time $t_s \gtrsim a/c_s \approx 10^{-6}\ s$ for a beam radius $a\gtrsim 0.1$ cm and a sound velocity $c_s\approx 10^5$ cm/s, i.e., over distances $L\approx 3\times 10^4$ cm for the optical response. In the case of thermal self-focusing, the waveguide and the acoustic line may persist for a very long time because the heat dissipation is slow.

Regardless of the lifetime of the waveguide which supports the backward propagation, the backward response is intensified in all cases because of the intensity increase which accompanies the contraction of the beam. The contraction rate for a fast nonlinearity can be estimated from the nonaberrational nonlinear refraction equation $a''_{zz}\approx A/a^3$, where $A\approx(\lambda^2/2\pi - n_2E_0^2a_0^2)$. In other words, a double integration yields

$a(z) \approx a_0(1 - z^2/L_f^2)$, where $L_f \approx a_0/\sqrt{A}$. The increase in the intensity $I(z) \approx P/\pi a^2(z)$ can be significant and can lead to not only a linear increase in the response but also a nonlinear increase, because of (for example) an increase in the efficiency of the thermoacoustic generation of sound at the surface of the object.

We have carried out an experimental study of the amplification of the response and the increase in the efficiency of subsurface imaging. For low-power beams in liquids, thermal refraction is important. It leads to a self-focusing in the case of a beam whose intensity decreases near the axis (a "banana" self-focusing of hollow beams[3]). In this case the distance to the focus is $L_f \approx d/2\theta_{nl}$, where $\theta_{nl} \approx \sqrt{n'_T \Delta T} \approx \sqrt{n'_T \alpha It/C\rho}$, n'_T is the derivative of the refractive index with respect to the temperature, ΔT is the temperature change during the heating, α is the absorption coefficient, It is the energy density of the light, $C\rho$ is the volume heat capacity, and d is the diameter of the inner spot.

The experimental layout is shown in Fig. 1. Hollow laser beam (1), produced by passing an ordinary beam through a glass plate with a small screen at the axis, enters cell (2), with a length from 10 to 25 cm, filled with a liquid (water or alcohol). The object to be detected, a small ball 1 mm in diameter (4), is placed near the beam axis, at a distance close to the focal length. The acoustic or optical response is detected by an acoustic or optical detector (3) and a photodetector or camera (5).

In the experiments we use a neodymium laser, whose beam is absorbed significantly by water ($\alpha \approx 0.15$ cm^{-1}), so the optical response is detected on the basis of the reflection and scattering from the object from one of the following signals: the fundamental wavelength (detected by a detector sensitive to IR light, a photocell of the FK series, or a photomultiplier); the second harmonic; or "coloring" light (6), e.g., the light from a cw helium-neon laser with a power of a few milliwatts, coupled into the system by reflection from an inclined plate. If the object is at a distance much greater than the absorption length for the main beam (the heating beam), the situation corresponds to the formation of a nonlinear lens near the entrance to the liquid or near its surface (in the case of incidence from above). This lens not only focuses the coloring light but also flattens out the scattering into a parallel beam, facilitating remote reception.

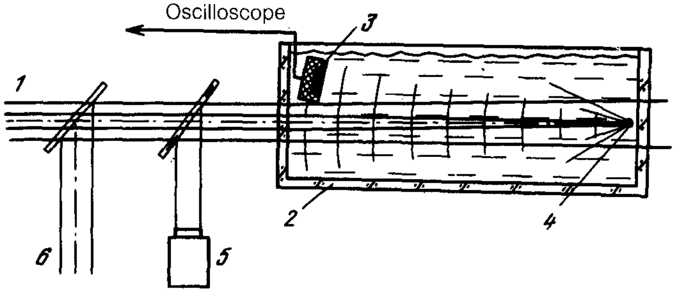

FIG. 1. The experimental layout. 1—Hollow laser beam; 2—cell with water; 3—piezoelectric detector or photodetector; 4—metal ball; 5—photocell of the FK series or photomultiplier, or camera; 6—supplementary illumination beam.

In the experiments we used lasers of two types.

1. The first laser, a neodymium laser based on a tunable, pulsed solid-state laser with a gadolinium-scandium-gallium garnet crystal, with a repetition frequency of 25 Hz in modulated operation, produces trains of 20 peaks separated by an interval of 20 μs and having a total average power of 2–3 W.

The outside diameter of the beam at the entrance to the water is 5 mm. The diameter of the intensity dip is 2.5 mm. This laser makes it possible to rapidly acquire information on the response for various positions of the object, but the beam intensity is limited by the time over which convection arises (~ 1 s).

2. The second laser, a neodymium laser based on a GOS-1001 device, with a beam

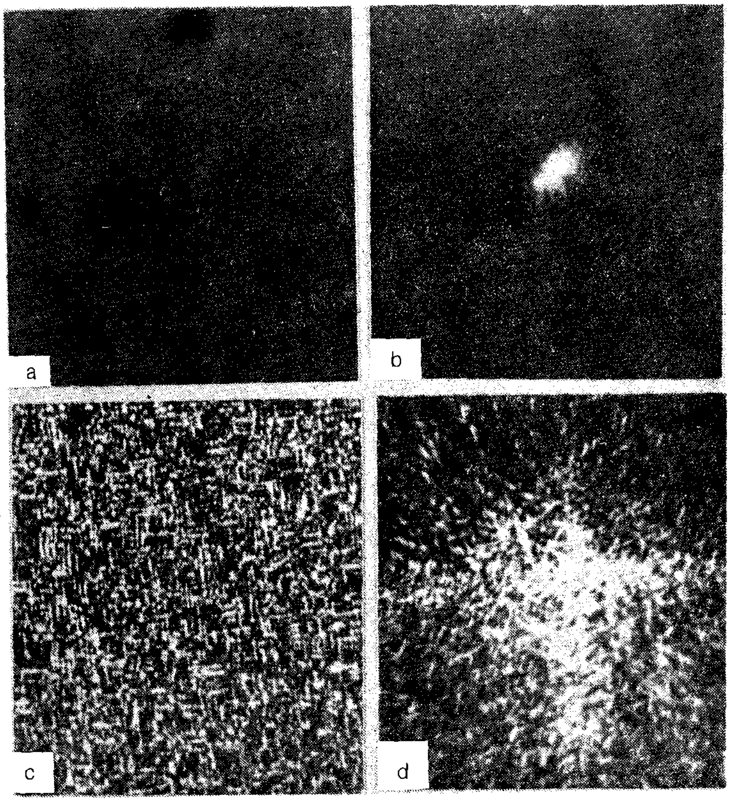

FIG. 2. Amplification of the optical response during self-focusing. The image is given in the beam of a helium-neon laser, which illuminates the wake of the invisible main beam. a—Barely visible image of a ball (the main beam is either turned off or made solid, to eliminate self-focusing); b—the main beam is hollow, and self-focusing occurs. The brightness of the image is sharply higher. The photographs were taken by a camera aimed at the object. c,d—The same, for an image deposited on an object. A manifestation of the structure or image during self-focusing can be seen. The photography was carried out directly on film without an objective. The main laser was based on a GOS-1001 device (type 2 according to the description in the text proper). The photography was carried out 1 s after the laser flash. The exposure time was 1/30 s on KN-4 film.

of the same small diameter, 5 mm, produces up to 50 peaks, each having an energy of 0.1 J, separated by intervals of 30 μs. The total energy ranges up to 5 J in 1.5 ms as the beam passes through the active element four times. During the pulse from this laser, the convective distortion is negligible, but the pulses arrive after long time intervals (~8 min).

Amplification of the optical response. We observed an amplification of the optical response: a scattering of the beam from the helium-neon laser from the object—a metal ball-during self-focusing of the light from the main laser of type 2. Figure 2a shows an image of an object without self-focusing (beam 1 is turned off, or there is no cutout at the axis); Fig. 2b shows a bright image during self-focusing of the main beam. Photographs were recorded on KN-4 film at a time 1 s after the shot; the exposure time was 1/30 s. The camera (5) (Fig. 1) was aimed at the object. A similar but lesser amplification was observed during photography at an angle from the axis of incidence.

Figure 2, c and d, shows the amplification of the image of a cross on an object during self-focusing. This photograph was recorded on film on the camera back (the objective was removed from camera 5).

We carried out a study of the amplification of the optical response over time, using a photocell of the FK series and a photomultiplier. These detectors detected the amplification of the response directly for the fundamental wavelength. We observed a severalfold amplification of the reflection by the time at which the bright spot appeared on the object. We observed no nonlinear scattering in the absence of the object.

Amplification of the acoustic response. Using a piezoelectric detector, we detected

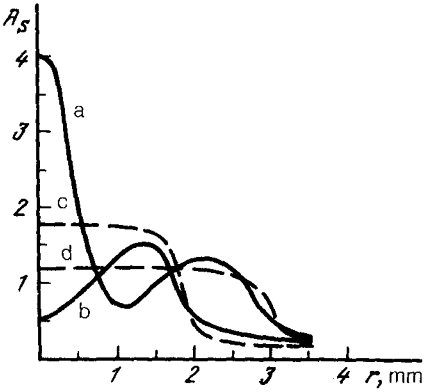

FIG. 3. Change in the acoustic response as a function of the radius separation of the object from the axis for various cases and for various stages of the nonlinearity. a—Signals after the formation of self-focusing (times of 1 s); b—before the formation of the nonlinearities (short times); c—signals in the spot of an initially uniform beam (without a cutout), before the nonlinear effects; d—in the spot of a self-defocused, initially uniform beam (without a cutout). The responses were recorded in a train of pulses from a laser of type 1, based a tunable pulsed solid-state laser, before the onset of convection ($t < 1$ s). The sharp increase in the amplitude and the resolution in the case of self-focusing can be seen.

the amplification of the thermoacoustic pulses which arose from a blackened ball during self-focusing of the beam from the main laser. In the case of laser 1 we studied the distribution of the acoustic response for various positions of the object with respect to the axis of the beam, at various times, characterizing various stages of the nonlinearity.

Figure 3 shows the distribution of the acoustic response. Line *a* corresponds to time at which the thermal self-focusing has occurred. Line *b* corresponds to an early time, while the beam in the medium is still hollow. Line *c* corresponds to the same early time, but for a beam without the axial cutout. Line *d* corresponds to times at which a solid beam is undergoing self-focusing. We see that the self-focusing not only increases the height of the acoustic pulses (at a fixed amplitude of the incident laser pulses) but also causes a marked improvement in the sharpness of the imaging of the object, to a point comparable to the dimensions of the object (this result shows that there is apparently still some margin for improvement in the sharpness). The position of the focus found from the maximum response can be compared with the distance found from the retardation of the arrival.

Let us estimate the energy which must be expended for the nonlinear subsurface imaging. For simplicity, we assume that the dimensions of the beam are held at their initial level.

In the case of strictive self-focusing, a power $P_{\rm cr} \approx \lambda^2 \pi^2 c/n_2$ is required [found from the condition $\theta_D^2 \sim (\lambda/2a_0)^2 \approx n_2 E_0^2$]. This power must persist over a time interval at least equal to the acoustic time $t_s \lesssim a_0/c_s$, required for the establishment of a contraction. The energy is therefore $\mathscr{E} \approx P_{cr} t_s \approx \lambda^2 \pi^2 ca/n_2 c_s$, where we have $n_2 \approx (\partial n/\partial \rho)^2 (1/c_s^2 (\pi/2\pi) \approx 10^{-12}$ abs, or, for the media of interest here, $P_{cr} \approx 1$ MW and $\mathscr{E}_{\rm cr} \approx 10$ J.

For a Kerr nonlinearity we would have $n_2 \approx 10^{-11}$ abs for the remote Kerr effect and $n_2 \approx 10^{-14}$ abs for the electron Kerr effect, but the times may be far shorter; i.e., the necessary energies may be small $(t/n_2 \ll t_s/n_{2\,\rm strict})$.

For intermediate power levels, and for thermal banana self-focusing, we would have $\theta_D^2 \approx \Delta n \approx n'_T q/C\rho$ where q_i is the energy evolution per unit length. The total energy is thus $Q \approx q_1 L \approx \theta_D^2 C\rho L/n'_T \approx 4 \times 10^{-2}$ J/m for $\theta_D > 10^{-4}$ rad, $C\rho \approx 4$ J/(cm^3·deg), $n'_T \approx 10^{-4}$ deg^{-1}, and $L \approx 1$ m.

For low-energy lasers, manifestations of these effects not only in media with a giant nonlinearity[4] but also in ordinary media[5] would be particularly interesting.

There is the possibility that the energy expenditure could be reduced by making repeated use of the thermal wakes formed by beams of substantial power and of low power. This approach would be particularly beneficial under conditions such that convection is slight: a small change in the density due to a temperature change $(\partial \rho/\partial T \to 0)$. Examples would be fresh water at a temperature close to 4° or salt water at 0 °C, a high viscous liquid, in weightlessness, a solid, and so forth, since the thermal dissipation of the wake would be quite slow.

All the circumstances would facilitate the realization of this high-resolution nonlinear subsurface imaging.

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