Acoustic analogues of nonlinear-optics phenomena

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This review discusses nonlinear acoustic phenomena which are analogous to corresponding phenomena in optics: self-interaction effects in acoustic beams, parametric effects, stimulated scattering of sound, wave-front (phase) conjugation of sound waves, and also techniques of active acoustic spectroscopy. The authors point out that these processes must evolve rather rapidly in space and time in order to avoid the formation of shock waves and the nonlinear dissipation of energy which accompanies them; this rapid evolution is provided by the interaction of sound with non-acoustic forms of fluid motion: convection, oscillating bubbles, and by thermal, hydrodynamic and concentration waves. Features which are peculiar to nonlinear acoustic phenomena are emphasized, i.e., the parametric mechanism for acoustic phase conjugation and the possibility of detecting stimulated acoustic scattering by single scatterers. The goal of the review is to draw additional attention to promising developments in nonlinear acoustics.

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INTRODUCTION

The order of words in the title of our article speaks directly of its acoustic orientation: the discussion will essentially concern those nonlinear wave phenomena which are well-known in optics (although without a long history there) and which show definite promise in the area of acoustics. And, like practically every review article covering these two areas of physics, our article cannot avoid some mention—and by no means a formal mention!—of the name of Rem Viktorovich Khokhlov. This mention is doubly appropriate once one begins to investigate the connection between nonlinear optics and acoustics; in truth, it was Rem Viktorovich who identified the physically meaningful differences between them, and by doing this—we are convinced!—added additional momentum to the ongoing investigations in each section of this review. His were the first works in which the strengths of the optics-acoustic analogies were explicitly exploited. In our review we will make use both of his specific works and also of the fundamental physics of nonlinear waves which are set forth in all the works of R. V. Khokhlov.

Nonlinear acoustics was born considerably earlier than nonlinear optics—it is sufficient to recall the works of Rayleigh at the end of the 19th century. However, nonlinear optics, which has not yet marked its twenty-fifth birthday, has quickly eclipsed nonlinear acoustics both through the wealth of its new ideas and the number of its applications. To its credit stand parametric conversion and generation of harmonics of light, stimulated scattering of light (SRS, SMBS, STS, and SRRS), active spectroscopy, and various forms of

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self-interaction such as self-focusing, self-defocusing and phase conjugation. High-intensity acoustics has much more modest goals, particularly with regard to applications: generation of harmonics in liquids and solids, nonlinear (Raman) spectroscopy of bubbles, parametric conversion of high-frequency sonic vibrations into low frequencies (parametric antennae), and achieving self-transparency in media with bubbles.[1-9]

To a certain extent, nonlinear acoustics can be regarded as "unlucky." The reason for this was understood long ago: it is due to the absence of dispersion of sound in practically all media and at all frequencies for which absorption over a wavelength is still small: $\delta\lambda \ll 1$ (δ is the absorption coefficient). The absence of this dispersion leads to the conversion of strong acoustic fields into shock waves, in which energy is continuously pumped into higher harmonics. High-frequency oscillations are strongly absorbed ($\delta \sim \omega^2$); as a result, the wave energy is rapidly dissipated by the liquid.

Is there any way to hinder this pumping of energy into higher frequencies? One technique is to engineer velocity dispersion into the wave motion, thereby destroying the synchronous propagation of harmonics and thereby weakening the dissipation. For example, one can place the liquid in a waveguide and make use of the guide dispersion.[10] However, this dispersion is sharply expressed only in waveguides whose transverse cross-section is several wavelengths in size. It is clear that it is difficult to observe phenomena which evolve along the wave front in such narrow tubes, so that this technique cannot be regarded as very versatile.

One can engineer dispersion by introducing air bubbles into a liquid[11]; because of the high compressibility of air, this technique also enhances the nonlinearity of the medium. This example effectively highlights the reason for the relative poverty of nonlinear acoustics phenomena: the phonon spectra of most condensed media do not have strong resonances in the region below 10–100 GHz. As a consequence of this, even smooth dispersion is absent, along with specific mechanisms for Raman scattering (in optics these are guaranteed by the wings of strong absorption lines which lie in the IR and UV regions of the spectrum). Bubble-induced resonances in liquids are so far the only systematically-discussed analogue of the Raman-active modes encountered in the optical region. At the same time, the possibilities here are far from exhausted; one approach which is promising, although unlikely to lead to rapid progress, is to use acoustically-induced structural vibrations, e.g., in associative solutions.

Liquids with gas bubbles serve as particular model systems in which sound interacts with "non-sonic" modes (in this case, mechanical); the general idea of using this or some other form of motion to provide dispersion and thus to tune out "undesired" waves has been discussed in a number of papers[11,12] and in Ref. 13. For nonlinear acoustics systems of this kind are of interest, if the characteristic length l_{NL} for growth of the nonlinear interaction of sound with "non-sound" is smaller than the length l_{sh} for the formation of discontinuities (shock waves):

$$l_{\text{нл}} < l_{\text{sh}} \qquad (1.1)$$

In this case, the nonlinear interaction evolves faster than the process of shock wave formation, which would lead to rapid dissipation of energy.

Keeping in mind that to a significant extent, progress in nonlinear optics has also relied on the interaction of light with "non-light" modes (it is enough to recall the strictive, temperature and orientational mechanisms for self-interaction, along with all the forms of stimulated scattering of light), in our search for the most efficient acoustic interaction it is doubtless useful for us to turn to acoustic analogues of well-known nonlinear-optics phenomena. However, although several analogues of this sort have already been partially studied (see Ref. 16, and also Section 4 of this review, which is devoted to stimulated acoustic scattering, and Section 5 which addresses the question of phase conjugation in acoustics), on the whole none of them have as yet served as the object of any systematic analysis.

In what follows, we specifically propose to discuss fruitful (as we see it) analogies between optics and acoustics, so as to direct the additional attention of specialists towards promising directions in nonlinear acoustics. The list we cite of analogies between optical and acoustic nonlinearities is of course not an exhaustive one. In particular, the following topics lie outside the framework of this review: studies of nonlinear effects in surface acoustic waves, of instabilities caused by the powerful sonic fields at boundaries between liquid regions and in liquids with discontinuous flows, of the interaction of sound with turbulence and surface hydrodynamic waves, and of the effect of negative absorption in flames and chemical reactions ("acoustic lasers"). Nevertheless, the analogies we describe, in our view, point to the existence of a large reservoir of evolving ideas in nonlinear acoustics.

2. PARAMETRIC PHENOMENA IN ACOUSTICS

Together with shock waves, whose observation in optics still remains an unrealized dream (for the most advanced appraisals see Ref. 15), parametric conversion is one of those areas of nonlinear wave phenomena whose theoretical study is more advanced in acoustics than in optics. Since we have set before ourselves the goal of describing nonlinear acoustic effects "induced" by optical analogies, we will be brief here. Furthermore, parametric conversion as a mechanism for phase conjugation will be discussed in Section 5.

2.1. Parametric amplification in liquids with gas bubbles

The injection of gas bubbles into a liquid leads to the appearance of sonic dispersion, at the same time increasing the degree of nonlinearity of the medium. If we drive the medium with sound vibrations of frequency 2ω close to twice the frequency of characteristic oscillation of the bubbles, we can provide conditions for amplification and generation of oscillations with frequency ω.[6,12] However, there are two problems which are hard to overcome in experiments: the size dispersion of the bubbles, which weakens the sonic dispersion, and additional absorption due to the bubbles. In short, the observation of parametric amplification—let alone parametric generation—turns out to be a difficult feat

to accomplish for the majority of liquids, including water. In fact, it has been possible in practice to exceed the threshold for parametric generation in a bubble-bearing medium only by artifically introducing waveguide dispersion.[14,16–18]

2.2. Parametric antennae

The operation of these devices is based on the phenomena of modulation and scattering of sound by sound.[19,20] Parametric antennae, first created in our country, are used for directed emission and reception of low-frequency sound waves excited in liquids as a result of the nonlinear interaction of high-frequency waves. Thus, when an acoustic radiator in a liquid is excited by powerful oscillations with nearly equal frequencies ω_1 and ω_2, a low-frequency (with frequency $\Omega = \omega_1 - \omega_2 \ll \omega_{1,2}$) extended source is formed, which has high directivity and acts as an antenna for traveling waves. A receiving parametric antenna senses not only the low-frequency signal but also the oscillations at the high combination frequencies $\omega_1 \pm \Omega$ which arise when the signal interacts with a powerful pump (frequency ω_1).

The principal inadequacy of parametric antennas is their low efficiency, which is characteristic of frequency down-conversion (according to the Manley-Rowe conditions, the conversion coefficient in this case is bounded by the ratio Ω/ω_1). However, in spite of their low efficiency, parametric antennae find applications in underwater acoustics.[5] Recently researchers have been looking for a way to increase their efficiency—for example, by introducing air bubbles into a liquid or generating air-filled cavities in it.[21–23] Calculations are based on an increase in the nonlinearity of gas-liquid media as compared to homogeneous liquids.

2.3. Parametric amplification of sound in solids

In this case the parametric effect can be realized using several schemes. To begin with, there is amplification in the field of an ultrasonic pump (this has already been observed in magnesium oxide crystals.[24] Interaction with spin waves can also serve as a mechanism for amplifying sound.[25,26]

One mechanism for parametric excitation of sound by an electromagnetic field is stimulated Mandelstam-Brillouin scattering (SMBS). In this case a pump with frequency ω_p generates an accompanying acoustic field with frequency Ω in a liquid, and a back-scattered electromagnetic wave with frequency $\omega_p - \Omega$.[27,28] The easiest way to realize SMBS is in the optical region of the spectrum; however, one cannot exclude the possibility of SMBS using a UHF pump.[29]

Another possibility is realized in piezoelectric semiconductors through amplification of an acoustic field by an electric current due to the interaction of sound with drifting electrons. The results of this kind of experiment performed in CdS[30,31] provided the first successful demonstration of parametric amplification in acoustics; incidentally, this is one of the rare cases where acoustics does not lag too far behind optics—the first parametric generators of light were created at approximately the same time (see the review of Ref. 32). However, the acoustic analogues do not yet approach the optical efficiencies. We also note that thresholds for SMBS are lower in piezoelectric semiconductors.[33,34]

Stimulated acousto-optical interactions in crystals mediated by photoelastic effects are phenomenologically close to SMBS (theory—Refs. 35, 36; experiment—Refs. 37, 38).

One final parametric mechanism related to the nonlinear piezoelectric effect was proposed in Ref. 39 and realized in Ref. 40. In piezoelectric semiconductors, parametric excitation due to the nonlinear piezoelectric effect, like SMBS, has a lower threshold.[41]

2.4. Electroacoustic echo

The phenomenon of electroacoustic echoes, observed in plasmas,[42,43] in spin systems[44] and in nonlinear optical media[45] has also been detected in acoustics.[8] The most studied effect is the double-pulse electroacoustic echo in piezoelectrics. This latter effect can be described as follows: a high-frequency electric pulse is fed into the piezoelectric; after a time τ, a second pulse is fed in. After the same time interval τ, an echo-pulse is generated. The cause of this behavior is parametric interaction of the second harmonic of the probe pulse with the "tail" of the first, which dissipates throughout the sample volume after a time larger than τ. Paramagnetic echoes in piezoelectrics were intensely studied by many authors[46–48]; the possibility of observing these echoes[53] was also considered for bubble-bearing media.[49–52] There exists an intimate connection between double-pulse echoes and the phenomenon of phase conjugation (see Section 5).

Parametric interaction of sound with surface waves adds to this list[54–55]; in the relevant references, however, the discussion centers on qualitatively different issues (parametric scattering by the sea surface is investigated) and on a much lower frequency band.

3. SELF-INTERACTION EFFECTS

3.1. Self-focusing and self-defocusing of sonic beams

Studies of these effects in acoustics have two fundamental aspects. One of these—the identification of limits on the possibility of transmitting sonic energy into thick layers of liquid or gas—particularly for the purpose of acoustic ranging. Another aspect is connected with the kinetics of damage to a material; here, the discussion can include not only cavitation and chemical dissociation, but also new physical processes—as in the analogous optical problems. The actual possibility of acoustic self-focusing was pointed out in Ref. 56; the theory and experiments for observing thermal self-interaction of sound in CdS crystals were described in Refs. 57, 58. The characteristics of self-interaction of sound in liquids are to a large degree determined by the ease with which acoustic streaming is excited, as shown in Ref. 59, and true self-focusing of a sonic beam is observed over a rather narrow range of radiation and medium parameters.[60]

Phenomenologically, thermal (chosen for definiteness) self-focusing of a sonic beam is entirely analogous to the mechanism of thermal self-focusing of light. Absorption of sound leads to an increase in temperature in the region occupied by the beam, and since in the majority of liquids the velocity of sound decreases (i.e., the index of refraction in-

creases) with an increase in temperature, the beam is compressed towards the axis due to the total internal reflection from its own edges. In water, focusing is possible only for temperatures $T > 74$ °C; for $T \lesssim 74$ °C the derivative of the velocity of sound $\partial c/\partial T$ with respect to temperature is positive and must lead to self-defocusing.[61]

The temperature mechanism for self-focusing is always weakened (or even overwhelmed) by defocusing due to streaming excited by the sonic beams in absorbing liquids.[62] Such streaming increases the sound velocity in the near-axis part of the beam and thereby contributes to transport of the acoustic oscillations out to its periphery. The nonlinear variation in the sound velocity due to this and other mechanisms is proportional to the absorption coefficient; its relative contribution, however, is determined also by non-dissipative parameters.[59] In the limit of long pulses (the acoustic pulse duration is $\tau > \rho a^2/\eta, a^2\rho C_p/\varkappa$; a is the beam radius, $\eta, \varkappa$ are coefficients of shear viscosity and thermal conductivity, ρ is the density of the liquid, C_p is the specific heat at constant pressure), the tendency to self-focus dominates if $|\partial \ln c/\partial T| > \varkappa/\eta c^2$. For self-focusing of short pulses (with the opposite constraint on τ) it is necessary to have the condition $|\partial \ln c/\partial T| > C_p/c^2$; it is fulfilled in many liquids.

The formation of a shock wave, and also superheating of the liquid (and the changes in the internal state connected with superheating) as a result of absorption of powerful sound are two more competitors for the self-focusing process. In this case we cannot speak of the suppression of the effect; we can only note the difficulty in controlling the distortion of the sonic beam parameters which accompany these processes. Besides, it is possible to find a region of parameters where they are negligible compared to the background of self-compression. Formation of a shock wave can in practice be excluded from self-focusing experiments ($l_{SF} < l_p$), if the pulse duration is

$$\tau > \tau_p = C_p (\varepsilon\omega a)^2 \left| \frac{\partial \ln c^2}{\partial T} \right|^{-1} \delta^{-1} c^{-5}, \tag{3.1}$$

ε is the elastic nonlinearity coefficient. This limitation is well-understood: the formation of a discontinuity is determined by the sonic intensity ($l_p \sim I^{-1/2}$), while the self-focusing length is determined by the energy [$l_{SF} \sim (a^2\tau I)^{-1/2}$]; the quantity τ_p is ~ 0.1 to 1 sec in most liquids, i.e., condition (3.1) can also be fulfilled.

The process which is a real threat to observing self-focusing is sonic convection; it restricts τ from above:

$$\tau < \tau_c = \eta \left| \frac{\partial \ln c^2}{\partial T} \right| \frac{a}{g\alpha\rho\lambda^2} \tag{3.2}$$

(g is the acceleration in free fall, α is the thermal broadening coefficient), and in essence it prevents the self-focusing of long pulses. Together with this restriction, the required power of the sonic source is increased, since the threshold energy, for which the focusing length of the nonlinear lens becomes comparable to the diffraction length ($\sim a^2/\lambda$)

$$W_{th} = (0{,}61)^2 \pi\rho C_p \lambda^2 \cdot \frac{1}{8} \left| \frac{\partial \ln c^2}{\partial T} \right|^{-1} \delta^{-1}, \tag{3.3}$$

must be injected within a time less than τ_c. However, all the conditions required for observing self-focusing can be fulfilled. Thermal self-focusing in liquids was observed for the first time in experiments[60] using benzene and an ultrasonic source at a frequency of 2 MHz with a power of ~ 15 W and an energy $W_{th} \sim 4$ J. Optical recording of the effect (by the "shadow" field method) allows direct observation of convective beam spreading which sets in, in agreement with estimates, for $\tau \gtrsim 2$ sec. Apparently, nonlinear refraction was observed in Ref. 110. Among the more noteworthy mechanisms for self-focusing of sound is the concentration-induced mechanism: a transverse pressure gradient in the acoustic beam creates an excess of the more "acoustically dense" component of a solution; the velocity of sound in the near-axis part decreases, i.e., a distributed acoustic lines is formed. There is special interest in this mechanism for layered binary solutions under subcritical conditions.[63] The requirements on the power of the acoustic source in order to realize this mechanism, generally speaking, are more stringent than for the thermal mechanism. However, the approach to the critical point for stratification has two consequences: first, the threshold energy can in fact be lowered by several orders of magnitude. Secondly, quantitative measurements of these effects contain direct information about the value of an important kinetic parameter—the mobility $\tilde{L}$, since in the non-steady-state regime the threshold energy density is

$$\frac{W_{II}}{\pi a^2} = \frac{(0{,}61\rho\lambda c)^2}{8\tilde{L}(\partial c/\partial n)\,\partial \ln(\rho c)/\partial n}, \tag{3.4}$$

n is the concentration of one of the components of the solution. The quantity $\tilde{L}$ at the present time has been directly estimated in a single optical experiment,[64] which in addition is a precise analogue of the situation that has just been described above.

3.2. Acoustic self-interaction effects in bubble-bearing liquids

To begin with, we will investigate the resonant self-interaction mechanism caused by non-linear oscillations in bubbles.[65] Its optical analogue—self-focusing or -defocusing (depending on the sign of the frequency detuning off resonance) in the case of resonance absorption of light by a two-level system—is practically always barely noticeable against the background of strong "plane wave" effects such as light-induced self-transparency, etc.[66] Observation of self-interaction of sound in a bubble-bearing medium faces similar difficulties, and here it is necessary to compare in detail many competing nonlinear processes. This analogy is naturally continued by the effect of the shift in the resonance frequency of the oscillator (bubble), which is proportional to the intensity of the acoustic oscillations (in optics, this is the high-frequency Stark effect). Estimates show that this shift can amount to a significant fraction of the resonance line width for moderate pumping ($I \sim 0.1$ W/cm^2).[67–69] If the scatter in bubble sizes is sufficiently small, near resonance the "Stark" shift in the resonance frequency can lead to a change in the sound velocity of the bubble-bearing medium, and thereby to focusing or defocusing of a sonic beam. One also expects that bubble-bearing media with a narrow size

distribution of bubbles will exhibit the property of bistability.

The self-transparency effect in bubble-bearing media under the action of intense sonic waves has already been observed experimentally.[70] It is manifested in a decrease in the absorption of sound with increasing intensity; however, the detailed mechanism still remains obscure. Self-transparency is connected with the generation of clusters of bubbles and fusion of bubbles under the action of the attractive Bjerknes force—with the consequent drift of the characteristic frequency of the bubbles out of resonance with the acoustic frequency[71] (see also Ref. 53).

Along with self-interaction in liquids with a specified distribution of bubbles, a more general process is possible for acoustics—sonic-induced changes in the distribution itself. In the most extreme case, this leads to the cavitation mechanism[72,73]: in the cavitation region, sound is slowed down, and as a consequence a focusing acoustic lens forms. Cavitational self-focusing was observed experimentally in Ref. 74.

3.3. Acoustic self-focusing at the boundary of two different media

The suggestion that self-focusing of an acoustic beam at the boundary between two media is possible was made in Ref. 56 as applied to the thermal mechanism for solid surfaces (see also Ref. 72, 75). A similar effect should also be directly observable at the boundary between liquids,[76] which is curved under the action of the radiation pressure of sound (Fig. 1). Thse first experiments, performed with water, confirmed this assumption.[77] Self-focusing of sound with a frequency $\nu = 1.5$ MHz was observed for $a = 0.5$ cm, $I \sim 1$ W/cm^2; the water surface was curved upward by several millimeters. When a certain critical value of the power is exceeded, a phenomenon is observed at the same time, which is naturally referred to as "acoustic self-concentration." In observing this effect, the beams reflected from the bulging surface of the liquid are directed upward, forming a fountain at the peak of the bulge (Fig. 2).

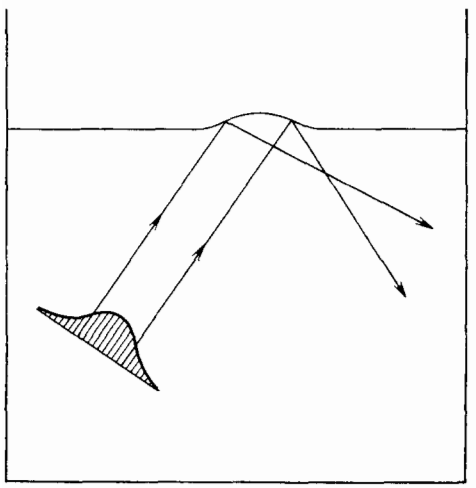

FIG. 1. Self-focusing of an acoustic beam at a boundary between two different media.

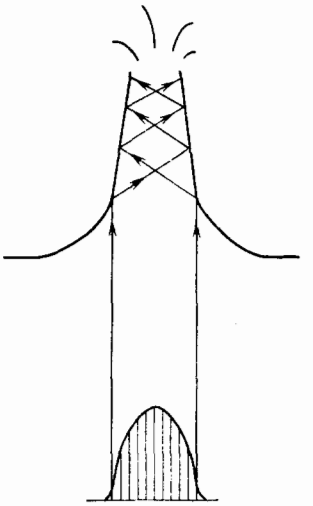

FIG. 2. "Self-concentration" of an acoustic beam at a boundary between two different media.

3.4. Self-transparency of viscous liquids in an acoustic field

Experiments reported in Ref. 60 showed that in liquids with high viscosity (e.g., glycerin) the self-focusing effect for ultrasonic beams is accompanied by self-transparency—the effective penetration depth of sound into the bulk of the liquid increases with an increase of the acoustic energy injected into it. If we are to be literally correct, the cause of self-transparency in glycerin is not so much its high viscosity *per se*, as it is the strong temperature dispersion of the absorption coefficient: for glycerin under normal conditions $d \ln \delta / dT = -0.07\ K^{-1}$, and the absorption length for acoustic energies of the order of a joule increases by several tens of percent.[60] However, in fact the magnitude of the viscosity, the absorption coefficient and the temperature dispersion are all varying sharply at the same time, in a temperature region over which qualitative changes are taking place in the short-range order (and perhaps long-range order as well) in the liquid (i.e., the so-called "relaxation region").

The usefulness of an optical-acoustical analogy is not limited merely to indicating the possibility of self-transparency in acoustics. The magnitude of self-transparency in optics[66] is determined by the parameters of the two-level system (in particular, near to resonance with a transition between a pair of atomic or molecular levels the effect is very strong), such as the equilibrium population of the levels, the probability of the light-induced transition between levels, and the width of the transition line. An analogous investigation of acoustic self-transparency, as a result of experiments of the sort given in Ref. 60, should give new information about the kinetics of intermolecular bonds when the experiments are carried out at temperatures closer to the relaxation region (for glycerin this is for temperatures $\leqslant 10$ °C). For the particularly important case of liquid water, for example, an adequate picture of the self-transparency mechanism is provided by postulating a pair of broadened levels, one of which corresponds to water molecules entering into hydrogen bonds, the other to breaking of these bonds.

4. STIMULATED ACOUSTIC SCATTERING (SAS)

All forms of stimulated scattering of light are caused by interactions of electromagnetic waves with some sort of "non-optical" motion of the medium. Hypersonic waves (stimulated Mandelstam-Brillouin scattering, or SMBS), intramolecular oscillations (stimulated Raman scattering, or SRS) and thermal waves (stimulated temperature scattering, or STS) are all motions of this sort. In real absorbing media stimulated scattering has a threshold: the exponential growth of spontaneous oscillations begins only as the result of interaction with a sufficiently energetic pump.[27,28]

The acoustic field is also capable of entering into interaction with various characteristic motions of the medium. The list of partners of the acoustic pump is potentially even longer than in optics, since it includes slow hydrodynamic motions, which "willingly" interact with sound but only weakly with light. The first suggestion that SAS was observable was related to studies of the air-liquid interface[78]; below, we will discuss bulk variants of SAS.

4.1. Stimulated acoustic Raman scattering (SARS) by air bubbles in liquids

The picture of stimulated Raman scattering of sound waves by air bubbles[79,80] can practically duplicate that of SRS of light by molecules, if we remain within the classical (nonquantized) formalism. If an acoustic pump wave p_1 with frequency ω_1 propagates in a liquid containing bubbles with a characteristic frequency Ω_0, then in the presence of a weak spontaneous Stokes component p_s with frequency $\omega_s = \omega_1 - \Omega$ (where $\Omega/\Omega_0 < 1 \pm Q^{-1}$, Q is the quality factor of the bubble) oscillations will be excited in the bubbles at a frequency close to the resonance frequency Ω_0. Scattering of the pump wave by the oscillating bubbles leads in turn to amplification of the Stokes component and, if we are provided with positive feedback, to generation of sound at the Stokes frequency.

The gain g for the Stokes component is determined by the concentration n of bubbles, their susceptibility ε to pressure, the attenuation coefficient $f = \Omega_0/Q$ and nonlinear oscillation coefficients α and β of the bubble

$$g = \frac{c\rho n\omega_s \chi^2 \varepsilon^2 |p_1|^2}{2(\Omega_0^2 - \omega_1^2)^2 (\Omega_0^2 - \omega_s^2)^2 \Omega_0 f} - \delta; \qquad (4.1)$$

$\chi = \alpha - \beta(\omega_1^2 + \omega_s^2 - \omega_1\omega_s)$. From (4.1) it follows that the coefficient g becomes positive if the pump intensity exceeds a certain value I_{1th}. For bubbles with resonance frequency $\Omega_0/2\pi = 20$ kHz, having a volume concentration $nv_0 = 10^{-5}$ for $\omega_1 = 1.5\Omega_0$, $\omega_s = 0.5\Omega_0$, the threshold pump intensity in water is $\sim 10^{-2}$ W/cm^2. For $I_1 \gg I_{1th}$, from (4.1) it follows that g is estimated to be $\sim 0.3\, I_1$ cm^{-1} (I_1 in W/cm^2).

4.2. Stimulated temperature acoustic scattering (STAS) and stimulated acoustic scattering by acoustic streaming (SASAS)

In the introduction, it was already mentioned that SAS by bubbles is the only mechanism which provides scattering of sound (up to frequencies of 10–100 MHz) in liquids with a large frequency shift (its optical analogue is scattering of Raman type). As for scattering of the Rayleigh type, when the frequency shift is of the order of the scattering line width, then acoustics admits a wider range of possibilities than optics: for example, scattering of sound by hydrodynamic modes has no optical analogue (in the absence of free charges in the medium).

An analysis of the fundamental system of hydrodynamic equations—the continuity equation, the force balance equation (Navier-Stokes) and the equation of thermal conductivity—reveals universal mechanisms for SAS, i.e., mechanisms which operate in any liquid. Corresponding to this system of dispersive equations, there are five solutions (the Navier-Stokes equation is a vector equation), two of which correspond to acoustic modes with mutually antiparallel propagation directions. The three other modes are of diffusive type: to them correspond three possible forms of SAS in a homogeneous viscous liquid. The possibility of observing one of these—SAS by a vorticity mode—was discussed in Ref. 81. An estimate given in this paper showed that this is really a gas-phase effect: in liquids, the threshold for observing it is high.

Basically, the STAS phenomenon[82]—this is the second type of SAS, of Rayleigh type—is due to the same simple mechanism as the stimulated temperature scattering of light. In both cases, the pump wave and scattered wave heat the medium, creating a temperature grating which is responsible for scattering.

The liquids in which one can observe STAS must satisfy rather stringent requirements (see Ref. 82). On the one hand, the viscosity must be large—only then can the conditions for absorption of sound give rise to temperature inhomogeneities of sufficient magnitude. On the other hand, the thermal conductivity must be weak, so that the temperature variations which arise do not have time to smooth out quickly. In addition, the original generic requirement must be fulfilled, i.e., that the length l_{ss} over which the stimulated scattering evolves should not exceed l_p and the characteristic scale of the convection (see Section 3.1).

The final kind of SAS in homogeneous liquids that we will discuss is stimulated acoustic scattering by (longitudinal) acoustic streaming (SASAS).[83] In this case, the scattering is due to variations in the velocity of the acoustic flow which arises under the influence of a strong pump. At high frequencies, SASAS evolves earlier than STAS, since the momentum $k = \omega/c$ imparted to the medium by an absorbed phonon is larger the higher is the frequency; conversely, at low frequencies temperature scattering prevails. The boundary frequency ω_B at which both effects are comparable in magnitude is determined by equating their threshold pump intensities:

$$I(\text{STAS}) = 8\varkappa\omega\left(c\left|\frac{\partial \ln \varepsilon^2}{\partial T}\right|\right)^{-1}, \qquad I(\text{SASAS}) = 4\eta c^2\delta. \qquad (4.2)$$

For a classical absorption mechanism ($\delta \sim \omega^2$)

$$\omega_B \approx \varkappa\rho\left(\eta^2\left|\frac{\partial \ln \varepsilon^2}{\partial T}\right|\right)^{-1}. \qquad (4.3)$$

For weakly viscous liquids (water, benzene) the boundary frequency is more than 1 GHz; for the much more viscous glycerin, $\omega_B/2\pi \approx 100$ kHz.

The pulsed amplification regime is typical for STAS and SASAS, since with the passage of time the thermal conductivity and viscous diffusion smooth out the sonic-induced variations in temperature and acoustic flow velocity. Typical time intervals for the phenomena amount to 10^{-3} sec at a frequency of 1 MHz.

4.3. Specific mechanisms for SAS

First of all, let us mention the possibility of concentration-induced SAS in solutions in which chemical reactions are taking place. A modulation of the concentration of a reacting material can be created by a dependence of the chemical reaction rate on the sonic intensity (for example, through thermal effects). One very promising candidate is SAS in gaseous media with exothermal reactions, for example in flames: here, small changes in temperature in the fields of counterpropagating pump and scattered signal waves can lead to strong changes in the rate of burning and concentration of the flammable component.

A variant of the concentration-induced mechanism is realized for SAS in liquids with suspended particles. In this case, the combined field of the pump and scattered signal leads to bunching of the suspended particles, for example due to radiation reaction. This mechanism ("diffusive"; in calling it this we underline the role of diffusion as a tendency to oppose the particle bunching) was suggested in Ref. 84 and—in contrast to all previous SAS mechanisms—has already been realized in the laboratory. Here one finds a very low threshold for generation: around 1 W/cm^2 for a 1% concentration of suspended particles.

Also of interest are the possibilities inherent in layered solutions. The thresholds for concentration-induced SAS in such solutions[85] become actually realizable only in the immediate vicinity of the critical point; this difficulty should be weighed against the high information content of the effect—its output characteristics are determined by the critical parameters (miscibility function, kinetic mobility), which are hard to measure by thermostatic methods.

4.4. Possible applications of SAS

As in optics, the basic region of applicability of stimulated scattering phenomena is spectroscopy, in the present case acoustic spectroscopy of liquids. For example, SARS gives direct information about bubble parameters—about their concentration and eigen-frequencies, and the size distribution function for the bubbles. Investigation of SAS in liquids with suspended particles allows us to obtain information about the diffusion coefficient of the particles. SAS spectroscopy has also proved useful in investigating microprocesses connected with phase transitions in liquids.

According to estimates made in Refs. 82–85 observation of SAS is not a simple problem; however, also in optics experiments which measure the characteristics of stimulated scattering of the Rayleigh type are accompanied by a number of difficulties. In addition to the above-mentioned stringent requirements on the pump, there are also problems of recording related to the smallness of the frequency shift. Here, therefore, it is required that the experimental geometry be optimized; in particular, the scheme of transverse pumping (scattering at 90°)[86] offers undoubted advantages. This method delivers, first of all, a low background contribution from the pump; secondly, cylindrical focusing of the pump makes it possible to exclude the effect of formation of a discontinuity with practically no decrease in the resonator Q-factor—the pump wave passes only through the thin layer of liquid occupied by the constricted beam. Finally, it is natural to use a resonator to lower the threshold for the effect.

5. WAVE FRONT (PHASE) CONJUGATION IN ACOUSTICS (PC)

5.1. The PC mechanism in optics and radio electronics

We customarily refer to a wave as "conjugated" when it differs from the incident wave only in its direction of propagation. Formally, this is expressed by changing the sign of the phase of the complex amplitude A_s of the signal wave. If the first wave is expressed in the form

$$p_s(\mathbf{r}, t) = |A_s(\mathbf{r})| \exp[iS_s(\mathbf{r}) - i\omega t], \qquad (5.1)$$

then for the conjugate wave we have (in the immediate vicinity of the PC device)

$$p_c(\mathbf{r}, t) = K|A_s(\mathbf{r})| \exp[-iS_s(\mathbf{r}) - i\omega t], \qquad (5.2)$$

where K is the amplification coefficient.

The important property of the conjugate wave consists of the fact that it focuses at the same point where the source of the first wave is located. In a homogeneous medium this property is obvious; however, it is also preserved in an *inhomogeneous* medium. It is this property which makes PC devices so interesting from a practical standpoint.

These ideas received currency roughly 10 years ago, after they were realized in optics, although in electronics their use (as adaptive receiving-transmitting antennae) had already started in the 60s. Let us briefly enumerate the basic methods of phase-conjugating a wave front proposed in optics and electronics.

In electronic systems, a phase-conjugated signal is synthesized in each receive-transmit element; the total field from all the elements then forms the conjugated wave. Parametric converters are also used in these systems, accompanied by a rather small frequency shift, and even digital devices.

In optics, several mechanisms for PC have been proposed.[87,88] The four-wave mixing mechanism assumes we make use of two counter-propagating pump waves, which by interacting with the signal wave in a nonlinear medium produce the conjugate wave. The value of this mechanism lies in the fact that it does not have a threshold and can provide amplification of the conjugate wave.[89] The scheme for conjugation, which uses not volume but surface nonlinear effects is a degenerate case of four-wave mixing.[90,91]

In the three-wave mechanism, conjugation is accomplished by parametric transformation of the signal (this conjugates the phase) with a forced change in the direction of

propagation with the help of external mirrors. This mechanism also gives rise to amplification, but has a significant drawback—the conjugation occurs within a rather narrow range of angles.

Systems which use stimulated scattering also have the ability to perform phase conjugation. These systems have thresholds, and do not provide amplification of the conjugated wave; however, they are characterized by simplicity, reliability and the capability to withstand high powers.[88] Other concepts have also been advanced, e.g., using nonlinear media with periodically varying parameters[92]; however, these have not yet been realized experimentally.

From the point of view of general principles, the possibility of realizing PC in acoustics is beyond question, since this is a general wave phenomenon. The only question which arises is: what method should be used to produce PC in acoustics? The most obvious method is to use approaches developed in electronics since, after the acoustic signal is transformed into an electrical one, all the acoustic problems are resolved by electronic means. Less trivial are the acoustic analogues of nonlinear-optics methods.[93,94] The most interest attaches to using four-wave mixing for PC; this method is capable of conjugating the wave with amplification. Also of interest is the surface mechanism in view of its ease of realization.

5.2. PC by four-wave mixing in acoustics

The interaction of two acoustic pump waves p_1 and p_2 with a signal acoustic wave p_s in a nonlinear medium leads to the appearance of a fourth wave p_c (Fig. 3). Its appearance can be explained qualitatively as follows: the signal wave p_s along with the wave p_1 gives rise to an interference pattern which modulates the sound velocity $c(\mathbf{r})$ in the nonlinear medium or, which is the same thing, the index of refraction $n(\mathbf{r}) = c_0/c(\mathbf{r})$. As a result, a volume diffraction grating appears which scatters the counter-propagating pump wave p, leading to the appearance of the conjugate wave p_c.

This qualitative explanation can be discussed with the help of concepts borrowed from holography: the waves p_1 and p_s record a volume hologram, while the wave p_2 reads it and generates the conjugate wave p_c. The four-wave mixing scheme for PC is thus naturally related to schemes for dynamic holography. The mechanism for recording and reading a volume hologram is conveniently visualized with the help of the diagram in Fig. 4, in which the propagating modulation in the index of refraction $n(\mathbf{r}) = n_0(1 + \mu \cos k\mathbf{r})$ is represented by the wavy line.[84,93]

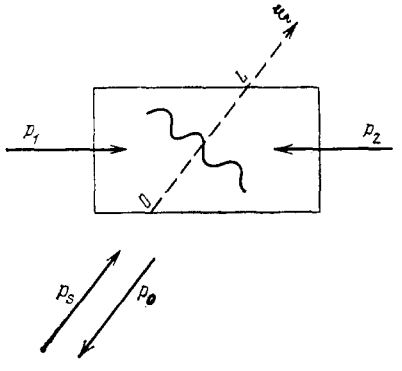

FIG. 3. A scheme for volume acoustic PC.

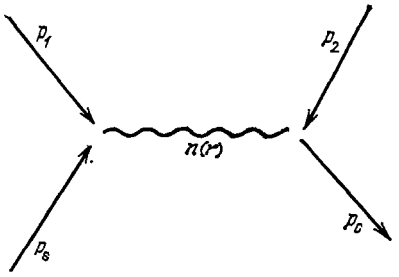

FIG. 4. A formalized diagram for volume PC.

One way to modulate the acoustic index of refraction is through the temperature mechanism which is mediated by inhomogeneous heating of the liquid at antinodes and nodes of the interference pattern.[95]

Equations describing the interaction of a signal acoustic pressure wave $p_s = A_s \exp(i\mathbf{k}_s\mathbf{r})$ and conjugate wave $p_c = A_c \exp(-i\mathbf{k}_c\mathbf{r})$ with two counter-propagating pump waves $p_{1,2} = A_{1,2} \exp(\pm i\mathbf{k}\mathbf{r})$ are entirely analogous to the corresponding equations of nonlinear optics:

$$\pm 2ik \frac{\partial A_{s,c}}{\partial \xi} = 2\tilde{\beta} A_1^2 A_{c,s}^* + \tilde{\gamma} |A_1|^2 A_{s,c}. \tag{5.3}$$

Here it is understood that the pumps p_1 and p_2 have the same amplitudes: $A_1 = A_2$. The coordinate ξ in (5.3) is measured along the direction of propagation of the signal wave (Fig. 3). The parameters β and γ are determined from the joint solution of the wave equation, taking into account the dependence of the sound velocity on temperature, and the equation of heat conduction:

$$\rho C_p \frac{\partial T}{\partial t} = \varkappa \nabla^2 T + Q, \tag{5.4}$$

where $Q = (\delta/\rho c)|p_1 + p_2 + p_s + p_c|^2$ is the power generated per unit volume as a result of absorption of sound; the coupling coefficients $\tilde{\beta}$ and $\tilde{\gamma}$ (see Ref. 95) depend on the angle θ and are proportional to the ratio $\omega^2\eta/\rho^2 c^5 \varkappa$. For the boundary condition $A_s(0) = A_{s0}$ (A_{s0} is the amplitude of the incident signal wave for $\xi = 0$), $A_c(L) = 0$ (at the boundary of the nonlinear medium $\xi = L$ the conjugate wave is absent), and assuming $A_1 = A_2$ are constant, equation (5.3) gives the following expression for the amplification coefficient of the conjugate wave:

$$|K| = \left|\frac{A_c(0)}{A_s(0)}\right| = \left|\operatorname{tg} \frac{\mu\omega L}{2c}\right|_s \tag{5.5}$$

where $\mu = 4\tilde{\beta}\rho c^3 I_1/\omega^2$ is the modulation depth of the index of refraction under the action of the pump. The amplification coefficient becomes infinite for $\mu\omega L/2c = \pi/2$, i.e., for $L = \lambda/2\mu$.

Another mechanism for PC is present in liquids with air bubbles, where the combined effects of the pump and signal lead to bunching of the bubbles and creation of an index of refraction grating.[95,96] In emulsions, and also in mixtures

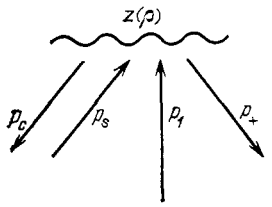

FIG. 5. A scheme for PC at a boundary between two different media.

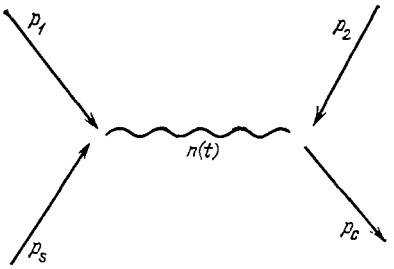

FIG. 7. A parametric PC scheme using temporal modulation of the sound velocity.

which stratify upon heating, we can expect high diffraction efficiency[84]; however, PC is difficult to realize in this case, because of the large value of the time needed to establish the nonlinearity.

5.3. Acoustic PC by surface waves

In this scheme, the pump wave p_1 and signal wave p_s create an interference pattern at the boundary separating two media (Fig. 5); because of nonlinear effects (for example, radiation pressure) a diffraction grating is imposed on this boundary, i.e., $z = z(\rho)$, where ρ is a coordinate vector along the surface. Scattering from this grating, the strong pump wave p_1 generates a diffraction spectrum p_+ and p_-, one of which corresponds to the conjugate wave: $p_c = p_-$. This conjugation mechanism is analogous to the surface scheme for Gabor holograms. The amplification coefficient due to the surface mechanism is always less than unity.

The concept of using a surface PC scheme in acoustics[97] was experimentally realized in Ref. 98. As expected, the amplification coefficient for the conjugate wave turns out to be small in magnitude: $K \sim 10^{-2}$. The smallness of K also favors self-focusing of the acoustic pump beam at the surface.

The amplitude of the surface waves—and thereby the amplification coefficient K—can be increased either by "weakening" the boundary (for example by decreasing the surface tension with surface-active materials, or using liquids with similar densities and liquids near their critical points), or by exciting resonant surface waves. In the latter case, the conjugation will occur with a change of frequency.

The transformation of waves through modulation of the surface $z(\rho)$ is illustrated in the diagram in Fig. 6. Here, one pump wave p_p is represented by two arrows, since it performs both the writing function (p_1) and the reading function (p_2) on the signal wave. This simple diagram which is similar to the volume diagram in Fig. 4, admits a series of nontrivial generalizations. First of all, the left and right pairs of arrows in Fig. 6 can correspond to waves of different physical natures. Thus, if p_1 and p_s are sound waves (left pair) while p_2 and p_c are light waves (right pair), Fig. 6 corresponds to the acoustic holography scheme. Secondly, fields of various physical natures can be represented by the upper and lower pairs of arrows. Thus, the conversion of a sound wave p_s into the conjugate wave p_c can be implemented with the help of an electric field. In this case, $p_1 = p_2$ represent the intensity of a variable electric field in a capacitor, within which the boundary between two media is located. Thirdly, diagrams 4 and 6 suggest that instead of spatial we use temporal modulation of the refractive index. This leads to a new parametric PC scheme which has no analogue in nonlinear optics.[84,94,99] In this case, the fields p_1 and p_s create a time-dependent modulation of the refractive index, while the pump p_2 again reads out the information, generating the conjugate wave p_c. The corresponding diagram is shown in Fig. 7.

5.4. Parametric mechanism for PC in acoustics

As was already stated, this PC mechanism has no optical analogues. The parametric PC arrangments, just as holographic types of arrangements (see Sections 5.2 and 5.3), can be proposed in two variants—a volume and a surface type. These arrangements are described in Refs. 84, 93, 95 and 99 under the name "POFUZ" (Russian acronym, standing for "parametric phase conjugating acoustic amplifier"). The volume "POFUZ" variant is shown in Fig. 8, using an electric pump. Here, an alternating electric field with frequency 2ω is applied across a capacitor; its action is to modulate the velocity of sound homogeneously through-

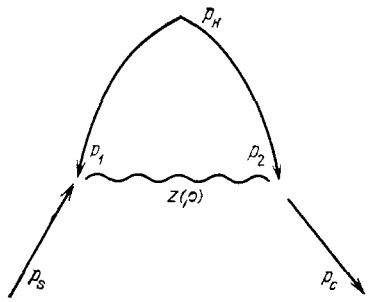

FIG. 6. A variant of surface PC using a single pump wave.

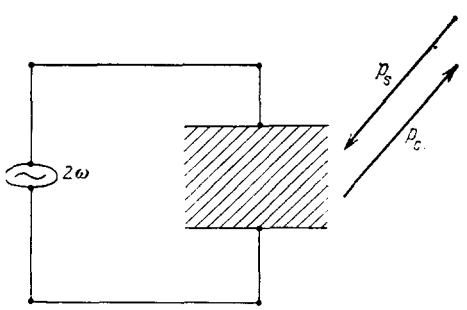

FIG. 8. The "POFUZ" scheme, using electrical pumping.

out the volume of the liquid located between the capacitor plates.

The incident signal field can generate an amplified conjugated wave p_c in the "POFUZ" [87]; the amplification coefficient, as in the case of a volume holographic arrangement (see Section 5.2), is given by the formula $|K| = |\mathrm{tg}(\mu\omega L / 2c)|$, in which μ is now the depth of time, and not space, modulation of the acoustic index of refraction: $n = n_0(1 + \mu \cos 2\omega t)$.

Parametric amplification of sound in piezoelectric solids placed in an electric field of frequency 2ω has been detected in many experiments, among which are the double-pulse echo experiments. However, phase conjugation in such systems has not been detected in any clear form. Only recently has the PC effect been successfully modeled for ultrasonic waves in piezoelectric films excited by randomly placed electrodes.[100]

The practical realization of phase conjugation of acoustic waves in liquids is hindered by the insufficiently high value of the coefficient μ for all well-known modulation mechanisms. Particular hopes are placed first on the acoustic analogue of the Kerr effect,[99] which consists of the change of the acoustic index of refraction under the action of an electric field E: $\mu \sim (\partial n/\partial E^2)\, E^2$. The electrostrictive mechanism turns out to be inadequate here, since homogeneous in-phase modulation can be achieved only on a scale that is small compared to the wavelength. An alternative mechanism is one which acts directly through the change in the intermolecular interaction potential in an electric field.[101] In this case, a useful liquid must possess a high dielectric susceptibility and a high threshold for electric breakdown. Highly purified water is the first candidate for this role. A second promising medium could turn out to be a liquid with air bubbles, placed in an electric field: under the action of ponderomotive forces the volume of the bubbles changes, and consequently also the velocity of sound in such liquids.[84] A third possibility might be to investigate the possibilities of still another variant of "POFUZ" using liquids with bubbles, but with an acoustic rather than an electric pump.[95] Finally, it is conceivable that other variants are possible which involve magnetic liquids and magnetic pumps.[87,95,102]

The surface version of the parametric PC arrangement proposed in Refs. 84 and 94 is simply a plate oscillating with frequency 2ω. The conjugation effect in such a device has been recorded in Ref. 103.

5.5. Possible applications of PC systems in acoustics

Just as in optics, acoustic PC systems can be made to address a wide range of applications. Let us point out several possibilities here.

First of all, with the help of a PC arrangement, we can effectively solve the problem of compensating phase distortions arising when sound propagates through a randomly inhomogeneous medium. This is particularly important in ocean acoustics, when applied to the problem of creating adaptive acoustic antennae similar to the adaptive antennae of the radio region, or in adaptive optics systems, as well as arrangements for active suppression of acoustic radiation.[104]

Furthermore, a PC arrangement operating in the generation mode, which is excited by feedback between the "PC mirror" and the object under study, can mediate a concentrated transfer of acoustic energy to the object.[84,87] Besides, the use of PC of acoustic beams is promising for solving problems of acoustic imaging, defect detection, medical diagnostics and ultrasound microscopy, as well as the mechanical and thermomechanical processing of materials.

6. ACTIVE ACOUSTIC SPECTROSCOPY

The basic idea of active spectroscopy is to create a preliminary excitation of the degrees of freedom under study by nonlinear interactions between pump oscillations. This idea, which has yielded important results in optics,[105–107] may also turn out to be useful in acoustics. However, since this is an entirely new direction in acoustics, on the one hand closely related to our theme of stimulated scattering (see Section 40), while on the other hand as yet still very limited in its results, we will be quite brief in what follows.

6.1. Active spectroscopy of bubbles

If with the help of two high-frequency pump waves with frequencies ω_1 and ω_2 we excite bubbles at a frequency $\Omega = \omega_1 - \omega_2$, close to the resonance frequency Ω_0 of a bubble, analysis of the frequency dependence of the amplitude of the induced oscillation with a probe acoustic signal makes it possible to determine the frequency and Q-factor of the resonance with high accuracy.[79,108]

This technique of recording the characteristic frequencies has understandable advantages over other well-known methods of bubble diagnostics, among them those that are highly effective—with the help of Raman-scattering analysis.[6,109] First, by scanning the frequency ω_1 (or ω_2) one can measure directly the size distribution of the bubbles. Second, when working with the high-frequency pumps $\omega_{1,2}$, one eliminates the background of low-frequency parasitic resonances. Thirdly, the method provides high sensitivity, which allows one the hope of detecting even a single bubble in the volume under study. Of course, these advantages can be realized only by using appropriate experimental equipment.

Acoustic active spectroscopy of bubbles admits a nontrivial modification connected with variations in the nature of the interacting fields (for example, replacing the acoustic pumps by electrical ones or using probes of laser radiation to read out the information concerning the excited bubbles).

Similar considerations also apply to active spectroscopy of surface waves. In this case, the principal problem is in providing a spatial synchronism of waves taking part in the interaction.

6.2. Stimulated Raman scattering by isolated bubbles

Whereas in optical stimulated Raman scattering very many molecules must take part at the same time, in acoustics it is actually possible to observe acoustic SRS with the participation of only one bubble.

Let the bubble undergo free oscillation with frequency Ω_0. When a high frequency wave falls on it with frequency

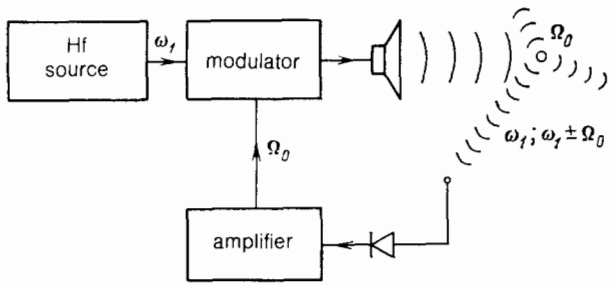

FIG. 9. Recording stimulated Raman scattering from isolated bubbles.

ω_1, in the scattered field there appear the sum and difference frequencies $\omega_{2,3} = \omega_1 \pm \Omega_0$ (Fig. 9). Detecting the resulting oscillations yields the low-frequency component Ω_0. If this component is amplified and the original frequency of the source is modulated by it, then the frequencies $\omega_{2,3}$ will appear in the irradiating field. Due to the nonlinearity of the bubble, a "force" will act on it at the resonance frequency Ω_0, equal to $\omega_2 - \omega_1$, or $\omega_1 - \omega_3$.

In the presence of this feedback, a regime of self-oscillation can arise in the system here described. Naturally, we still require a detailed estimate of the possibility of picking out a signal at the frequencies $\omega_{2,3}$ above the noise background.

7. CONCLUSION

The intensive incorporation of optical "ideology" into nonlinear acoustics in the course of the last several years has already made it possible to obtain a number of new results described above. In order to realize the overwhelming majority of the cases which are possible in principle, however, a large body of both theoretical and experimental investigation must still be carried out. This is connected with the inherent difficulties of acoustics, both fundamental and technological. A full list of those difficulties which are already understood can be assembled from the literature listed below; here we mention only those which, in our opinion, are fundamental and which are clearly evident from a comparison with optics.

When the discussion turns to experiments on a laboratory scale involving liquid media, the first problem which must be faced in high-intensity acoustics is acoustic-induced convection. In such a common liquid as benzene, after one or two seconds an acoustic beam with a power of ~ 10 W renders its own self-induced flow fully turbulent,[60] thereby "smearing out" the regular nonlinear effect under study. The closest optical analogue to this is laser-induced breakdown; however, its threshold is usually higher than the thresholds for stimulated light scattering, parametric generation, etc. In this regard, acoustics in liquids is clearly in a disadvantageous position.

Also very important is the difference between spatial scales in optical and acoustic wave experiments (the wavelength serves as a natural scale, of course). It is entirely possible to create a smooth coherent laser beam with a diameter of 1 cm whose transverse cross-section contains up to 10^5 wavelengths; in ultrasonic acoustics of liquids, the technology of radiator fabrication limits this quantity to a level of $a \sim 10^2\lambda$. This in turn limits the quality of acoustic resonators and the efficiency of designs using PC—the ratio of the corresponding diffraction lengths is 10^6. Specific difficulties are also caused by the detuning of the various interacting waves in frequency and direction. Further problems are diffractive divergence of the beam, limitations on the beam cross-section, the finiteness of the dimensions of the liquid under study, etc.

Nonlinear acoustics (this refers in particular to acoustics in liquids) is also beset by significant theoretical problems. As long as we are dealing with simple nonlinearity mechanisms (heating, flows, bubbles), estimates can be carried out using results of measured parameters in weak acoustic fields. However, here too the predictive power of the theory is not great, since the individual effects are observed only within a narrow range of parameters. At this time, theoretical acoustics is ill-prepared to make the transition to, for example, the range of relaxation processes that contains new physical data.

At the same time, however, analysis of the first experiments discussed in our review give no basis for pessimism, since the difficulties mentioned above can be avoided in a number of cases. Thus, in experiments of the type described in Ref. 60, the transition to liquids with high viscosity excludes the development of convection within times less than 10^2 sec. Furthermore, several advantages are revealed which are available only to acoustic experiments. For example, in Ref. 60 where experiments are described which are quite familiar to us, use of the pulsed "shadow" method allowed the authors to obtain directly, on photographs which are to scale, an image of the changing curvature of the phase front in the acoustic beam as it penetrates deep into the liquid, which is impossible to achieve in experiments on self-focusing of light.

These considerations, and also, of course, to a greater degree the importance of the physical and applied problems which, as we have tried to show in this article, can be solved using optical-acoustic analogies, in our opinion leave little doubt of the promise of the directions being pursued.

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