Self-focusing of ultrasound by random scattering objects in a liquid via parametric phase conjugation

A. P. Brysev, F. V. Bunkin, and A. D. Stakhovskiĭ
Institute of General Physics, Russian Academy of Sciences, 117333 Moscow, Russia

L. M. Krutyanskiĭ, V. L. Preobrazhenskiĭ, and Yu. V. Pyl'nov
Moscow Institute of Radio Engineering, Electronics, and Automation, 117454 Moscow, Russia

(Submitted 23 December 1994; resubmitted 19 January 1995)
Pis'ma Zh. Éksp. Teor. Fiz. **61**, No. 6, 454–457 (25 March 1995)

A self-focusing of sound by a stream of air bubbles in water has been realized experimentally and visualized by an optical method. The focusing occurs as the result of parametric phase conjugation in a solid. The active medium which is responsible for the phase conjugation of the ultrasound scattered by the bubbles is a $NiFe_2O_4$-based ferrite in the alternating magnetic field of a longitudinal pump. © *1995 American Institute of Physics.*

The interest in acoustic phase conjugation is due in large part to the possible utilization of this effect for self-focusing of waves by scattering objects in an acoustically transparent medium. These objects may be randomly distributed. There is particular interest in physical processes which result in phase conjugation accompanied by amplification in real time.

Mechanisms for acoustic phase conjunction in nonlinear and parametric media have been discussed in many places, in particular, in connection with the development of phase-conjugation apparatus in nonlinear optics.[1-3] In recent years, the most important experimental results on phase conjugation of ultrasound accompanied by amplification have been obtained with the help of nickel ferrites.[4-6] Phase conjugation has been observed during parametric pumping of a ferrite by a pulsed rf magnetic field. When the active medium was far from equilibrium, an amplification of the conjugate wave amounting to more than 90 dB with respect to the incident wave was achieved above the threshold for an absolute parametric instability of magnetoelastic waves. The high intensity of the sound in the conjugate wave simplifies the use of methods for optically visualizing acoustic fields. A visualization method has demonstrated phase conjugation in a ferrite of plane and cylindrical ultrasonic waves in optically transparent solids and liquids.[4,5]

In this letter we are reporting the observation of a self-focusing of sound by scattering objects moving in a liquid. The focusing was realized by means of above-threshold parametric phase conjugation in a ferrite. In contrast with the experiments of Refs. 4 and 5, in which essentially the entire signal beam was incident on the phase-conjugation medium, the conditions for phase conjugation in the present study were more restrictive:

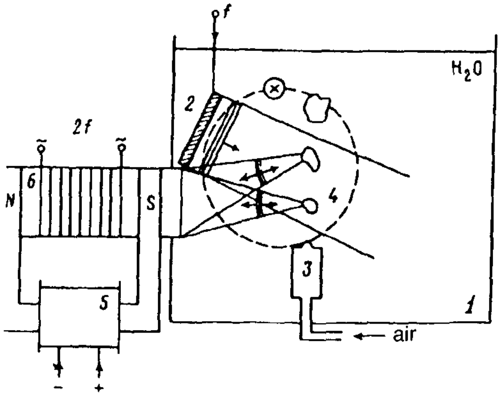

FIG. 1. Experimental layout. 1—Tank; 2—ultrasonic piezoelectric transducer; 3—atomizer; 4—stream of bubbles; 5—electromagnet; 6—ferrite sample with pumping coil. The dot-dashed line shows the observation region; the × shows the direction of the light beam.

Only a small fraction of the signal beam scattered by the objects took part in the parametric interaction in the ferrite.

Figure 1 shows the experimental layout. A signal ultrasonic wave in a pulse 40 μs long with a carrier frequency of 5.7 MHz is radiated by a piezoelectric transducer 24 mm in diameter in a water-filled tank. The signal wave is directed toward a stream of air bubbles. After it is scattered by them, it reaches the end surface of the ferrite. The stream of bubbles is generated by an electric pump connected by a flexible tube to an atomizer. The size of the bubbles can be varied by varying the air pressure head in the connecting tube. The sizes of the bubbles are 3–15 mm, considerably larger than the length of the ultrasonic waves in the water ($\lambda = 0.26$ mm). The polycrystalline ferrite sample used as the parametric medium is a cylinder 38 mm in diameter and 150 mm long. This ferrite was prepared from a starting mixture with the following composition (these are mole percentages): 46.8 Fe_2O_3, 1.28 CoO, 1.34 CuO, 1.49 Sm_2O_3, and otherwise NiO. The sample is part of a magnetic circuit of an electromagnet, which produces a magnetizing field $H \approx 400$ Oe. Longitudinal parametric pumping at twice the acoustic frequency is carried out with the help of the output-circuit coil of an rf pulse generator with a pulsed output power up to 50 kW. The length of this coil is 70 mm. The duration of the pump pulses is varied over the interval 70–100 μs. The amplitude of the pump field exceeds the threshold for an absolute parametric instability by a factor of at least 2.5. This threshold was determined from the onset of spontaneous parametric generation of sound in the absence of a signal wave. The acoustic fields are visualized by a shadow method in a stroboscopic regime. For illumination we use the second harmonic of the output from a pulsed neodymium laser. The aperture of the laser beam is expanded to a diameter of 100 mm by a collimator. This expanded beam is directed through the region of the liquid under study in a direction parallel to the end surface of the ferrite and the plane of the piezoelectric transducer. After emerging from the tank, the light beam passes through a converging lens. The blocking of the zeroth order of Raman–Nath diffraction by a point screen is deliberately kept incomplete, so that an image of the bubbles can be formed in the transmitted rays. In this case the bubbles can be observed quite easily at the same time that we observe the images of the ultrasonic fields. The resulting pattern is projected onto a flat screen and recorded with a video camera. The photographs shown in this letter

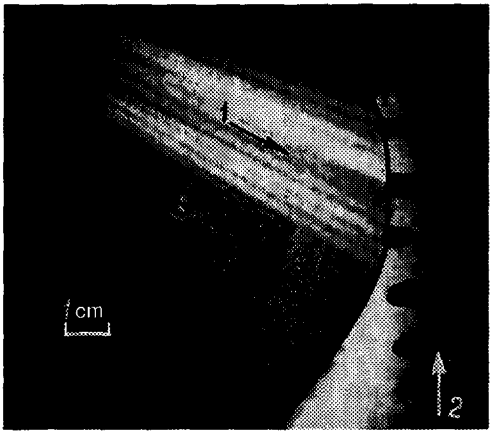

FIG. 2. Image of a signal-wave pulse radiated by a piezoelectric transducer toward the stream of bubbles. 1—Pulse of signal wave; 2—bubbles. The arrows show the propagation directions of the ultrasonic wave and the bubbles.

are photographs of the screen of a video monitor in stop-frame operation. The pulses of the signal acoustic wave, the pump, and the light are synchronized in time with a variable delay, so that it is possible to observe the transmission of the pulses of the signal and conjugate waves through the visualization region at different times.

Figure 2 shows an image of an ultrasonic signal pulse incident on bubbles. The bright half-moon region on the right on this and the following images was formed because of the incomplete blocking of the zeroth diffraction order. On the left, this bright region is bounded by the shadow zone of the screen; on the right it is bounded by the edge of the aperture of the laser beam. Images of the bubbles were thus obtained in the form of dark spots on a bright region, while images of the ultrasonic fields were obtained in the form of bright regions against the background of the shadow of the screen. When the pump field is turned on during the propagation of the signal-wave pulse scattered by the bubbles through the volume of the active zone of the ferrite, an intense emission of acoustic waves directed toward the bubbles is observed in the spatial region between the bubbles and the end of the ferrite. Corresponding images are shown in Fig. 3. Here we can clearly see a self-focusing of the conjugate waves by the bubbles. Their number and positions can be quite arbitrary, as we see. Focusing in this arrangement requires that only the radiation scattered by the objects reach the phase-conjugating medium. These properties justify the use of the term "self-focusing." Experimentally, the self-focusing region is bounded by the aperture of the signal beam and the width of the angular distribution of the phase-conjugation efficiency in a ferrite sample, which was studied in Ref. 5. The conditions under which the signal wave is scattered are determined by the random nature of the shape and orientation of the time-varying reflecting surface of a bubble. Accordingly, there may also be bubbles at which we do not observe a focusing (the upper bubbles in Fig. 3, a and b). In the acoustic field radiated by the ferrite we detected some of the acoustic rays whose directions were uncorrelated with the spatial arrangement of bubbles. The formation of this "unconjugated" component of the acoustic field, which disappeared in the absence of a signal wave, was apparently due to complex multiple reflections of waves inside the ferrite and the bounded aperture of the ferrite. The distortion of the structure of the acoustic field during the phase conjugation was also due in part

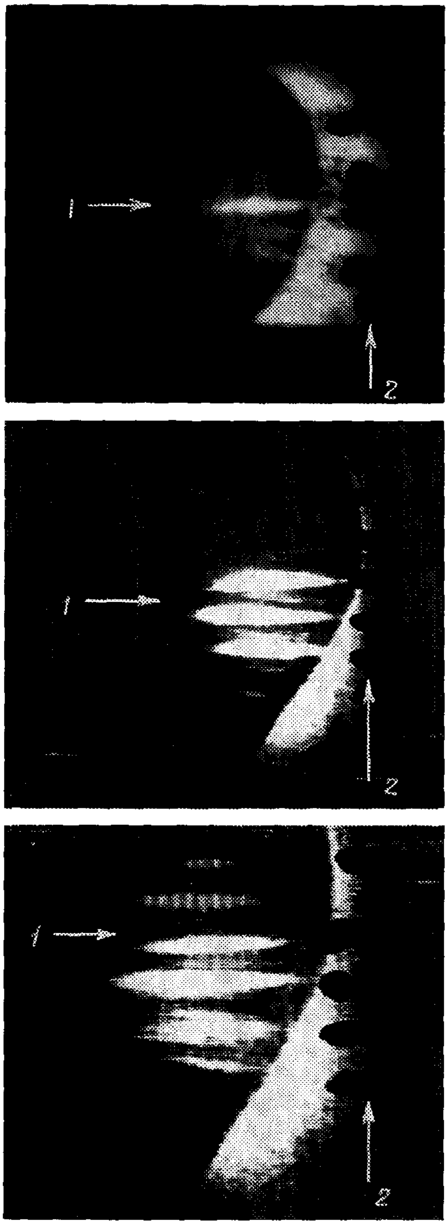

FIG. 3. Image of ultrasonic pulses focused at bubbles. 1—Ultrasonic pulses focused at bubbles; 2—bubbles. The arrows show the propagation directions of the ultrasonic pulses and the bubbles. a—Self-focusing of ultrasound by one bubble in the aperture of the signal beam; b, c—self-focusing of ultrasound by several bubbles simultaneously in the aperture of the signal beam.

to the nonuniform distribution of the phase-conjugation efficiency with respect to the angle of incidence of the signal waves on the end surface of the ferrite.[5] This distribution could be smoothed out significantly by using a more complicated configuration of the active element. An analysis of the available data from this standpoint is the object of a separate study, which goes beyond the scope of the present letter.

On the whole, these experimental results indicate that it is possible to use above-threshold parametric processes in polycrystalline ferrites for an experimental realization of various effects in acoustics which are specific to phase conjugation in real time.

We wish to thank I. N. Andreeva and N. N. Ryzhova for assistance in the development and fabrication of the active element.

This study was carried out with support from the International Science Foundation (Project MJZ000) and the Russian Fund for Fundamental Research (Project 1993-02-15458).

[1] F. B. Bunkin, D. V. Vlasov, and Yu. A. Kravtsov, Kvant. Élektron. (Moscow) **8**, 1144 (1981) [Sov. J. Quantum Electron. **11**, 687 (1981)].
[2] F. B. Bunkin, D. V. Vlasov, and Yu. A. Kravtsov, in *Phase Conjugation of Radiation in Nonlinear Media* [in Russian] (Izd. IPF Akad. Nauk SSSR, Gorki, 1982), p. 63.
[3] F. B. Bunkin, D. V. Vlasov, and Yu. A. Kravtsov, Preprint 90, P. N. Lebedev Physics Institute, Academy of Sciences of the USSR, Moscow, 1982.
[4] A. Brysev, F. Bunkin, L. Krutiansky *et al.*, Opt. Acoust. Rev. **1**, 107 (1990).
[5] L. Krutiansky, V. Preobrazhensky, Yu. Py'lnov *et al.*, Phys. Let. A **164**, 196 (1992).
[6] V. Preobrazhensky, Jpn. J. Appl. Phys. **32**, 2247 (1993).

Translated by D. Parsons