New studies in optothermoacoustics

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A directed propagation of sound along the wake of a light beam in a medium has been studied for the first time. The wake of the light beam, characterized by heating and bubbles, has a long lifetime. There are large abrupt changes in the acoustic properties of acoustic lines containing bubbles. Experiments have also been carried out on the optoacoustic detection and study of inhomogeneities in transparent and turbid media. Some possible applications are pointed out.

Optoacoustic and nonlinear acoustic effects have recently been studied in detail (see, e.g., the reviews in Refs. 1–3). In the present letter we report the first observation of a directed propagation of sound along the wake left by a light beam, as proposed in Ref. 4. We have also studied the possibility of optoacoustic subsurface imaging. In the experiments we use a neodymium laser, whose beam passes through a window into a 50-liter tank filled with water (Fig. 1). The laser is operated as a free running laser (with an energy of 300 J) with or without contraction of the beam by a telescope: or it is operated as a Q-switched laser with modulation by a passive solid-state shutter of LiF with F-centers. In this case the energy in each pulse is 10 J without pulse contraction. We also make use of the second-harmonic beam.

As media we use service water, water with B_4C or soot as an absorbing suspension, or solid media (a material similar to Plexiglas, etc.). The ceramic piezoelectric

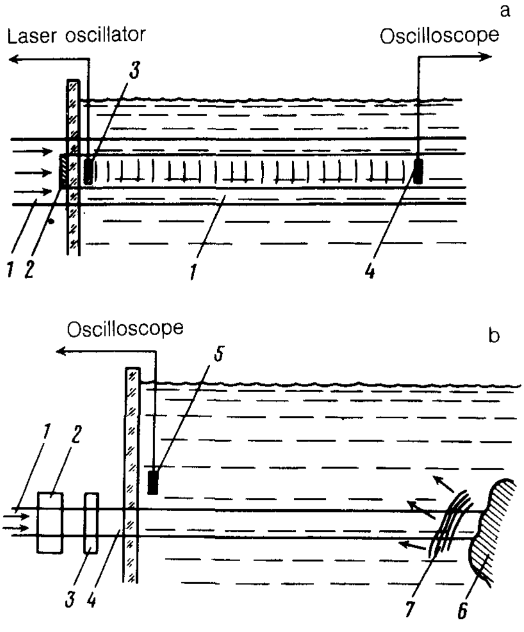

FIG. 1. The experimental arrangement. (a)—Transport of sound along the wake of the laser beam; (b)—optoacoustic detection of inhomogeneities.

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transducers and receivers, disks 0.5–1 cm in diameter, have resonant frequencies $f = 1$ MHz and 60 kHz.

1. *Transport of sound along the wake of a tubular light beam* (*optoacoustic line*). A laser beam alters the acoustic properties of a medium,[4] thereby reducing the divergence of sound waves due to refraction and reflection. The changes in the acoustic properties can be caused by basically two factors: the heating of the medium and the formation of bubbles. The change in the sound velocity due to heating is $\Delta c_s = (dc_s/dT)\Delta T$; for water over a broad temperature range we would have $dc_s/dT \cong 4$–5 m/(s · deg) > 0. The change in sound velocity upon the appearance of bubbles (for simplicity, we will ignore the damping of the oscillations of the bubbles) is

$$c_s^{-2} = c_{s0}^{-2} + \frac{na}{\pi(f_r^2 - f^2)}\,; \quad \Delta c_s = -\frac{anc_s^3}{2\pi(f_r^2 - f^2)}\,.$$

Here a is the average radius of the bubbles, n is their concentration, c is the velocity of sound, f is the sound frequency,

$$f_r = \frac{1}{2\pi a}\left(\frac{3\gamma p_0^s}{\rho}\right)^{1/2},$$

is the resonant frequency of the bubble oscillations, p_0 is the external hydrostatic pressure, γ is the adiabatic index of the gas in the bubble, and ρ is the density of the liquid.

In the experiments [Fig. 1(a)] we use a hollow laser beam (1). The beam intensity near the axis is reduced by a washer (2), 0.5 cm in diameter, in the window through which the beam enters the tank. The sound transducer (3) is positioned on the beam axis, and the receiver (4) is 35 cm away. The washer (2) is acoustically isolated from the tank.

In experiments in pure water, with contraction of the beam from the free-running laser by a telescope, we immediately achieve a focusing of the sound in the thermal wake. The hollow laser beam heated the water by an amount $\Delta T \cong Q_1/C\rho L_a \sim 10^0$, at an incident energy density $Q_1 \cong Q/\pi(R_1^2 - R_2^2)$ in a contracted beam with $C\rho \cong 4$ J/cm^3 and at an absorption depth $L_a \cong 6$ cm. We find $\Delta c_s/c_s \cong 3 \times 10^{-2}$. This change Δn_s in the refractive index for sound waves squeezes the sound inward for angles $\theta \sim \sqrt{\Delta n_s} \cong 0.2$ rad. The angle of the diffractive divergence of the sound beam is $\theta_s \lesssim \lambda_s/d \lesssim 0.3$ rad; i.e., the sound beam is trapped.

Since the receiver is at a distance equal to several times the absorption length, the contraction does not occur over the entire path. Without contraction, the size of the cross section of the sound beam at a distance L is $d_0 + \theta_s L$; with contraction over a part L_1 of the path, the radius of the cross section is $d_0 + \theta_s(L - L_1)$. If the initial dimensions of the cross section of the sound beam are small, the sound amplitude would therefore be amplified by a factor of $L/(L - L_1)$. In our case, with $L \cong 35$ and $L_1 \cong 10$ cm, we expected an amplification of the sound by a factor of 1.5–2. The experiments reveal an amplification of the amplitude by a factor of two. Figure 2 shows oscilloscope traces of the signal from the piezoelectric receiver; part *a* corresponds to the case in which the output beam from a free-running laser is contracted by a telescope. The beginning of the amplification is marked (the sweep time is 0.5 ms/

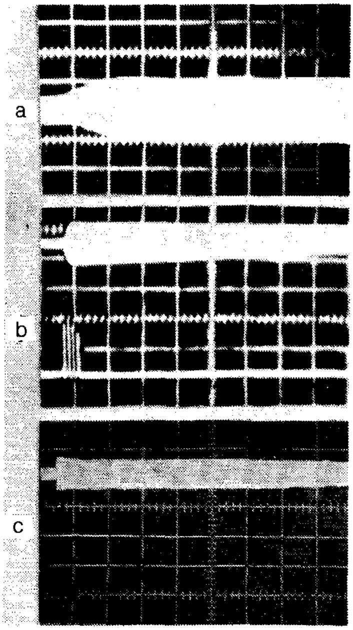

FIG. 2. Signals from the piezoelectric receiver during the transport of sound along the wake of a laser beam. (a)—Beginning of the amplification of sound (the sweep time is 0.5 ms/div); (b,c)—focusing of the bubbly wake of a laser beam in the case of a pulse from a Q-switched laser in a medium with suspensions; (b)—beginning of amplification (1 ms/div); (c)—focusing of sound with a frequency of 60 kHz in fresh tap water (25 ms/div). The sweep is triggered before the laser pulse.

div). The duration of the amplification ranges up to 1 s; i.e., the sound-transmitting wake appears rapidly (during the laser pulse) and persists for a very long time, until convection carries it away from the sound beam.

The laser is operated as a Q-switched laser in order to produce a bubbly wake. The hollow beam, not contracted, is sent through water made turbid by suspensions, which serve as centers of the nucleation of bubbles during pulsed local heating (the small dimensions of the suspensions result in a long settling time, ~3 days). The bubbles may grow because of dissolved gas. This type of acoustic line provides large drops in acoustic properties and requires only a small expenditure of energy per unit length. Oscilloscope traces of the focusing of the sound in this case are shown in Fig. 2, (b) and (c). Figure 2(b) shows the beginning of focusing (the sweep time is 1 ms/div), while Fig. 2(c) shows that the amplification lasts a long time, ~0.5 s, pulsating at a period of 50 ms. The working frequencies $f \cong 1$ MHz correspond to a resonance of a bubble a fraction of a micron in size; i.e., the focusing apparently corresponds to an increase in the sound velocity in the wake ($f > f_r$). However, an amplification is also possible in the case in which the velocity is reduced, by virtue of a reflection at the boundary with the change in properties, since this boundary cannot be regarded as smooth. The pulsations of the bubbles may be caused by not only changes in the sizes of the bubbles but also by oscillations of a layer of bubbles.

The ability of the liquid to evolve gas and the strong effect of this evolution on the sound velocity made it possible to achieve the transport and trapping even of sound with a frequency of 60 kHz and a large divergence (Fig. 2(c); the sweep time is 25 ms/div).

When we interchanged the piezoelectric transducer and receiver, we observed an amplification of the reception in an optothermal arrangement of a receiving acoustic line and a concentrator near the receiver (see Ref. 5 regarding the rf analog).

The observed phenomena may be manifested in or used to control the sound flux during stimulated Brillouin scattering: By shaping the profile of the light intensity, one can defocus or focus sound, changing the interaction lengths and the nonlinear effects of the sound on the medium.

2. *Optothermal acoustic detection and study of inhomogeneities in transparent and turbid media.* It is difficult to detect inhomogeneities in a medium by monitoring the reflection of light if the slab of medium is turbid or if the inhomogeneities absorb the light strongly or do not reflect it. In this case we turn to optothermal acoustics (cf. the analog in Refs. 1 and 3); i.e., we can locate the object on the basis of the sound pulse which arises upon the absorption of light by the surface of the object or the boundary of the absorbing layer. We have carried out an experimental study of this optoacoustic subsurface imaging (a horizontal version; Fig. 1(b)). The pulses (1) from the Q-switched laser have an energy of 10 J. They pass through a KDP crystal (2) and an S3 filter (3), which cuts off the fundamental frequency. The green beam (4) enters the water-filled tank, which holds a piezoelectric receiver and dark metal and insulating objects (6). The distance to an object is determined from the delay in the arrival at the detector (5) of the sound pulse (7) after the laser pulse. The nature of the sound pulse may be related to the thermal expansion or boiling of the liquid near the surface of the object.

Figure 3 shows oscilloscope traces of laser pulses (the lower trace) and of the signals from the piezoelectric receiver (the upper trace). Part (a) shows the signal from a blackened metal cylinder 10 cm in diameter, at a distance of 30 cm (sweep time of 100 μs/div). We observed a sharp intensification of the signal upon focusing of the beam.

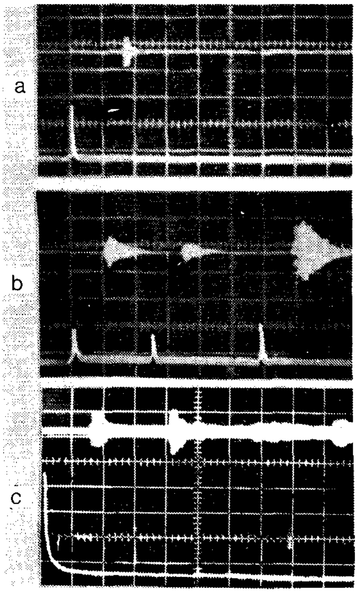

FIG. 3. Signals recorded during the optoacoustic detection of objects in media with a green light beam. Lower traces: Laser pulses. Upper traces: Signals from piezoelectric receiver. (a)—Location of an object, a blackened metal cylinder, in water by Q-switched laser pulses (100 μs/div); (b)—signals from a rubber coating (50 μs/div); (c)—signals during the vertical application of a laser beam to the front of a bottom layer of silt. First pulse—From "thermosound" during absorption of light at the boundary of the layer; second pulse—from the sound transmitted into the layer and reflected from the bottom ($h_1 = 10$ cm, $h_2 = 19$ cm, sweep time of 50 μs/div).

Figure 3(b) shows signals from a rubber coating at a distance of 8 cm (50 μs/div). This signal is anomalously intense, possibly because of the strong absorption, poor heat conduction, and roughness of the surface or a coverage of the surface with gas during heating.

We also observed signals revealing absorbing inhomogeneities in the interior and at the surface of a material similar to Plexiglas.

Optoacoustic subsurface imaging can also be realized if the inhomogeneity is in the part of a medium which is opaque to light (e.g., in the bottom layer of silt or soft soil). Sound pulses then appear at the optical absorption boundary and propagate away from and into this boundary, e.g., upward and downward. The upward pulse arrives with a delay $t_1 = h_1/c_s$, where h_1 is the depth of the absorption boundary. The pulse moving downward is reflected from the bottom or from an object and arrives without a delay

$$t_2 = [h_1 + 2(h_2 - h_1)]/c_s = (2h_2 - h_1)/c_s,$$

where h_2 is the total depth of the bottom or the inhomogeneity bed, which we are seeking. If t_1 and t_2 are known, we can determine $h_2 = (1/2)(t_1 + t_2)c_s$ for arbitrary h_1.

In the present experiments, a green laser beam is incident from above on the surface of water in a tank. Absorbing soils are used to make the water turbid in a layer 9 cm thick at the bottom. The depth of the absorption front is $h_1 \cong 10$ cm. The "thermosound" propagating upward from this front produces a first pulse [Fig. 3(c)], while the sound propagating downward passes through the turbid wake, is reflected from the bottom, propagates upward, and produces the second pulse. The quantity $(1/2)(t_1 + t_2)c_s$ turns out to be extremely close to the total depth of the water.

These studies may be useful for optoacoustic subsurface imaging and for locating inhomogeneities in liquids, solids, and gases; for monitoring the homogeneity of media, etc.; and for developing an optoacoustic microscope and optoacoustic holography systems. Interestingly, the divergence of the acoustic response can be reduced by using an initiating light beam with a reduced intensity near its axis. The effect is to provide a reverse transport of the sound.

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