Lasers in acoustics

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The subject of lasers in acoustics covers the following topics: lasers as unique sources and detectors of sound, coherent optical analysis of signals in multichannel acoustic data systems, and laser-acoustic technology. The results of research at the interfaces between acoustics, quantum and physical electronics, and fiber and integrated optics provide opportunities for developing new methods for experiments in physics and new technical means which can be used to carry out tasks that cannot be performed by traditional methods. An analysis is made of the characteristics of laser generation of sound in condensed media and of the applications of lasers for remote detection of acoustic fields and vibrations. The principles of operation of fiber-optic sound detectors are described. An analysis is made of the possibility of using optical generation and detection of sound in technology and in instruments for nondestructive testing, as well as in multichannel acoustic data systems.

Laser excitation of sound.—Laser methods for remote investigation of acoustic fields and vibrations.—Fiber-optic sound detectors.—Laser-acoustic technology.—Coherent optical analysis of signals in acoustic data systems.

1. INTRODUCTION

The twenty-fifth anniversary of the discovery of the laser was celebrated in 1985. Modern lasers emit in a wide range of wavelengths and major progress has been made in the development of tunable dye lasers, as well as of gas and solid-state lasers. Semiconductor lasers are now mass-produced and represent the smallest as well as the most reliable components of quantum electronics.[1] In the last 25 years lasers have become generally accepted in science and technology, as well as in industry, medicine, and protection of the environment. In practically all applications the introduction of lasers has led to or will lead to revolutionary changes. The development of lasers and their applications is an on-going process. A.M. Prokhorov described the current status graphically: "We can definitely say that we are in the linear stage of the development of lasers and there are as yet no signs of saturation."[2] Extensive applications of lasers in acoustics are being explored.

Lasers in acoustics represent unique sources and detectors of sound, and they are also used in coherent optical analysis of signals in multichannel acoustic data systems as well as in laser-acoustic technology. The results of research at the interfaces between acoustics, quantum and physical electronics, and fiber and integrated optics provide opportunities for developing new experimental methods and technological techniques for tasks which cannot be tackled by traditional methods.[3]

The last decade has seen publication of the results of many theoretical and experimental investigations of the generation of sound as a result of interaction of coherent optical radiation with condensed media. There have been many papers on the applications of lasers in contactless remote optical methods for the investigation and detection of acoustic fields and vibrations. The construction of lasers and fiber lightguides has made it possible to study and develop new acoustic detectors in the form of fiber-optic sound detectors. The first papers appeared in the second half of the last decade. Various configurations of such detectors have been considered in numerous studies and the results have been reported. Coherent optical computing devices are being used more and more for the acquisition, storage, and processing of data. Modern acoustic data systems are employing more and more channels, and the use of coherent optical computing devices in such systems is a pressing task.

The use of lasers and of the progress made in fiber and integrated optics in the development of new sources and detectors of sound, and use of coherent optical processors for the analysis of multichannel acoustic data are opening up new opportunities in technology. In some cases it is possible to combine the progress made in laser technology with the traditional ultrasonic technology in the development of new methods and devices for nondestructive testing and improvements in physicochemical properties or materials.

This introduction shows how extensive are the opportunities for the use of lasers in acoustics.

2. LASER EXCITATION OF SOUND

In 1880 A. Bell first observed the optoacoustic effect in the form of pulsations of pressure in a closed gas-filled chamber when it was exposed to a modulated infrared radiation flux.[4] From the early forties this effect has been used extensively in qualitative and quantitative analyses of mixtures and subsequently in photo-acoustic spectroscopy of matter.[5,6] However, in view of the low efficiency of the conversion of the optical energy into the acoustical energy, the optoacoustic effect has become important in the generation of sound only after the appearance of lasers. In the early sixties A. M. Prokhorov and his colleagues observed formation of shock waves due to the interaction of a laser beam with water.[7] In recent years many papers have been published on the laser generation of sound both in the Soviet Union and abroad, so that it is now possible to speak of optical or more usually optoacoustic sources of sound.

Optoacoustic sources have a number of advantages over the older acoustic radiators: sound can be generated remotely; there is no direct contact with the medium along which sound is propagating; it is possible to alter easily the geometric parameters of an optoacoustic antenna and the range of

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the emitted frequencies; sources of sound moving at practically any (subsonic, sonic, or supersonic) velocity can be constructed and these sources do not suffer from the effects of flow of a medium past the radiator in the traditional sense. Optical methods can be used to generate sound in a very wide frequency range—from very low acoustic to hypersonic—frequencies.

We shall now consider the characteristics of optoacoustic sources of sound, but we shall do it in a concise manner (the reader is directed for details to Refs. 8–12). We shall assume that a laser beam is incident on the surface of a liquid or a solid (Fig. 1). The action of light on matter creates perturbations of the medium which are accompanied by the emission of sound. There are many mechanisms of this effect and they depend primarily on the volume density of the energy dissipated in matter and on the way in which this energy is evolved. The mechanisms of generation of sound include thermal expansion, surface evaporation, explosive boiling, and optical breakdown.

In light-absorbing media at low densities of the dissipated energy the main role is played by the thermal mechanism of the generation of sound which is usually called the thermooptic excitation process. In this case there is no change in the aggregate state of matter in the region of absorption of light and sound is generated by thermal expansion of the parts of the medium heated by optical radiation. An increase in the energy density dissipated in a medium enhances the effects associated with an increase in the rate of expansion of the heated part of the medium and the changes in the thermodynamic parameters of the medium in the course of its interaction with laser radiation. A further increase in the energy density gives rise to more complex processes of the generation of sound involving phase transitions and optical breakdown.

2.1. Thermooptic excitation of sound

We shall now assume that the intensity of laser radiation is varied periodically (modulated) at the frequency of sound and that the density of the energy which is evolved is low. Then, in a surface layer of a liquid (for simplicity, we shall consider a liquid, although the analysis applies also to a solid) a pulsating region is formed and this region emits sound. Its dimensions can be less than, comparable with, or greater than the acoustic wavelength, depending on the diameter of the illuminated spot on the surface of the investigated liquid.

The acoustic pressure in the far-field zone in the liquid is[9]

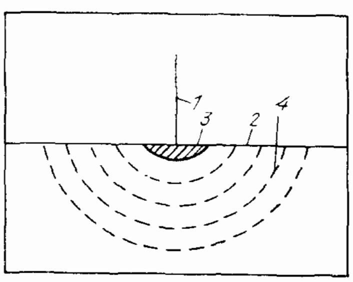

FIG. 1. Optical excitation of sound: 1) laser beam of variable intensity; 2) air-liquid interface; 3) optoacoustic source of sound (region of absorption of light in a liquid); 4) acoustic waves in the liquid.

$$p(r)=\frac{\omega m \varkappa A I_0 a^2}{2C_p}\,\frac{\exp(ikr)}{r}\,\frac{\mu k\cos\theta}{\mu^2+k^2\cos^2\theta}\times\exp\left(-\frac{k^2a^2}{4}\sin^2\theta\right); \quad (1)$$

here, p is the acoustic pressure; $\varkappa$ is the volume thermal expansion coefficient; C_p is the specific heat of the liquid; $k=\omega/c$ is the wave number of sound; c is the velocity of sound in the liquid; I_0 is the intensity of light in the incident laser beam; m is the modulation index; ω is the angular frequency of sound (modulation frequency of light); μ is the absorption coefficient of light in the liquid; A is the transmission coefficient of light at the boundary of the liquid; a is the radius of the illuminated spot on the surface of the liquid; Θ is the angle between the direction of the laser beam and the direction of the line from the point of observation to the origin of the coordinate system; r is the distance from the point of observation to the origin of the coordinates.

It follows from Eq. (1) that the amplitude of the acoustic pressure rises on increase in the laser power proportionally to I_0a^2, and it also increases on increase in the frequency and modulation index. The directionality of the acoustic radiation depends on the parameters ka and $k\mu^{-1}$.

If $k\mu^{-1}\ll 1$ and $ka\ll 1$, the emission of sound is a dipole process, because under these conditions a monopole source appears on the free surface of a liquid and the radiation field of this source represents a field of a dipole because of the influence of the free surface (Fig. 2a).

If $k\mu^{-1}\gg 1$ and $ka\ll 1$, sound is emitted mainly along the surface. A set of volume sources forms a thin (in the transverse direction) and long (compared with the acoustic wavelength) vertical antenna directed along the laser beam (Fig. 2b).

If $k\mu^{-1}\ll 1$ and $ka\gg 1$, the antenna is in the form of a disk with a diameter much greater than the acoustic wavelength. The sound is emitted mainly along the direction of the laser beam (Fig. 2c).

An analysis of Eq. (1) shows also that the optimal conditions for the generation of sound by laser excitation[12] are observed when $k\approx\mu$. This imposes certain requirements on the frequency (wavelength of light) emitted by a laser.

The distance traveled by laser radiation (quantity μ^{-1}) in a liquid (or in matter generally) depends on the radiation frequency (wavelength of light). For example, the distance traveled by infrared radiation (from a CO_2 laser) in water is approximately 10^{-5} m, whereas blue-green light (from a copper vapor laser) penetrates to a depth of tens of meters. Variation of the laser emission frequency, focusing and defocusing of the laser beam on the surface of a liquid, and variation of the frequency of light modulation can be used for remote control of the characteristics of the acoustic field in a liquid. If a laser beam scans the surface of a liquid, a moving

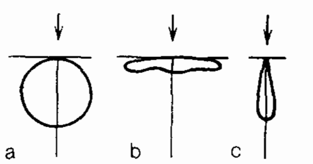

FIG. 2. Angular distributions of the radiation from an optoacoustic source: a) dipole radiation; b) radiation oriented along the surface of a liquid; c) radiation oriented along the direction of propagation of a laser beam in a liquid.

optoacoustic source can be constructed and the velocity of motion of this source can be subsonic, sonic, or supersonic.

Under real conditions it is found that for a variety of reasons the surface of a liquid is frequently disturbed by waves (uneven) and the liquid may be optically and acoustically inhomogeneous: it may be stratified and may contain suspensions and gas bubbles. The influence of the surface unevenness and of the inhomogeneities of a liquid on the characteristics of optoacoustic sources of sound has been discussed in detail on numerous occasions (see Refs. 13–15). It has been shown that if the displacements of the surface are large compared with the wavelength of sound, and if they are also statistically homogeneous, isotropic, and obeying the normal distribution law, the average field is directional and for the angles of observation $\Theta < \Theta_0 = \tan^{-1}(\sqrt{2}\sigma/a)$ the unevenness of the surface has a considerable influence on the directionality; here, σ is the rms value of the height of a statistically rough free surface of a liquid perturbed by waves. In the range of angles $\Theta > \Theta_0$ the directionality depends mainly on the ratio of the acoustic wavelength to the dimensions of the illuminated spot, and in this case the unevenness of the surface has practically no influence on the formation of the field of an optoacoustic source. An analysis has also been made[16] of the influence on the optical generation of sound of small (compared with the acoustic wavelengths) irregularities of the surface and the important case of the influence of a boundary representing a superposition of large and small irregularities has been considered.[16]

The influence of inhomogeneities of the medium on the optical generation of sound is influenced greatly by the scale of the optical and acoustic inhomogeneities and on the distance traveled by light in a liquid. For example, if the dimensions of an optoacoustic source are small, i.e., if they are less than the characteristic scales of optical (in the surface layer) and acoustic inhomogeneities, the acoustic field of such a source can be calculated stage by stage: we can first calculate the characteristics of an optoacoustic source on the assumption that the medium is optically homogeneous (quasihomogeneous) and we can then calculate the field of a source of sound of the computed efficiency, as is usual in the case of an acoustically inhomogeneous medium.[17] In the opposite case it is possible to carry out calculations using, for example, the transfer function of the medium which allows for the role of optical and acoustic inhomogeneities.[17,18]

The excitation of sound by laser pulses is particularly interesting. Operation of lasers in the pulsed regime makes it possible to attain very high powers of optical radiation and, consequently, generate acoustic fields of very high amplitude. There have been many theoretical and experimental investigations of the process of thermooptic generation of sound by laser pulses (see Refs. 11 and 19–23).

The acoustic pressure in the far-field zone in a liquid acted upon by laser pulses is[19]

$$p(r,\ t)=\frac{A\varkappa I_0a^2}{4\pi C_p\tau_\mu^2 r}\left[\int\limits_{-\infty}^{+\infty}\exp\left(-\frac{u^2s^2}{4}+iuv\right)F\left(\frac{u}{\tau_\mu}\right)du - \int\limits_{-\infty}^{+\infty}\exp\left(-\frac{u^2s^2}{4}+iuv\right)\frac{F(u/\tau_\mu)}{1+u^2}du\right], \qquad (2)$$

where

$$u=\omega\tau_\mu,\quad v=\left(\frac{r}{c}-t\right)\tau_\mu^{-1},\quad s=\frac{\tau_a}{\tau_\mu}$$

and $\tau_\mu=\frac{\cos\Theta}{\mu c}$, $\tau_a=\frac{a\sin\Theta}{c}$

are the characteristic times of the delay of sound from elementary sources in the vertical and horizontal sections of the region where thermal sources are located (Fig. 3), and

$$F\left(\frac{u}{\tau_\mu}\right)=f(\omega)=\int\limits_{-\infty}^{+\infty}f(t)\,e^{i\omega t}\,dt$$

is the spectrum of a laser pulse $f(t)$.

An analysis of Eq. (2) is based on the fact that the spectral width of the functions in the integrand depends on the characteristic time scales which are the pulse duration τ, and the delay times τ_a and τ_μ. In fact, in the case of the spectrum of a laser pulse we have $\omega \leqslant c_1/\tau$, for an exponential function we have $\omega \leqslant c_1/\tau_a$, and for a rational function we have $\omega \leqslant c_1/\tau_\mu$, where c_1 is a constant.

For example, it follows from Eq. (2) that in the case of long laser pulses when $\tau \gg \tau_a$ and $\tau \gg \tau_\mu$, the profile of an acoustic pulse is governed by the second derivative of the envelope of a laser pulse:

$$p(r,\ t)\approx -\frac{A\varkappa I_0a^2}{4\pi C_p r}\tau_\mu f''\left(t-\frac{r}{c}\right). \qquad (3)$$

If $\tau_a \ll \tau$, but $\tau_\mu \gg \tau$, i.e., when the region of effective heat evolution (or, in other words, an optoacoustic antenna) is in the form of a narrow cylinder, an acoustic signal is a rarefaction pulse, which has the same shape as an envelope of an "inverted" laser pulse $f(t)$ with a positive correction proportional to the small parameter τ/τ_μ. If $\tau_a \gg \tau$, the profile of an acoustic pulse is universal, is independent of the laser pulse envelope, and is governed by the ratio s' of the characteristic times.

Investigations of an acoustic field excited in a liquid by a sequence of laser pulses were published in Refs. 20 and 21. A special feature of such an acoustic field is the generation of a large number of acoustic harmonics. The width of the excited spectrum is governed by the repetition frequency of the laser pulses, by their duration, and by the coefficient of absorption of laser radiation in matter. The spectrum of the acoustic field may include harmonics whose generation is optimal compared with others if a given spectral component satisfies the conditions for optimal excitation, i.e., $k_n \approx \mu$,

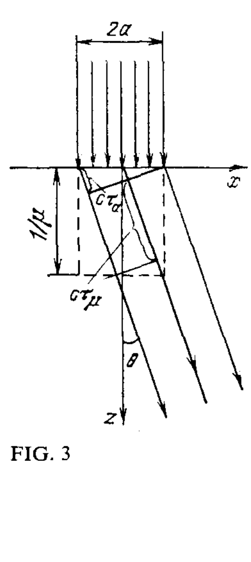

FIG. 3

where k_n is the wave number of the nth acoustic harmonic. When sound is excited by a sequence of laser pulses, the efficiency of transformation of the energy of laser radiation into sound is enhanced.

Detailed investigations have been made of the field of a moving pulsed optoacoustic source (see, for example, Refs. 23 and 22). The following cases have been analyzed: a) rectilinear and uniform motion of a beam along a finite trajectory; b) oscillatory motion of a beam; c) uniform motion of a beam along a circle, etc. The fundamental result of these investigations is that the generation of sound by a pulsed optoacoustic source moving uniformly along a straight line occurs in the same manner as in the case when the laser beam does not move along the surface but is "compressed" by a factor of $|1-\tilde{M}|$ and the effective duration of a laser pulse then becomes $\tau|1-\tilde{M}|$, whereas its profile is described by

$$f\left(\frac{t}{|1-\tilde{M}|}\right)|1-\tilde{M}|^{-1}, \qquad (4)$$

where $\tilde{M}=(V/c)\sin\Theta\cos\varphi$; V is the velocity of a laser beam on the surface of a liquid; Θ and φ are the angular coordinates describing the direction toward the point of observation. In other words, practically all the comments and results on the generation of sound in a liquid by laser pulses obtained for the case of a static laser beam can be applied to a moving beam if we consider an effective laser pulse defined as above.

Theoretical relationships characterizing the process of thermooptic generation of sound in a liquid are supported convincingly by numerous experiments.[24-26] For example, it follows from the theory of such generation that the amplitude of the acoustic pressure rises linearly on increase in the optical radiation power. This has been confirmed experimentally. A continuous line in Fig. 4 is the theoretical dependence and the circles are the experimental results.[26] The ordinate gives the acoustic pressure on the axis of an optoacoustic source, i.e., in the direction of propagation of a laser beam. The pressure is reduced to a distance of 1 m and is normalized to 10^{-6} Pa. The abscissa gives the change in the optical radiation power in kilowatts. The experiments reported in Ref. 26 were carried out in a lake. A neodymium laser ($\lambda_{opt}=1.06\ \mu$m) operated in the pulsed regime and intrapulse modulation of the intensity of optical radiation was imposed. The modulation frequency was such that the generation of sound in water was a quasimonochromatic process.

Figure 5 shows the theoretical (continuous curve) and experimental (points) angular dependences of the acoustic

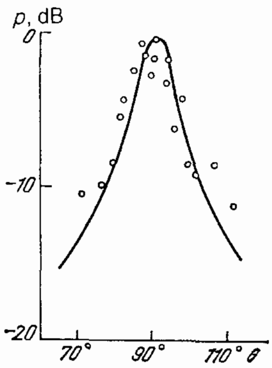

FIG. 5. Angular distribution of the acoustic field generated by laser excitation in water.[26] The continuous curve is theoretical and the circles are the experimental results.

field generated by laser excitation.[26] The frequency of sound was $f=50\times10^3$ Hz, the condition $ka\ll1$ was observed, measurements were made at a distance of 16.8 m, and the absorption coefficient of light in water was $\mu=15.7\ \mathrm{m}^{-1}$.

Figure 6b shows acoustic pulses predicted theoretically on the assumption that a laser pulse has a rectangular shape,[14] whereas Fig. 6a shows pulses recorded experimentally.[25] The calculations were based on the experimental results of Ref. 25. However, these relationships cease to be valid as the volume energy density dissipated in matter is increased, because of the increasing role of nonlinear effects resulting from thermodynamic and hydrodynamic nonlinearities. In the former case the heating of a liquid during a laser pulse alters the thermal expansion coefficient of a liquid (which increases on increase in temperature). This increases the efficiency of conversion of optical energy into acoustic energy during the action of a laser pulse, and the amplitude of the acoustic pulse increases. The hydrodynamic nonlinearity begins to play a role when the velocity of particles in a liquid in the heat evolution region becomes significant compared with the velocity of sound in a liquid. It is possible to provide a theoretical description of the operation of optoacoustic sources in this case also and this can be done by modifying the relevant equations[27] and using an inhomogeneous equation of the Burgers type.[28]

2.2. Evaporation mechanism

As pointed out above, a further increase in the density of the energy evolved as a result of absorption of laser radiation in matter gives rise to complex processes of the genera-

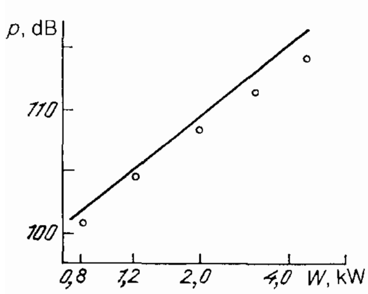

FIG. 4. Dependence of the acoustic pressure on the axis of an optoacoustic source on the laser power.[26] The continuous line is theoretical and the circles are the experimental results.

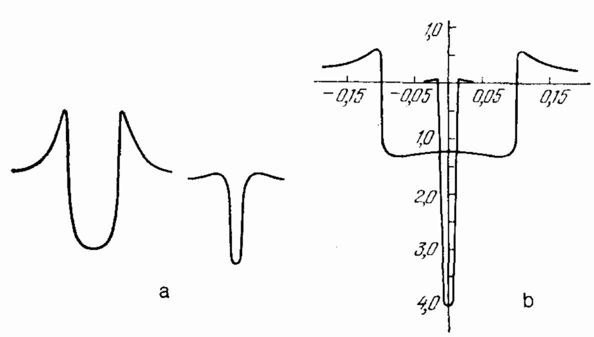

FIG. 6. Sound pulses recorded experimentally[25] (a) and those predicted theoretically[14] (b).

tion of sound associated with phase transitions. The generation of sound as a result of evaporation of matter becomes significant when the temperature of a substance is increased by laser radiation (for example, by a laser pulse) until it approaches the boiling point. When the boiling point is reached at the end of a laser pulse, an acoustic signal has an additional pressure peak in the "tail" part of the signal and this is due to thermal expansion of the medium. An increase in the density of the evolved energy increases the amplitude of this acoustic pressure peak. When the intensity of laser radiation reaching the surface of a liquid is increased still further, rapid boiling takes place in the surface layer and a stream of vapor emerges from the liquid antiparallel to the laser beam. Such a vapor jet enters the air above the liquid at a high velocity and generates there a strong shock wave, whereas the recoil impulse acting on the surface of the liquid creates a compression wave in the liquid. At the end of the laser pulse the reflection of the compression wave from the surface of a liquid produces a rarefaction wave. The latter causes cavitation: easily observable bubbles appear in the surface layer of the liquid. This behavior is observed when the volume (bulk) density of the optical energy delivered to matter is below a certain critical value at which optical breakdown occurs in the vapor of the investigated substance. In particular, optical breakdown takes place when infrared radiation of 10^8 W/cm^2 intensity interacts with the surface of a nonconducting liquid, and also when optical radiation of 10^6–10^7 W/cm^2 intensity interacts with the surface of a metal. Optical breakdown in the vapor of the evaporated substance produces a plasma which partly absorbs the incident radiation and screens the target. This stops the rise of the amplitude of an acoustic compression wave on increase in the intensity of light in the incident laser beam.

We can thus distinguish arbitrarily three cases of laser excitation of sound on evaporation of matter: weak evaporation when the density of the energy involved in matter is close to the heat of vaporization; explosive boiling when the energy density exceeds considerably the heat of vaporization, but optical breakdown does not occur in the vapor; plasma regime when the intensity of light is sufficiently high for optical breakdown of the evaporation products and a plasma is formed (this plasma absorbs the laser radiation and screens the target).

This separation of the regimes of laser generation of sound during evaporation of matter is obviously very arbitrary, because the underlying process of transformation of a condensed material into the gaseous one (evaporation) under the action of laser radiation is generally accompanied by complex nonlinear effects.[29-33] However, this arbitrary division makes it possible to develop in some cases a theory of the generation of sound and, in particular, to estimate the efficiency of conversion of optical energy into acoustic energy.

In particular, an approximate calculation of the pressure acting on the surface of a liquid in the field of high-intensity laser radiation ($I_0 = 10^8$ W/cm^2) is made in Ref. 30 for the case of strong evaporation of a liquid but below the plasma formation threshold. The time dependence of the pressure on the surface of a liquid is found using a theory of an explosive wave and also the results of Ref. 31. The calculated pressure on the surface of water interacting with CO_2 laser pulses is plotted in Fig. 7. In these calculations it is assumed that $I_1 = 10^7$ W/cm^2, $I_2 = 10^8$ W/cm^2, $\tau = 10^{-6}$ sec, and $2a = 30.48$ cm. The maximum pressure on the surface of water is 4.8 and 22.2 MPa for the two values of the laser radiation intensity assumed in the calculations.

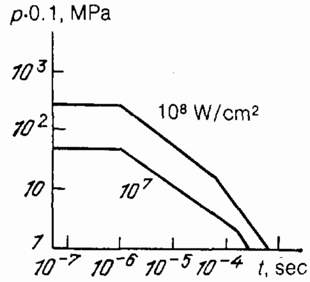

FIG. 7. The dependence of the pressure on the surface of water for different intensities of CO laser radiation in the form of pulses of 10^{-6} sec duration.[30]

More rigorous calculations allowing for the formation of a surface Knudsen layer in the process of evaporation can be found in Ref. 32. The results of the numerical calculations given in Ref. 32 show that laser radiation of 10^6 W/cm^2 intensity incident on an aluminum target in air at atmospheric pressure creates a pressure of 2 MPa which acts on the aluminum target. These numerical estimates are in satisfactory agreement with the results of experiments and demonstrate that laser excitation of sound can be used to achieve very impressive amplitudes of acoustic signals.

2.3. Generation of sound during optical breakdown of a medium

Optical energy is converted particularly effectively into acoustic energy under conditions of optical breakdown of a liquid (or other substance) when laser radiation is focused inside a liquid. In this case the density of the evolved energy may be sufficiently high for explosive boiling of the liquid in the focal region, producing a rapidly expanding vapor and generating a compression wave. At even higher light intensities and densities of the evolved energy we can expect optical breakdown. Microexplosions appear in the focal region and cavities filled with a dense luminous plasma are observed. Laser radiation is absorbed in the plasma imparting an additional energy to the cavity. The increase in the pressure causes expansion of the cavity and creates a shock wave. At the end of the laser pulse no further energy arrives in the plasma cavity, the gas cools, the radiation disappears, and a bubble exhibiting several pulsations is formed. Although optical breakdown and prebreakdown phenomena in liquids have been the subject of many experimental investigations, a theory of this effect as a whole and of the excitation of shock waves in particular is still at the early stage of development. Calculations of the excitation, propagation, and evolution of compression waves are made using a very simple model of the effect based on the experimental observations and on the ideas developed in a theory of underwater explosions and pulsed electric discharges in water.[34,35]

2.4. Efficiency of optoacoustic conversion

The efficiency of conversion of optical energy into acoustic energy is undoubtedly of interest. This efficiency can be described by the ratio of the total power of sound to the power of laser radiation or by the ratio of the evolved acoustic energy to the energy of a laser pulse.

In the case of the thermal mechanism of optical generation of monochromatic sound in an optoacoustic source in the form of a disk, i.e., in the case of a wide laser beam, the efficiency is described by[12]

$$\eta_1 \approx \frac{c}{\rho}\left(\frac{Am\varkappa}{2C_p}\frac{\mu k}{\mu^2+k^2}\right)^2 I_0. \quad (5)$$

The maximum efficiency corresponds to $k=\mu$ and it is then given by

$$\eta_{1\,\max} \approx \frac{C}{\rho}\left(\frac{Am\varkappa}{4C_p}\right) I_0. \quad (6)$$

We can see that the efficiency of conversion in the case of the thermal mechanism is directly proportional to the optical radiation intensity. For example, in the case of water, we have $\eta_{1\max} = 5\times 10^{-12} I_0$, where I_0 is in watts per square centimeter. An increase in the intensity of light can increase considerably the efficiency of conversion of optical energy into sound. However, this is true only as long as the thermal mechanism of the excitation of sound is operating, i.e., as long as the density of optical energy evolved in a liquid is low compared with the heat of vaporization.

An estimate of the conversion efficiency in the case of strong evaporation of a substance under the action of laser radiation can be obtained using a somewhat modified theoretical model[32] as is done in Ref. 10.

The expression for the conversion efficiency is then

$$\eta_2 = \frac{\gamma(\gamma+1)^{2/3}(\gamma_1-1)^{4/3}p_0^{2/3}I^{1/3}}{\rho c c_0^{4/3}}, \quad (7)$$

where p_0 and c_0 are the equilibrium values of the pressure and velocity of sound in air; γ is the adiabatic exponent for air; γ_1 is the adiabatic exponent for the vapor of the investigated liquid; ρ and c are the density and velocity of sound in the liquid.

We shall now give a numerical example. Let us assume that a CO_2 laser pulse of $I = 10^8$ W/cm^2 intensity is incident on the surface of water above which there is atmospheric air at a pressure of $p_0 = 0.1$ MPa. The fraction of the energy carried away by an acoustic wave is approximately $\eta_2 = 10^{-2}$ of the energy of a laser pulse.

The efficiency of conversion of optical radiation energy into acoustic energy in the case of optical generation of sound under optical breakdown conditions is given by[10]

$$\eta_3 \approx \frac{3}{2}(\gamma_2-1)\frac{1}{M\ln(r/R_0)}; \quad (8)$$

here, γ_2 is the adiabatic exponent for a plasma inside an expanding cavity in the case of laser breakdown of a liquid (for water and a low-temperature plasma it is assumed that $\gamma_2 = 1.27$); R_0 is the radius of the cavity; $M = R_0/c\tau$; τ is the duration of a laser pulse; c is the velocity of sound in the liquid. This formula is valid only if $\ln(r/R_0) \geqslant 1/4M^3$ (since it is derived on the assumption that the work of expansion of the cavity is small compared with the internal energy stored in the cavity). Estimates indicate that the value of η_3 may reach 10%.

3. LASER METHODS FOR REMOTE INVESTIGATION OF ACOUSTIC FIELDS AND VIBRATIONS

Contactless optical investigation methods play an important role in acoustics. In such methods a body in which acoustic vibrations are excited is illuminated with a beam of coherent light and then a study is made of light transmitted by this body or that scattered by its vibrating surface or by optical inhomogeneities in the interior. Optical contactless methods are used in acoustics to determine the nature and profiles of vibrations of bounded bodies,[36] to calibrate sources and detectors of sound,[37,38] and to study the propagation of ultrasonic and hypersonic waves in various media.[36,39,40] These methods are employed very extensively in the visualization of ultrasonic images[41,42] and in ultrasonic holography,[43,44] as well as in "readout" of surface acoustic waves in acoustoelectronic devices. Contactless optical methods are being developed for remote detection (reception) of ultrasonic waves in condensed media in the case of laser-acoustic sounding.[45,46] An important advantage of contactless optical methods for the detection and reception of sound is the absence of a mechanical contact with the investigated object and a high sensitivity, which makes it possible to detect acoustic waves at a distance in large-volume media when the investigated object is far away. Optical methods for the detection of optical fields and vibrations have been in use well before the appearance of lasers. However, the availability of coherent light sources have not only made these methods very popular, but have given rise to fundamentally new applications.[47]

Optical methods for the investigation of acoustic fields are based on the physical mechanisms of the interaction of sound and light. The effect of sound on light results in spatial and temporal modulation of light. This acoustooptic interaction reduces to modulation of the amplitude, phase, and polarization of an optical wave. An investigation of the modulation of light requires special methods for the detection and analysis of optical fields. The numerous methods available at present can be divided arbitrarily into two groups. Some of them are based on the fact that the investigated optical signal wave is subjected to spatial or temporal filtering followed by determination of the spatial distribution or of the time dependence of the intensity of the affected wave. Methods belonging to the second group reduce to a study of changes in the intensity of light as a result of interference of a signal wave with a reference wave whose amplitude and phase are known. These are optical interference methods. We can include in this group the relatively new holographic methods.

The subject of optical detection and investigation of acoustic fields is very wide and we shall consider only remote methods based on lasers.

3.1. Diffraction of light by sound

This effect has been investigated thoroughly both theoretically and experimentally.[36,39] Propagation of an acoustic wave is accompanied by changes in the optical refractive index of the medium and these changes are proportional to acoustic deformations.

When a plane optical wave is incident on a plane layer of a medium in which an acoustic wave is propagating parallel to the boundaries, the optical field at the exit from the layer consists of a discrete set of plane waves. Information on the acoustic field in the medium is contained in the spatial-temporal spectrum of the transmitted light. If the process of the acoustooptic interaction can be analyzed by the geometric-optics method and the bending of light rays in a medium (layer) can be ignored, and if the beam of light rays trans-

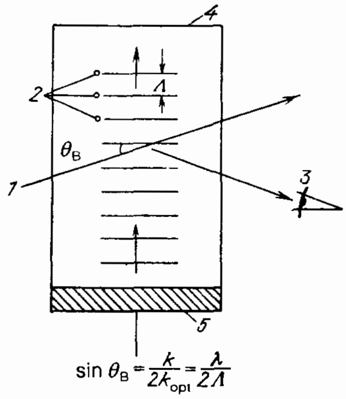

FIG. 8. Diffraction of light by sound when the Bragg condition is satisfied: 1) laser beam; 2) fronts of acoustic waves; 3) diffracted (transmitted) light beam; 4) acoustic cell; 5) ultrasonic transducer; λ is the wavelength of light and Λ is the wavelength of sound.

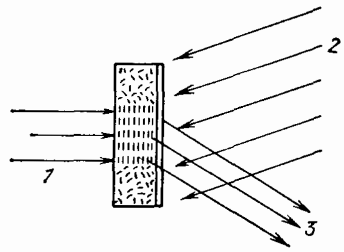

FIG. 9. Diffraction of light by sound: 1) acoustic beam; 2) laser beam incident on an acoustic cell; 3) beam of light diffracted at the Bragg angle.

mitted across the medium acquires only an inhomogeneous phase distribution over its cross section, we are dealing with the Raman-Nath diffraction. If the process of interaction of light with sound is affected significantly by the diffraction of light, then the most interesting case is the Bragg diffraction when a light wave is incident at the Bragg angle Θ_B relative to the front of the acoustic wave. This angle satisfies the condition

$$k = 2k_{opt}\sin\Theta_B , \quad (9)$$

where k and k_{opt} are the wave numbers of sound and light. In this case only one of the diffracted waves is of significant intensity and it is a wave whose wave vector makes the same angle Θ_B with the front of the acoustic wave; the other diffracted waves are subject to interference suppression (Figs. 8 and 9). The wave vectors of the acoustic wave and of the incident and diffracted light waves form a "resonance triplet" in the Bragg diffraction case.

It follows from the Bragg condition (9) that the diffraction of light in the backward direction, relative to that of the incident light wave, is possible only at extremely short acoustic wavelengths. This limits the potential use of the diffraction of light by sound (by a volume acoustic diffraction grating) in remote laser detection of acoustic waves to the range of hypersonic frequencies (Fig. 10). However, it should be pointed out that acoustic waves with these frequencies are always present in a medium because of thermal fluctuations. It is pointed out in Ref. 46 that the diffraction of a laser beam by hypersonic waves, which are due to thermal fluctuations in a liquid, can be used to determine the velocity of sound and the temperature of a medium, and this opens up the possibility of using this effect for the determination of the velocity of sound and of the temperature in surface layers of seawater.

3.2. Diffraction of light by acoustic perturbations of interfaces between media

An acoustic wave incident on an interface between two media modifies the initial shape of the interface. This gives rise to diffraction of light reflected by the interface. In fact, when a plane monochromatic acoustic wave is incident on a plane interface, the distortion of this interface represents a traveling "surface" wave with an amplitude proportional to the amplitude of the displacements of the medium in the field of the acoustic wave and the "surface" wavelength is $\lambda_s = \lambda/\sin\Theta$, where Θ is the angle of incidence. Light reflected from such a perturbed surface contains frequency-shifted diffracted components. If the size of the incident beam of light is considerably greater than the "surface" wavelength λ_s, then the reflected light represents a set of beams traveling along a discrete set of directions Θ_m described by $\lambda_s k_{opt}(\sin\Theta_0 - \sin\Theta_m) = 2\pi m$, where Θ_0 is the angle of incidence of the original light beam. The frequency of light in each of these beams is shifted relative to the initial value because of the Doppler effect by an amount $m\omega = (2\pi m/\lambda_{opt})v_s$, where $v_s = c/\sin\Theta_0$ is the velocity of propagation of the "surface" wave, c is the velocity of sound in the investigated medium, and ω is the frequency of sound. Usually the amplitude of the displacements of the surface is considerably less than the optical wavelength, so that only the diffraction spectra of the first two orders are of significant intensity. Their amplitudes are in the ratio to the amplitude of the regularly (specularly) reflected wave as $2k_{opt}\xi\cos\Theta_0$, where ξ is the amplitude of the peaks in the "surface" wave[48] (Figs. 11 and 12).

Spatial separation of specularly reflected and diffraction components occurs at large distances from the surface, i.e., it definitely occurs in a zone which is far in terms of the "surface" wavelength. If we consider coherent optical remote methods for the investigation of acoustic fields of the sonic and ultrasonic frequencies and if we ignore the spatial separation of the diffracted components, then in this case (i.e., in the case of superposition of the specularly reflected wave and of the diffracted components) we can expect to

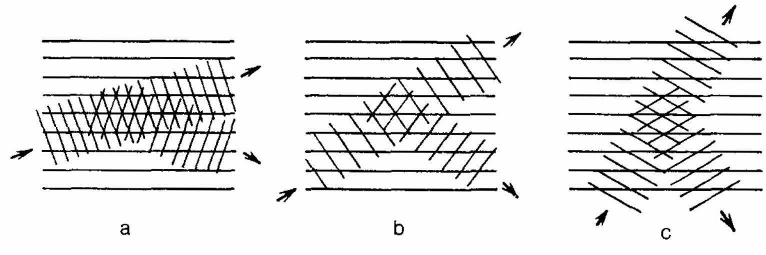

FIG. 10. Different cases of diffraction of light when the Bragg condition is satisfied: a) optical beam incident at the first ($m = 1$) Bragg angle (short light wavelength, $\lambda < \Lambda$); b) optical beam incident at the first Bragg angle (long wavelength, $\lambda > \Lambda$); c) optical beam incident at the second ($m = 2$) Bragg angle.

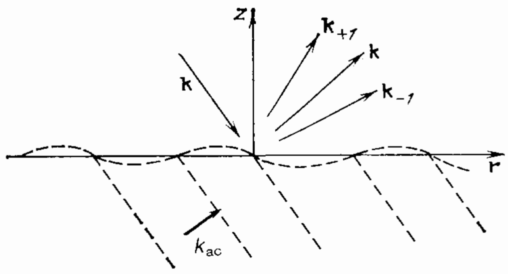

FIG. 11. Diffraction of light by the surface of a liquid vibrating under the action of an incident acoustic wave. Here, $\mathbf{k}_{ac}$ is the wave vector; $\mathbf{k}$ is the wave vector of light; $\mathbf{k}_{+1}$ and $\mathbf{k}_{-1}$ are first-order diffracted components of an optical wave.

observe amplitude-phase modulation of the reflected light.[49]

If the dimensions of the incident optical beam are small compared with the "surface" wavelength, then the superposition of the various components of the reflected light gives rise to two effects. Firstly, the phase of the optical wave is modulated in time at the frequency of sound, but it is homogeneous over the cross section of the beam. Secondly, the beam "swings" at the frequency of sound around the specular reflection direction. The amplitude of such swings is proportional to the angle of inclination of the surface in the "surface" wave.[50]

Under real conditions the interface between two media is practically always uneven. In particular, if we consider the interface between air and a liquid, then the surface irregularities may be due to external perturbations of the liquid surface. In the case of the boundary of a solid the irregularities represent the surface roughness or the unevenness due to technological reasons. If these irregularities and the acoustic perturbations of the surface are small compared with the wavelength of light, then they have little effect on the diffraction of light by the "surface" acoustic wave.[51] The small irregularities simply give rise to additional scattered light waves, but these (if the irregularities are in motion) act as noise in optical detection of an acoustic wave. Very small moving irregularities are always present on the surface of any body because of thermal fluctuations. This effect is particularly noticeable on the free surface of a liquid in which case it reduces considerably the signal/noise ratio in the process of optical detection of acoustic waves of frequencies in the range $1-10^4$ Hz (Ref. 52).

Moving large-scale (compared with the wavelength of light) irregularities alter considerably the spectral composition of light scattered by acoustic vibrations. The spectrum now consists not of discrete components separated by an interval equal to the acoustic frequency, but of a set of "broad" lines. The positions of the maxima of these lines coincide with the positions of the initial discrete components. The line "wings" overlap in the case of large or rapidly moving irregularities and the energy spectrum of the scattered light would seem to carry no information on the acoustic wave. A theoretical analysis of this problem[53] shows however that this wide-band "noise" is modulated at the frequency of sound.

If there are irregularities of two scales on the surface and the wavelength of sound is considerably less than the longitudinal scale of the large irregularities, the diffraction of light by a "surface" acoustic wave is observed on small parts of irregularities of the surface near the specular reflection points and the influence of small-scale irregularities can be of the same nature as in the case of a plane surface.[54]

When light is scattered by a surface with large-scale irregularities in the presence of sound, it is of interest to consider the behavior of some other parameters of the scattered light wave. For example, if the intensity of the incident light wave is modulated harmonically, it is of interest to study the change in the modulation of the wave intensity at the modulation frequency and at combination frequencies. The spatial and temporal dependence of the modulation index of the incident light wave is described, as is known, by a modulation wave. This wave travels at the same velocity as the incident wave, but its frequency is equal to the modulation frequency. It is found that the behavior of the average modulation index can be interpreted as the result of diffraction of the original wave by the "surface" acoustic wave. One can then observe spatial separation of the diffracted components, since the modulation wavelength may be comparable with the surface acoustic wavelength. The short wavelength of the carrier radiation (i.e., the optical wavelength) makes it possible to ensure a narrow angular distribution of the incident modulation wave.

If the surface irregularities which scatter modulated light are large compared with the modulation wavelength and with the acoustic wavelength, then diffraction of the modulation wave is most effective when the wave vectors of the incident modulation and acoustic waves satisfy the Bragg condition. Only one diffracted component can be of significant intensity and its amplitude is independent of "nonacoustic" large-scale and small-scale irregularities of the surface.[55] Manifestation of the Bragg diffraction properties in the diffraction of the modulation wave by the "surface" acoustic wave can then be explained by the fact that the volume structure of the acoustic wave is manifested on an uneven surface.

3.3. Raman scattering of light by scatterers moving in an acoustic wave field

If the height of the surface irregularities is great compared with the optical wavelength and the correlation radius

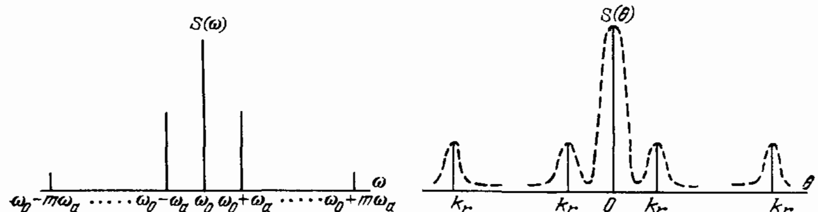

FIG. 12. Frequency $S(\omega)$ and angular $S(\vartheta)$ spectra of a light beam diffracted by the boundary of a liquid which interacts with an acoustic wave. Here, ω_0 is the angular frequency of light, ω_a is the angular frequency of sound, k is the wave number of light, and k_r is the radial component of the wave vector of light scattered by the boundary.

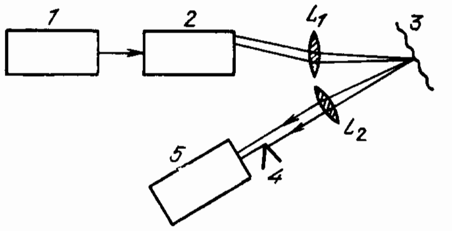

FIG. 13. Optical method for detection of acoustic vibrations of a surface by the shadow method: 1) laser; 2) scanner; L_1 and L_2 are lenses; 3) "acoustic relief" on a vibrating surface; 4) spatial filter (knife edge); 5) photodetector.

of these irregularities is small compared with the acoustic wavelength, then the diffraction of light by a "surface" acoustic wave is not manifested in the light scattered by the surface. Different points on the surface scatter noncoherently; the light scattered by them is only frequency-modulated because of the motion of the scatterers in the field of the acoustic wave. The frequency of modulation is equal to the frequency of sound and, consequently, the spectrum of the scattered light contains Raman components. In the case of large amplitudes of the surface displacements the spectrum is strongly broadened and the scattered light is not coherent with the incident light. It should be noted that the last circumstance is the basis for the widely used method of multiple exposure in holographic recording of vibrations.[56]

Raman scattering occurs also when light is scattered by internal scatterers moving in the field of an acoustic wave. This effect was investigated experimentally for air when the amplitudes of the displacements of the scatterers were large compared with the wavelength of light[57] and in liquids when the displacements were small.[58]

3.4. Shadow method and its analogs

The shadow method was evidently the first optical technique used in the investigation of acoustic fields.[36] It belongs to a class of widely used methods for the visualization of optical phase inhomogeneities.[59] The basis of all these methods is as follows. An optical signal beam with an inhomogeneous distribution of the phase over its cross section is subjected to a spatial Fourier transformation by a lens. The spectrum of the beam is filtered by an amplitude-phase filter located in the Fourier plane (known as the spatial frequency plane) and this is followed by an inverse Fourier transformation carried out by a second lens.[59] The simplest filtering method involves stopping of zero frequencies in the spatial filter.[36] Consequently, only those spectral components which are due to phase inhomogeneities in the investigated beam participate in the inverse Fourier transformation. Interference between the Fourier images of these components reveals phase inhomogeneities. There are several types of spatial filters that can be used in visualization of phase inhomogeneities. In addition to the filtering method just mentioned, wide use is made of a filter which stops half the Fourier plane (knife edge). Such a filter performs essentially a one-dimensional Hilbert transformation of an optical signal. In many respects the Hilbert transformation is analogous to differentiation and this accounts for the visualization of phase inhomogeneities.[59] The shadow method makes it possible to visualize both volume and surface waves.[60,61] The varying distribution of the intensity of light can be recorded employing a fast-response photodetector (Fig. 13).[61] This figure shows a method for optical detection of vibrations of a boundary to an incident acoustic wave which creates a "surface wave" or what is known as an "acoustic relief." A lens L_1 is located so that the boundary is in the focal plane of L_1, and a lens L_2 is located so that the spatial filter (knife edge) is in the spatial frequency plane. Recently attempts have been made to combine the shadow method with computer tomography in order to reconstruct the volume distribution of an acoustic field.[62] Transformation of the spatial spectrum is the basis of several other methods for investigating acoustic fields, particularly the diffraction grating method.[63] The latter method is being developed rapidly for the purpose of "readout" of surface acoustic waves in acoustoelectronic devices based on surface acoustic waves.[64]

3.5. Methods for detection of frequency-modulated light

These methods allow us to investigate acoustic waves by detection of a frequency-modulated scattered (signal) light wave. The frequency shift of optical oscillations due to the diffraction of light by an ultrasonic wave was measured back in 1886 (Ref. 36). However, the use of narrow absorption lines in optical investigation methods and in detection of acoustic fields, which was essentially established at that time, has not been practiced until the appearance of lasers. Lasers have enhanced interest in the methods of demodulation of frequency- and phase-modulated light with the aid of narrow absorption lines. The high frequency stability and the high intensity of laser radiation makes it possible to detect very weak phase modulation of light reflected from, for example, a surface vibrating in the field of an acoustic wave.[65] High-intensity laser radiation can "burn out" part of the absorption line and thus increase the slope of the frequency characteristic of the medium.[65] The difference between the absorption coefficients of different frequency components of the investigated light results in conversion of frequency modulation into modulation of the intensity of light, which can be recorded directly with a photodetector. The sensitivity of such methods is governed by the shot noise during recording. Moreover, the intensity of light at the exit from a medium is less than at the entry, so that the sensitivity determined by such noise is comparable with the sensitivity of interferometric methods (see below) for the determina-

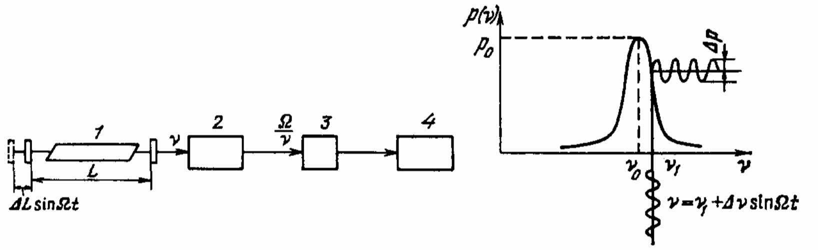

FIG. 14. System for measuring small displacements using optical resonances[66]: 1) laser with one of the resonator windows vibrating acoustically at a frequency Ω (ν is the frequency of light); 2) optical resonance filter; 3) photodetector; 4) recording system.

tion of weak phase modulation only if the width of the absorption line is comparable with the frequency of sound. This restriction can be lifted if an absorbing medium is placed inside a laser resonator and small vibrations of one of the resonator mirrors are investigated[66] (Fig. 14). However, in a situation of this kind the range of applications of the method is limited. All these shortcomings can be avoided if we do not use absorption but the amplification of light in an active medium. It is then found that even allowing for a new source of noise which appears in this case (which is the noise of spontaneous emission by the active medium) the sensitivity of the method is not inferior to that of interferometers provided the gain is sufficiently high.[67]

3.6. Interferometric optical methods

One of the methods for "readout" or reconstruction of a surface acoustic relief or a surface acoustic wave at the interface between two media involves determination of the phase modulation of a light beam, which is narrow compared with the wavelength of a surface acoustic wave, by a vibrating surface. Interferometers with photoelectric recording of the interference pattern are used most frequently for this purpose.[68] An important restriction on interferometers with photoelectric recording is that the dimensions of the sensitive area of a photodetector should not exceed one interference fringe in the field formed by interference of signal and reference light beams. If this condition is not obeyed, the interference pattern is averaged in the recording process and the contribution of the alternating part of the photocurrent to the total current becomes negligible.[69,70]

Principles of interferometric optical measurements of small vibrations have been developed well before the appearance of lasers.[71,72] The use of lasers has increased considerably the precision and sensitivity of interferometric measurements. The sensitivity is now $\sim 10^{-13}$–10^{-14} m (Ref. 68). The main trend of current efforts is to increase the sensitivity of measurements by avoidance of noise. It has been shown long ago[71,72] that the shot noise is the main component. It is frequently not possible to reach the sensitivity set by the shot noise because of the effects of random changes of the distance to the investigated object that alter the phase advance of the signal beam. A reduction in the influence of this type of noise is based on the fact that the characteristic time for such a change in the phase is, as in the propagation path of a signal beam, considerably greater than the acoustic frequency period. Therefore, random phase shifts could be compensated by automatic tracking without affecting the useful signal (Fig. 15). In some investigations[73,74] the phase shift has been compensated by displacements of a mirror in the reference arm. A detailed analysis of the problem of compensation of this type of noise can be found, for example, in Ref. 75 where an analysis is made of optimal and suboptimal processing of interferometric signals and an experimental study of a suboptimal processing system is reported.

3.7. Holographic optical methods for investigation of acoustic fields

These methods are clearly most promising when applied to remote investigations and measurements of acoustic fields with the aid of laser radiation. Optical holography makes it possible to record and reconstruct full information on optical radiation in the form of the distributions of the

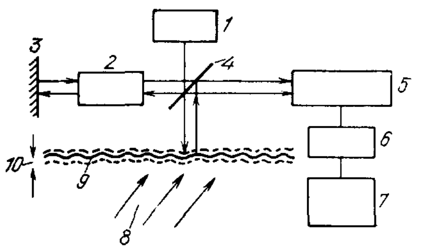

FIG. 15. System for optical interferometric recording of acoustic displacements of the surface of a liquid with an automatic tracking system which compensates for slow "nonacoustic" displacements of the surface: 1) laser; 2) automatic tracking system for compensation of the change in the phase in the reference optical beam; 3) mirror; 4) semitransparent mirror; 5) photodetector; 6) amplifier; 7) display; 8) direction of propagation of the acoustic beam incident on the surface; 9) surface of a liquid perturbed by sound; 10) slow (large) "nonacoustic" displacements of the liquid surface.

amplitude and phase of an optical wave, and also of the polarization.[76] This is attained by recording the intensity distribution in the course of interference of the investigated (object) optical wave with a known (reference) optical wave.[59] Interference patterns are recorded making use of media whose optical properties are modified by the influence of light. Numerous applications of holography in recording acoustic vibrations are based on the ability to observe interference of object waves at different moments in time. This is achieved by simultaneous reconstruction of holograms recorded at different moments. These holograms can be recorded in the same carrier (medium). In dynamic holography (discussed in greater detail below) such a comparison is possible also because a dynamic hologram does not disappear instantaneously, but after a finite time. The disappearance time is governed by relaxation characteristics of the medium used for recording purposes.[77] Selection of media with different relaxation times makes it possible to study processes characterized by different time scales.

The first holographic method for the investigation of vibrations was proposed in 1965 and it can be described as follows.[56] An investigated object with a vibrating rough surface is illuminated with coherent light and a hologram of the object is recorded. The exposure time is considerably longer than the vibration period. Time averaging of the interference pattern has the effect that the reconstructed distribution of the illumination in the image of the object, i.e., the distribution obtained by reconstruction of a hologram, is not the same as the distribution of the illumination in the object because the reconstructed illumination distribution in the image $I_s(u, v)$ is related to the corresponding distribution of the illumination of the object $I_s(x, y)$ by

$$I_s(u, v) = \beta J_0^2\left(\frac{n\pi}{\lambda_{opt}}\xi(x, y)\right) I_s(x, y), \tag{10}$$

where β is a constant factor; $J_0(\ )$ is a Bessel function of zeroth order; u and v are the coordinates in the image plane; x and y are the corresponding coordinates on the surface of the object; λ_{opt} is the optical wavelength; ξ is the amplitude of vibrations of the object. Therefore, bright and dark regions appear in the image of the object. The darkest regions correspond to the amplitudes $\xi = \delta\lambda_{opt}/4\pi$, where δ represents a zero of the Bessel function. This method is suitable only for the determination of amplitudes satisfying the condition $\xi \geqslant \lambda_{opt}/4$ and the difference between the amplitudes of vibrations at two points is deduced from the number of the dark fringes located between them. This method is known as the multiple exposure or averaging method.[78,79] The most valuable information on vibrations of the surface of an object is provided by the averaging method when an analysis is made of standing vibrations, i.e., when the natural profiles of the vibrations of the surface are being recorded. In the case of propagating vibrations the result of averaging at all points is approximately the same and the image of the object is characterized by uniform illumination.

A different holographic method involving double exposure is used more widely.[78] In this method the same carrier (medium) is used to record a hologram at two moments in time. The time required for a single exposure is now short compared with the vibration period. In the process of reconstruction of a hologram the object waves corresponding to different moments in time interfere. Their interference results in an inhomogeneous distribution of the illumination in the image of the object. This distribution is now described by the expression

$$\cos^2\left(\frac{4\pi}{\lambda_{opt}}\frac{\xi_1-\xi_2}{2}\right),$$

where ξ_1 and ξ_2 are the amplitudes of the vibrations at the two moments of exposure. Variation of the time interval between the exposures makes it possible to investigate vibrations of different frequencies, including propagating vibrations.

The next method—holographic interferometry in real time—involves recording of a hologram of an object in the absence of vibrations; subsequently, an object wave reconstructed with the aid of this hologram interferes with a signal wave, i.e., a wave scattered by a vibrating object or by an interface between media perturbed by acoustic vibrations. Such interference again produces an inhomogeneous distribution of the illumination in the image of the object. The illumination is described then by

$$I_s(u,\ v)=I_s(x,\ y)\left[1+J_0\left(\frac{4\pi}{\lambda_c}\xi(x,\ y)\right)\right]. \qquad (11)$$

The method of holographic interferometry in real time makes it possible to observe changes in the vibration pattern. However, if in the course of observation an object is subject to displacements and deformations, the pattern of the distribution of the amplitude of the vibrations becomes distorted because the object wave reconstructed from a hologram is not the true object wave.

These problems are avoided in a method in which a hologram of an object is recorded by a television camera and the distribution of vibrations is displayed on a television screen after suitable electronic processing of the video signal.[80] In the literature outside the Soviet Union this method is known as electronic speckle pattern interferometry (ESPI). In the ESPI method an image of an object is formed in coherent light on the sensitive area of a television camera and a reference beam of coherent light is directed to the same area. The intensity distribution includes a slowly varying constant background as well as interference fringes characterized by a contrast which depends on the amplitude of the vibrations of an object in the same way as in the multiple exposure method. Therefore, a high-frequency component is present in the video signal against the background of a constant component. After filtering and square-law detection, the video signal represents the distribution of the contrast in the interference pattern and this is displayed on a television screen. The ESPI method can be used to detect vibrations down to 10^{-11} m in amplitude.[80,81]

3.8. Dynamic holographic methods

Materials, in which changes in the optical properties occur directly under the action of optical radiation and a hologram disappears in the absence of illumination, have been used recently to record holograms.[82] A hologram formed in this way is known as dynamic. Changes in the optical properties of a material under the influence of light are due to its optical nonlinearity. The third-order optical nonlinearity is used in dynamic holography.[77,82] Reconstruction of an object (investigated) optical beam in dynamic holography occurs simultaneously with the recording of a hologram, i.e., in the presence of the true object wave. The difference between the reconstructed and object waves may give rise to a variety of effects: enhancement, weakening, shift of the phase of the object wave, or time modulation of the object wave when the reference wave is modulated (Fig. 16). The development of the principles of holography and of high-sensitivity fast-response materials have made dynamic holography attractive to investigators employing optical methods in studies of dynamic processes.[83,84]

Dynamic holography methods make it possible not only to apply all the principles developed for the study of vibrations in conventional holography, but also opens up new opportunities. In the case of materials for which the hologram recording and decay times are long compared with the characteristic time scale of the investigated effect (for example, the vibration period), dynamic holography provides a natural opportunity for implementation of holographic interferometry in real time. A hologram records only the interference pattern which is averaged over one interference period.[84,85] A wave reconstructed by such a hologram has a phase front coinciding exactly with the phase

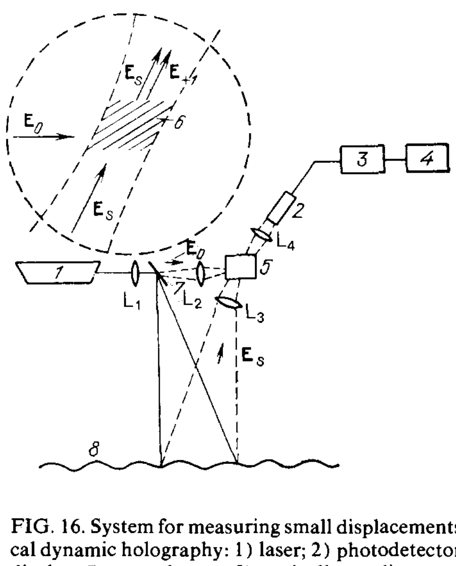

FIG. 16. System for measuring small displacements of the surface by optical dynamic holography: 1) laser; 2) photodetector; 3) amplifier filter; 4) display; L_{1-4} are lenses; 5) optically nonlinear medium; 6) interaction region; 7) semitransparent mirror; 8) displacements of the surface; $\mathbf{E}_0$ is the intensity vector of the optical reference wave; $\mathbf{E}_s$ is the field vector of the object wave; $\mathbf{E}_{+1}$ is the component of the reference wave diffracted by a phase grating in the optically nonlinear medium.

front of the signal wave, i.e., the optical wave reflected from the investigated object. Interference between these waves results in demodulation of the investigated phase-modulated wave.[84,85]

Demodulation of phase-modulated light may occur in dynamic holography not only in the case of the relationship between the time constants indicated above. Any medium suitable for dynamic holography transforms the modulation of interacting light beams because of relaxation and inertial properties of the medium.[82] Under dynamic holography conditions it is possible to demodulate phase-modulated light with an arbitrary phase front, in contrast to conventional interferometry for the investigation of small vibrations.[86-88] The use of dynamic holography makes it possible, in principle, to improve considerably the sensitivity of interferometers in the determination of small vibrations under conditions when phase distortions are present in the probe beam.[67,86-88]

Extensive opportunities are provided by the circumstance that dynamic holography can be used for the reversal of the wavefront of the investigated wave in real time by reconstruction ("readout") of a hologram with a coherent optical beam traveling opposite to the reference beam.[89] This property is employed in the method of two-exposure holographic interferometry in real time with wavefront reversal.[89] The essence of the method is as follows (Fig. 17).[90,91] A light beam is transmitted by an investigated object characterized by moving phase inhomogeneities and it is used to record a dynamic hologram in an optically nonlinear material. The object beam is then interrupted by a shutter and a hologram is illuminated with a light beam traveling opposite to the reference beam. The reconstructed reversed wave passes for the second time through the object and interferes with an elastic reference wave on the screen of the recording device (television tube). The interference pattern reflects the changes which have occurred in the object during the time between the exposure of the hologram and the reconstruction of the reversed front. Variation of this time makes it possible to investigate selectively the processes characterized by different time scales.

All these holographic methods can be used to study vibrations of the surface of the investigated object and also the phase modulation of light which occurs during propagation in an optically transparent medium in the presence of an acoustic wave.[80]

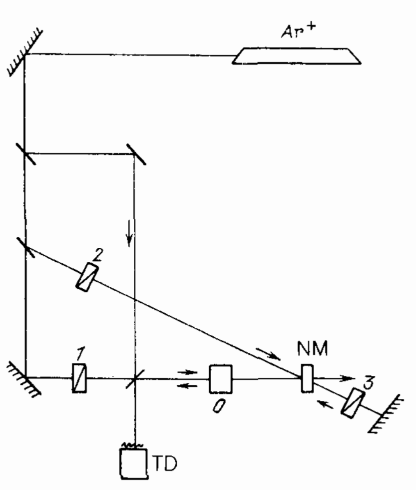

FIG. 17. System for two-exposure holographic interferometry in real time. Here, Ar^+ is an argon ion laser; 1)–3) optical shutters; NM is a nonlinear material; O is an object; TD is a television display.

We shall conclude by noting that the noise and the sensitivity of the holographic methods determined by it depend on the method of recording of the resultant intensity distribution. In the photographic recording method the main contribution to the noise comes from the graininess of the photographic emulsion, in which case the sensitivity usually does not exceed $\lambda_{opt}/4$ (Ref. 78). One can also use photoelectric recording, in which case the sensitivity is considerably higher and it is governed by the shot noise and by the speckle inhomogeneity of the investigated field.

Some techniques for increasing the sensitivity have been developed for holographic interferometry. One of the most widely used involves modulation of the phase of the reference beam at the frequency of the investigated vibrations.[92,93] Then—for example—if the method of multiple exposure is used, the distribution of the illumination of an object is given by the expression

$$I(u, v) = I_0(u, v) J_0^2 \left(\frac{4\pi}{\lambda_c} [a^2(x, y) + m^2 - 2ma(x, y) \times \cos(\varphi(x, y) - \varphi_2)] \right), \quad (12)$$

where m and φ_2 are the amplitude and phase of modulation of the reference beam; a and φ are the amplitude and phase of the vibrations of the object. We can see that apart from increasing the sensitivity in the case when $m \geqslant 1$, the intensity distribution carries also information on the phase of the vibrations of the object.[92,93] Holographic methods for the investigation of acoustic fields open up extensive opportunities and are being developed rapidly on the basis of new ideas in holography.

4. FIBER-OPTIC SOUND DETECTORS

Fiber and integrated optics has become an independent field of applied research about 15 years ago. This field is developing explosively because of the availability of lasers and construction of fiber-optic waveguides. The appearance of low-loss optical fibers has stimulated progress in the development of integrated systems which incorporate miniature laser sources and photodetectors. Progress in the development of low-loss fibers with specified parameters, miniature laser sources, and photodetectors has made it possible to begin the development of fiber-optic sound detectors (FOSD).

Fiber-optic sound detectors are based on the following idea. The transmission of sound by a medium in which light is propagating alters the optical path of light and this changes the phase of the optical wave. The change may be detected by the usual interferometric methods. Under certain conditions we can expect the following other mechanisms of the acoustooptic interaction to play a significant role: the Raman-Nath diffraction, the isotropic and anisotropic Bragg diffraction, and several other effects. In general, an acoustic field interacts in a complex manner with an optical wave causing amplitude, polarization, and frequency-phase modulation of the latter. A similar effect is exerted by sound generally on any medium. However, fiber waveguides are particularly suitable for the detection of sound because a considerable length of the acoustooptic interaction region can be ensured in view of the low losses in fibers.

The magnitude of modulation is generally proportional to the length of the acoustooptic interaction region and to the acoustic pressure. Therefore, a sufficiently general characteristic of a fiber waveguide as the sensitive element of an FOSD is provided by the coefficient of proportionality between the modulation index (representing modulation of the amplitude, polarization, phase) and the product of the length of the acoustooptic interaction region and the acoustic pressure. For example, in the phase modulation case this quantity is

$$\beta := \frac{\Delta\Psi}{\Psi p} = \frac{\Delta\Psi}{k_{\mathrm{opt}} L p}$$

(in some cases use is made of $\beta = \Delta\Psi/pL$), where $\Delta\Psi$ is the modulation index of the phase Ψ in the length L of the acoustooptic interaction region; p is the amplitude of the acoustic pressure; k_{opt} is the wave number of light in the fiber waveguide. Similarly, in the amplitude modulation case we have $\beta = \Delta P/pLP$, where $\Delta P/P$ is the modulation index of the optical power at the exit from a fiber waveguide. Since the factor β is governed by the properties of the waveguide, it is convenient to call β the sensitivity of the fiber waveguide in contrast to the sensitivity of an FOSD, which is defined as the increment in the alternating component of the voltage at the photodetector output u_{out} to the acoustic pressure p, i.e., $M = u_{\mathrm{out}}/p$. The sensitivity M, measured in microvolts per pascal, is a generally accepted characteristic of sound detectors. However, in the case of FOSD it is not always convenient because it depends strongly on the nature and parameters of a photodetector (on its gain and load resistance) and does not allow for the intrinsic noise in an FOSD. Therefore, FOSD are frequently described by a sensitivity threshold or the noise-equivalent level of the acoustic pressure p_{th}, i.e., by the minimum acoustic pressure which can be detected by an FOSD at the intrinsic noise level. The sensitivity threshold depends on the sensitivity M and on the intrinsic noise level u_{n} at the detector output. It is usual to assume that $p_{\mathrm{th}} = u_{\mathrm{n}}/M$.

The simplest FOSD represents an interferometric system (Fig. 18) with a signal waveguide subjected to an acoustic field in one arm and a reference waveguide protected from sound in the other arm. The reference and signal light beams produce an interference pattern on the photocathode of a photodetector and the nature of this pattern is determined by the interaction between the acoustic field and the signal waveguide. An electric signal of acoustic frequency is observed at the photodetector output.

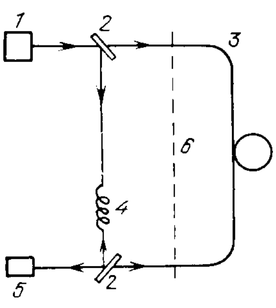

FIG. 18. Fiber-optic sound detector: 1) laser; 2) beam-splitting plate; 3) signal lightguide; 4) reference lightguide; 5) photodetector; 6) atmosphere-liquid interface.

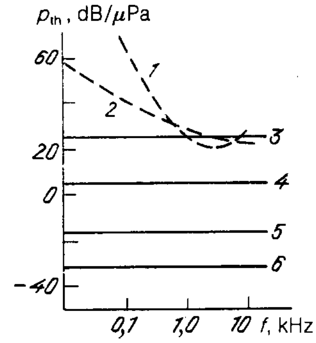

FIG. 19. Comparative characteristics of sensitivity thresholds of piezoelectric and fiber-optic sound detectors[95]: 1) audibility threshold; 2) N56 piezoelectric hydrophone; 3)–6) theoretical sensitivity limit of fiber-optic sound detectors utilizing fiber waveguides of different lengths L = 1, 20, 100, and 1000 m (curves 3, 4, 5, and 6, respectively).

The great interest in FOSD is due to the advantages of these sound detectors over conventional (for example, piezoelectric) acoustic detectors: simplicity, small mass, simpler and compact analysis system, considerable interaction length, which makes it possible to achieve a high sensitivity or a low sensitivity threshold (Fig. 19), and a specified directionality. The flexibility of the sensitive element in the form of a fiber makes it possible to construct FOSD in the form of a great variety of configurations (see, for example, Fig. 20). Fiber-optic sound detectors are practically insensitive to electromagnetic strays and can readily withstand corrosion.

Many theoretical and experimental papers (including reviews[94-96]) have been published on the subject of FOSD.

4.1. Fiber-optic sound detectors based on amplitude modulation

Amplitude modulation of light propagating in a fiber lightguide is primarily due to the appearance of additional losses as a result of the interaction of acoustic vibrations with a fiber.[97] These are, firstly, the losses at bends and microbends, secondly, the losses due to the diffraction of light by sound (at sufficiently high frequencies) and, thirdly, the losses due to a reduction in the numerical aperture of a fiber under the action of acoustic vibrations.[98] The main role is played by the losses at bends and microbends. It has been established experimentally[97] that such losses cause modulation of the intensity of light propagating in a lightguide and this modulation represents a few percent of the intensity. The modulation efficiency is largely determined by the static configuration of a fiber and by the vibration frequency. A

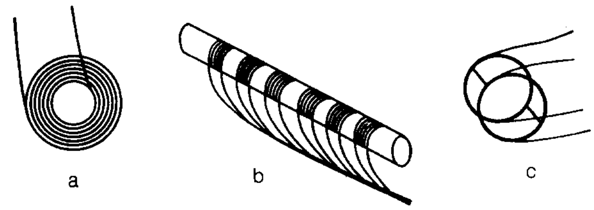

FIG. 20. Configuration of a lightguide in fiber-optic sound detectors[95]: a) flat configuration (ring in a plane); b) linear configuration of detector; c) pressure gradient detector.

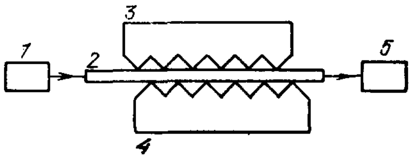

FIG. 21. Fiber-optic sound detector based on microbending of a waveguide: 1) laser; 2) waveguide; 3), 4) plates with corrugated surfaces; 5) photodetector.

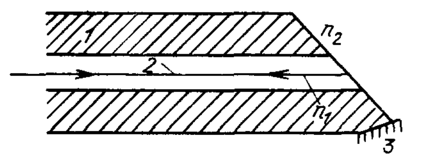

FIG. 23. Sound detector with critical angle modulation: 1) fiber lightguide cladding; 2) lightguide core; 3) reflecting coating; n_1 and n_2 are the refractive indices of the core of the lightguide and of the ambient medium.

linear dependence of the modulation of the intensity of light in a fairly wide range of amplitudes of sound has also been established.[97]

An FOSD shown schematically in Fig. 21 is characterized by a fairly high sensitivity.[99-101] The sensitive element is a multimode optical fiber. Microbending of this fiber due to the action of an acoustic pressure causes interaction between the optical modes and this redistributes the energy between the modes. Some of the energy of the modes in a fiber core penetrates to its cladding and causes amplitude modulation of the optical wave. The interaction occurs between optical modes with the propagation constants $k'_{\rm opt}$ and $k''_{\rm opt}$, satisfying the relationship $k'_{\rm opt} - k''_{\rm opt} = \pm 2\pi\Lambda$, where Λ is the spatial scale of the bend. It was established experimentally[99] that the sensitivity threshold $p_{\rm th}$ of an FOSD shown schematically in Fig. 21 was 60 dB/μPa and the minimum detected vibrational displacement of particles in a medium was 0.8 Å. It is pointed out in Ref. 95, where the results of Ref. 99 are discussed, that the measurements reported in the latter case were not carried out under the optimal detection conditions so that a further increase in the sensitivity of the detector should be possible. The frequency characteristic of the detector was found to be uniform in the frequency band 20–1100 Hz, but in the region of 100 and 200 Hz the sensitivity rose significantly. The dynamic range of this detector exceeded 110 dB.

Different amplitude modulation mechanisms were used in the detectors shown schematically in Figs. 22 and 23. When the cores of two single-mode optical fiber lightguides are located close to one another (within a few microns) over a certain distance (amounting to several centimeters), then—as shown in Fig. 22—light may penetrate from one fiber to another. Such a wave interaction is very sensitive to acoustic fields. Determination of the sensitivity[102] (when the separating medium was water and the interaction length was $L = 4$ cm) gave $M = -212$ dB·V^{-1}·μPa^{-1} and $p_{\rm th} = 52$ dB/μPa. In the experiments described in Ref. 103 the sensitivity threshold of a similar FOSD was 50 dB/μPa; the limiting factor was the shot noise in the photodetector. An important feature is that in a detector of this kind it is possible to replace quite successfully a single-mode lightguide with a multimode one.[104] It should be pointed out that the FOSD shown schematically in Fig. 22 may be very difficult to manufacture on an industrial scale because of the extremely high precision necessary in the fabrication. This applies also to sound detectors with modulation of the critical angle[105] (Fig. 23). In the latter case the sound is detected by an optical ray reflected from the interface between two media with different refractive indices at an angle close to the internal reflection angle. The use of an optical fiber in such a sound detector avoids many problems associated with the need to generate and direct a plane optical wave to an interface at the required angle with a sufficiently high accuracy. In an FOSD of this type a single-mode fiber is cut at an angle slightly smaller than the critical value. If the critical angle is not close to 45°, an additional cut is necessary to ensure that the ray returns to the core. An acoustic pressure alters the refractive index of the core n_1 and of the cladding n_2 of a fiber by different amounts and shifts the critical angle slightly, and this alters the power of the reflected light. The sensitivity of such an FOSD can be calculated from[105]

$$M = qRP_0\cdot 4nK\,(n_2^2-1)\,\frac{n_2^2+2}{6n_1n_2\cos^2\Theta\,(n_2-\sin^2\Theta)^{1/2}}\ ;$$

here and later we shall use the following notation: n_1 and n_2 are, respectively, the refractive indices of the core of a fiber and of an external medium; Θ is the angle of incidence; $n = n_2/n_1$; K is the compressibility of the outer medium (it is assumed that it is much higher than the compressibility of the fiber material); q is the sensitivity of the photocathode of a photodetector; R is the load resistance of the photodetector; P_0 is the optical power reaching the photocathode; e is the electron charge; Δf is the frequency band of the FOSD. The sensitivity threshold can be calculated from[105]

$$p_{\rm th} = \left(\frac{2e\Delta f}{qP_0}\right)^{1/2}\cdot\frac{6n_1n_2\cos^2\Theta\,(n^2-\sin^2\Theta)^{1/2}}{4nK\,(n_2^2-1)\,(n_2^2+2)}\ .$$

When the outer medium is water and $\Theta - \Theta_{\rm cr} = 0.02$, estimates give $M = -261$ dB·V^{-1}·μPa^{-1} and $p_{\rm th} = 101$ dB/μPa. This relatively low sensitivity can be greatly enhanced by selecting the cut to be close to the critical angle. The main advantage of this detector is that it can be used in situations when its dimensions have to be very small.

In the above FOSD with amplitude modulation of the intensity of light the sensitive element is the optical fiber itself. However, there are also FOSD in which a fiber is used only to transmit light from the point of measurement to a

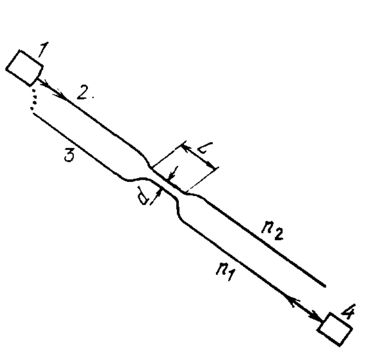

FIG. 22. Fiber-optic sound detector with light tunneling[105]: 1) laser; 2), 3) cores of lightguides; 4) photodetector; L are the interaction lengths; n_1 and n_2 are the refractive indices of the core materials in the lightguides; d is the separation between the cores.

photodetector. Sound then modulates the amount of light entering the end of a fiber.[95,105-109]

It follows from the above analysis that FOSD based on amplitude modulation are characterized by a relatively high sensitivity, can be constructed from multimode lightguides, and in most cases have a simple configuration. However, on the whole, they are inferior in sensitivity to detectors based on polarization and phase modulation methods.

4.2. Fiber-optic sound detectors based on polarization modulation

In a straight single-mode fiber of perfectly circular cross section in the absence of any stresses it is possible to propagate two degenerate optical radiation modes. The state of the polarization of light traveling in such a fiber remains constant. The various inhomogeneities in a real fiber result in the interaction between these two modes, so that beats are generated and energy is exchanged between the modes. The state of polarization of light along a fiber is affected and a real fiber lightguide behaves as an anisotropic (birefringent) crystal.[110-114] The birefringence of a fiber is generally due to internal (noncircular cross section of the core, residual transverse stresses) and external (transverse force, twisting, bending) factors.[115] It is therefore possible to control the polarization of optical radiation transmitted by a fiber lightguide without breaking up the light-conducting system. In the absence of losses any segment of a fiber can be regarded as an ideal phase plate. Such a plate can be described by a suitable Jones matrix[116-118] with parameters dependent on the internal and external factors mentioned above. Experiments do indeed confirm that some types of single-mode fiber lightguides behave as linear phase plates. It is possible to use a Jones matrix for such fibers and show that external inhomogeneous stresses give rise to polarization modulation of an optical wave. Consequently, if a polarization-sensitive photodetector is located at the exit from a fiber lightguide, then the polarization modulation gives rise to components of the detector current alternating at the modulation frequency.

The method of polarization modulation is used to detect sound in, for example, detectors of the type shown schematically in Fig. 24. This FOSD (described in Ref. 119) consists of a laser source 1 and a single-mode optical fiber 2 bent uniformly relative to its axis and subjected to an acoustic wave field in such a manner that an acoustic pressure creates anisotropic stresses in the fiber material. These stresses can be generated by, for example, placing the fiber in a recess of cylinder 3 or by bonding a fiber externally to the cylinder wall. In this configuration of a sound detector an external pressure alters the birefringence of the lightguide. The sign of the change in the birefringence and its magnitude

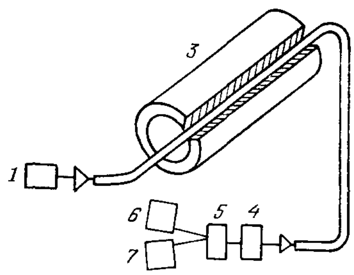

FIG. 24. Fiber-optic sound detector based on polarization modulation.

depend on the orientations of the principal axes of the ellipsoid of the refractive index of the lightguide relative to the surface of the cylinder. A Babinet compensator 4 is located at the lightguide exit and it is tuned in such a way that the difference between the phases of the rays with polarizations corresponding to the principal axes of the fiber is $\pi/2$ (in the absence of sound). Beyond the compensator the rays are separated spatially by a Wollaston prism 5 and are directed to photodetectors 6 and 7. The signals from the photodetectors were analyzed in an experiment[119] by a spectrum analyzer. A sound detector based on this polarization modulation method was described in Ref. 120 (Fig. 25).

Advantages of the polarization FOSD include their simplicity and reliability. They differ from the detectors based on amplitude and phase modulation by less stringent conditions for the optimization of reception and by a relatively high stability when temperature is varied.

4.3. Fiber-optic sound detectors based on phase modulation

Phase modulation of light in an optical fiber under the influence of sound is due to several mechanisms, such as the change in the refractive index of the core of the fiber (photoelastic effect), a change in the length of the fiber, and a change in the diameter of the core (Poisson effect). These mechanisms make contributions of the same order of magnitude under the influence of longitudinal or transverse stresses.[121] However, in the case of longitudinal stresses the phase shift is influenced more by the change in the fiber lightguide length, whereas in the case of transverse stresses it is affected more by the change in the refractive index.

Practically all FOSD utilizing phase modulation are interferometers. Selection of a particular interferometer is determined by the specific tasks and experimental conditions or applications of a fiber-optic detector. The most frequently utilized interferometers are of the Mach-Zehnder, Fabry-Perot, and differential types. Each of them has its own advantages and shortcomings.

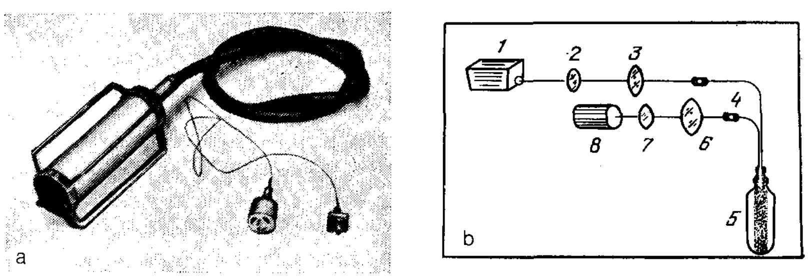

FIG. 25. External appearance (a) and schematic representation (b) of a fiber-optic sound detector based on polarization modulation developed at the N.N. Andreev Acoustics Institute. 1) Laser; 2) quarter-wave plate; 3), 6) lenses; 4) fiber lightguide; 5) sensitive component in the form of a lightguide; 7) Polaroid; 8) photodetector.

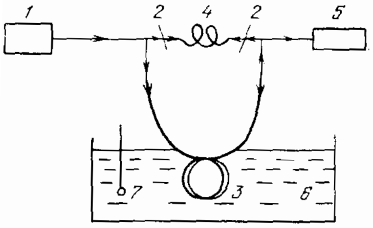

FIG. 26. Fiber-optic sound detector with a Mach-Zehnder interferometer: 1) laser; 2) beam-splitting plates; 3) signal lightguide; 4) reference lightguide; 5) photodetector; 6) bath with liquid; 7) source of sound.

4.3.1. Mach-Zehnder interferometer

In a Mach-Zehnder interferometer (Fig. 26) a laser beam is split by a plate into two components, one of which serves as a signal beam and the other is isolated from the acoustic field and acts as a reference beam. The acoustic field modulates only the signal beam. The use of the Mach-Zehnder interferometer in an FOSD ensures an exceptionally high sensitivity, which is not inferior to the sensitivity of the best piezoelectric detectors. Adopting the standard calculation method of Refs. 122–127, we obtain the following formula for the sensitivity threshold of an FOSD with the Mach-Zehnder interferometer:

$$p_{\text{th}} = \frac{[hc\Delta f\,(P_1+P_2)/P_1P_2\cdot 4\pi\eta K]^{1/2}}{\gamma L\,[(n^3/2)\,(q_l+2q_t)-(k/3K)]}; \tag{13}$$

here h is the Planck constant; c is the velocity of light; Δf is the pass band of the FOSD; P_1 and P_2 are the powers of the signal and reference light beams incident on the photocathode; η is the quantum efficiency of the photomultiplier; K is the bulk modulus of the fiber core material; γ is the homodyne efficiency of the photocathode of a photodetector; L is the length of the acoustic interaction region; q_l and q_t are the longitudinal and transverse elastic moduli of the core material; n is the optical refractive index of the core material.

We shall now discuss Eq. (13) in greater detail. First of all, we can see that the value of p_{th} is smallest when the optical powers of the interfering beams are equal, i.e., when $P_1 = P_2$ (under the condition that $P_1 + P_2 = \text{const}$). There is also an optimal length L of a waveguide,[128] because the power of the optical radiation P_0 at the entry to the waveguide is given and it falls exponentially with distance because of the attenuation of light in the fiber. We can show that the optimal interaction length is $L_{\text{optim}} = 8.7/\alpha$, where α is the attenuation of light in the waveguide (dB/km) and L_{optim} is the length (km).

Under the optimal conditions, i.e., when $P_1 = P_2 = P_0/2$ and $L_{\text{optim}} = 8.7/\alpha$, the expression for the sensitivity threshold becomes

$$p_{\text{th}} = \left(\frac{hc\Delta f}{2\pi\eta k_{\text{opt}} P_0}\right)^{1/2} \alpha \left\{8.7\gamma\left[\frac{n^3}{2}\,(q_l+2q_t)-\frac{n}{3}\,K\right]\right\}^{-1}. \tag{14}$$

We shall demonstrate the potentialities of an FOSD with the Mach-Zehnder interferometer by numerical estimates. By way of example, we shall assume that a lightguide is made of borosilicate crown glass, characterized by $\alpha = 10$ dB/km, $q_l = 0.315\times10^{-12}$ Pa^{-1}, and $q_t = 1.92\times10^{-12}$ Pa^{-1}. We shall also assume that $\eta = 0.2$, $\gamma = 0.5$, $P_0 = 1$ mW, $\Delta f = 1$ Hz, $K = 4.23\times10^{10}$ Pa, $n = 1.5$, and the optical wave number is $k_{\text{opt}} = 10^7$ m^{-1}. Substituting these values in Eq. (14), we find that $p_{\text{th}} = 3$ dB/μPa for the optimal length $L_{\text{optim}} = 870$ m.

Estimates indicate that for realistic lengths of the fiber waveguides and low optical powers, we can detect acoustic vibrations much weaker than those corresponding to noise levels in the ocean.

The shortcomings of a detector based on the Mach-Zehnder interferometer is its poor immunity to noise in the presence of stray perturbations of the phase shift between the reference and signal beams due to mechanical vibrations and not due to the acoustic wave. The detector is also perturbed by fluctuations of the temperature and stresses in the light-conducting medium. Some ways of reducing the influence of these factors on the operation of this detector will be considered later.

4.3.2. Fabry-Perot interferometer

The Fabry-Perot interferometer is very effective when used to detect sound in fiber-optic devices.[129-131] An FOSD with the Fabry-Perot interferometer is usually a single-mode fiber lightguide with reflecting coatings at its ends (Fig. 27). Such a detector exhibits a high sensitivity per unit length of the fiber and a high optical stability, but suffers from the shortcoming that the dimensions of the fiber lightguide are limited by the coherence length of laser radiation. The sensitivity of this FOSD is usually of the same order of magnitude as the sensitivity of a detector with a Mach-Zehnder interferometer.

The advantage of a detector with a Fabry-Perot interferometer compared with that with a Mach-Zehnder interferometer is the much higher immunity to variations in temperature and external vibrations. This immunity is due to the fact that the interfering light beams travel along the same fiber. The shortcoming of the detector under consideration is the restriction of the length of the fiber to the coherence length of laser radiation, which is a fairly serious problem, so that a detector with a Mach-Zehnder interferometer is preferable if long waveguides have to be used.

4.3.3. Differential interferometer

An FOSD with a differential interferometer (Fig. 28) is a variant of a ring interferometer in which light propagates along two opposite directions in a ring after splitting by a suitable beam splitter. Part of the waveguide ring is exposed to an acoustic field whereas the other part is isolated from this field. The two light beams (each propagating in its own direction) are modulated by the acoustic waves, but this occurs at different times because one of them reaches the acoustic field region directly after the beam splitter and the other has to pass through the ring in the opposite direction creating a delay. Hence, two-beam interference occurs in the photodetector. The advantage of a sound detector with the

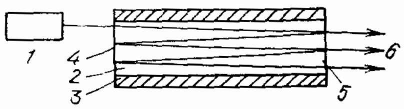

FIG. 27. Fiber-optic sound detector with a Fabry-Perot interferometer: 1) light source; 2) core of lightguide; 3) cladding of lightguide; 4), 5) reflecting surfaces; 6) transmitted optical beams which have experienced different orders of reflection.

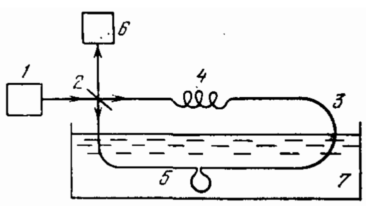

FIG. 28. Fiber-optic sound detector with a differential interferometer: 1) laser; 2) beam-splitting plate; 3) lightguide; 4) delay arm; 5) region of interaction with an acoustic wave; 6) photodetector; 7) bath with liquid.

differential interferometer over the more traditional Mach-Zehnder interferometer is a higher immunity to external vibrations and temperature variations.[98] The influence of temperature on an FOSD with the differential interferometer is at least three orders of magnitude less.[132] However, the sensitivity of such a sound detector is relatively low and the detector is much inferior in this sense to fiber-optic sound detectors with the Mach-Zehnder or Fabry-Perot interferometers.

Table I gives the expressions for the sensitivity thresholds of FOSD based on phase modulation and utilizing the three interferometers discussed above.

The validity of the calculations of the sensitivity of FOSD given above has been confirmed experimentally on many occasions.[122-124,126,133] A satisfactory agreement between numerical estimates and the results of experiments has been established. By way of example, Table II gives the experimental results demonstrating a fully satisfactory agreement with the theory. The experiments were carried out on detectors with a Mach-Zehnder interferometer. The optical powers in the reference and signal beams were $P_1 = P_2 = 9.5$ nW, a signal lightguide of length 1 m was in the form of a ring $D = 5$ cm in diameter, the sensitivity of a photodetector was $\gamma = 2100$ A/W, and the load resistance of this photodetector was $R = 50\ \Omega$. An optical fiber with losses of $\alpha = 0.25$ dB/m at $\lambda = 632.8$ nm was employed.

In the sound detectors based on phase modulation it is usual to employ single-mode fiber lightguides. However, multimode fiber lightguides have been used as sensitive elements in phase-modulation FOSD.

Relatively little work has been done on multimode FOSD. Difficulties are encountered in a theoretical analysis when the wave equation is being solved for a fiber lightguide with a complex refractive index in order to determine the mode structure. The problem is essentially soluble only for a narrow class of the refractive index profiles.[134-136] For example, the theoretical sensitivity of sound detectors based on multimode fiber lightguides with a rectangular refractive index profile was considered recently in Ref. 137.

4.4. Influence of a lightguide coating on the sensitivity of fiber-optic sound detectors

Real lightguides have not only a core and a cladding (or several claddings) but usually an external protective coating. Various resins, thermally stable plastics and elastomers irradiated with ultraviolet radiation, are normally employed as coatings.

The selection of the coating can increase or reduce the sensitivity of a fiber lightguide to the acoustic interaction and, therefore, it can alter the sensitivity of an FOSD. For example, the sensitivity of a single-mode fiber lightguide with a plastic coating (of the Hytrel type) increases on an increase in the coating thickness.[95] The sensitivity of a fiber lightguide rises on an increase in the coating thickness but not without limit and when a certain value of this thickness is reached, there is a tendency to approach asymptotically a constant value which is governed by the bulk modulus of the coating material.

In selecting the coating material we must bear in mind that the coating alters somewhat the frequency characteristic of a sound detector. This effect is small in the case of nylon and considerable for elastomers irradiated with soft ultraviolet. The latter materials can be used as an acoustic filter selecting only high-frequency acoustic signals.[95] We have mentioned earlier that the selection of a coating can not only increase, but also reduce the sensitivity of a fiber lightguide to an acoustic interaction. The reduction can be achieved by, for example, a coating made of a metal or of certain types of glass. The reduction in the sensitivity by a coating is very convenient in, for example, a reference lightguide or in that part of the signal lightguide which is used for transmission.

4.5. Noise in fiber-optic sound detectors

In the above expressions for the FOSD sensitivity the limiting factor is assumed to be the shot noise of the photodetector. However, in some cases noise of a different origin predominates: the laser noise due to instability of the emission; the noise in the surrounding medium caused by temperature fluctuations and random external stresses (vibrations), etc.[95,138]

Temperature fluctuations and vibrations are most important in the case of phase-modulation sound detectors

TABLE I. Sensitivity threshold p_{th} of fiber-optic sound detectors based on interferometric systems.

Interferometer	p_{th}
Mach-Zehnder	$\left(\frac{h_c c\Delta f}{2\pi k P_0}\right)^{1/2}\left[\beta L T\left(\frac{\partial n}{\partial \rho}+\frac{n}{L}\frac{\partial L}{\partial \rho}\right)\right]^{-1}$
Fabry-Perot	$\xi\left(\frac{hc\Delta f}{2\pi k P_0}\right)^{1/2}\left[\beta L T\left(\frac{\partial n}{\partial \rho}+\frac{n}{L}\frac{\partial L}{\partial \rho}\right)\right]^{-1}$
Differential	$c\left(\frac{hc\Delta f}{2\pi k P_0}\right)^{1/2}\left[\beta l_2 T \omega_s (l_1-l_3)\, n\left(\frac{\partial n}{\partial \rho}+\frac{n}{l_2}\frac{\partial l_2}{\partial \rho}\right)\right]^{-1}$

TABLE II. Comparison of experimental and theoretical results of recording of sound by a fiber-optic sound detector.

Detector characteristics	Theoretical values	Experimental values
p_{th}, $dB \cdot \mu Pa^{-1} \cdot Hz^{-1/2}$	121	119
M, $dB \cdot V^{-1} \cdot \mu Pa^{-1}$	−268	−264

with systems similar to the Mach-Zehnder interferometer. These factors create fluctuations of the initial phase shift, which is equivalent to an additional acoustic interaction with the sensitive element of a detector. For example, the temperature coefficient of the change in the phase between 20 and 75 °C is 1.3 rad/°C for a single-mode fiber.[132] A strong influence of temperature on the phase is due to thermal expansion of matter. The influence of vibrations affects primarily the ratio of the lengths of the interferometer arms. Passive and active suppression methods have been used to reduce the influence of these factors.[68,139–141]

Active methods for suppression of stray perturbations can be used if the frequency ranges of vibrations and temperature fluctuations do not overlap the range of the investigated acoustic field frequencies. As a rule, the spectrum of destabilizing perturbations lies at low frequencies. Therefore, active methods are suitable for the investigation of acoustic waves of relatively high frequencies. Fluctuations of the initial phase shift in the interferometer can be compensated by an electrooptic or electromechanical servo system which alters the length of the reference arm.[73] An electromechanical servo system displacing the interferometer mirror can also be used.[142–144]

Passive methods usually involve rigid mounting of the components of an optical system, use of integrated-optics elements, protective coatings of lightguides characterized by low thermal conductivity, and special types of construction.

An analysis of the noise in phase-modulation FOSD allowing for laser noise is made in detail in Ref. 145, where the influence of the laser parameters and of the interferometric system on the threshold sensitivity of a sound detector is considered specifically. Fluctuations of laser radiation are due to natural and technical factors. Natural fluctuations are due to the atomic structure of the active material and the quantum nature of radiation. Obviously, it is impossible to eliminate natural fluctuations but they can be reduced by, for example, increasing the laser power.[146–148] Technical fluctuations are normally much stronger than natural fluctuations. Technical fluctuations are due to deformation of the resonator, instability of pumping, fluctuations of a gas-discharge plasma, etc. There are various active and passive methods for reducing technical fluctuations. Passive methods involve, for example, an increase of the rigidity of the resonator and use of stabilized power supplies.[149] Active methods for reducing the amplitude noise of a laser include control of the pumping,[150] control of the output power by a magnetic field,[151] use of a controlled optical attenuator,[152,153] and a change in the resonator parameters.[150] Active stabilization of the laser frequency requires the use of electromechanical and electrooptical servo systems mentioned above.

Lowering of the noise in FOSD is a very important task which involves satisfying specific requirements in respect of the optical components of a detector, their structure, light sources, and photodetectors. Noise reduction should make it possible to use FOSD effectively in practice and to realize more fully their capabilities and advantages over piezoelectric ceramic detectors.

5. LASER-ACOUSTIC TECHNOLOGY

Lasers are used increasingly in modern industrial technology. Production efficiency will depend significantly on the development of laser technology. An important place in the task of increasing production efficiency and quality of products is, as before, occupied by ultrasonic technology. Combination of laser and ultrasonic technologies and the use of lasers for the excitation and detection of ultrasonic vibrations opens up new avenues for nondestructive quality control and for the influencing of the structure and physicochemical properties of materials.[1,154] Only two examples will be given concerning quality control of products and one concerning influencing the properties and structure of solids.

5.1. Laser-acoustic microscopy

Traditional methods for the investigation and visualization of small objects, such as optical or electron microscopy, suffer from a number of limitations. For example, optical and scanning electron microscopes have a high resolution, but they are not very suitable for the investigation of the interior of opaque materials. In the case of x-ray microscopes with television monitors there are difficulties in the interpretation of the images, particularly in the case of low-contrast objects.

These shortcomings are absent in the case of laser-acoustic (more usually called photoacoustic) microscopes.[155] The principle of operation of a photoacoustic microscope is the generation and propagation of acoustic (more precisely thermal) waves excited by probe laser radiation which is intensity-modulated. It should be noted that it is usual to ignore heat conduction in the generation of sound because the dimensions of the region where heat is evolved are always large compared with the thermal wavelength. In contrast, in the case of a photoacoustic microscope the laser beam is focused, the dimensions of the region in question are small, and thermal waves are of fundamental importance. Acoustic vibrations of an object are recorded with sound detectors. An acoustic signal depends on the local physical properties of the object so that an optoacoustic image of the object can be obtained by scanning it with a laser beam along two mutually perpendicular directions. In general, such an image is the result of three processes: variation of the absorbed power of laser radiation because of changes in the optical properties of the object from point to point; the interaction of thermal waves with thermal inhomogeneities in the object; the interaction of acoustic waves with elastic inhomogeneities of the object.

The first process carries information only on the absorption and reflection properties of the object. When this process predominates, an optoacoustic image is essentially identical with an optical image. The resolution of a photoacoustic microscope is then governed by the diameter of the probe laser beam, and the depth of visualization of the subsurface structure is determined by the depth of penetration of light. The second process involves the interaction of thermal waves with microinhomogeneities of the object and it carries basically new information, which greatly extends the range of data which can be obtained on the physical properties of the object. The third process provides information on mechanical irregularities of the object. It plays an important role if the acoustic wavelength is of the same order of magnitude as the dimensions of inhomogeneities of the object (this usually occurs at modulation frequencies exceeding 100 MHz). In this case an optoacoustic image is identical with an acoustic image (such as that obtained in an acoustic microscope) and the resolution is of the order of the acoustic (hypersonic) wave.

A typical photoacoustic microscope is shown in the schematic diagram of Fig. 29. A laser beam (which may be infrared, visible, or ultraviolet) is intensity-modulated and it scans the surface of the investigated object. Modulation is performed by mechanical or electrooptical methods. An acoustic signal from a detector is passed through a preamplifier to a lock-in detector. The output of this detector reaches some visualization device (display, X-Y plotter, storage oscilloscope) the sweep of which is synchronized with the system for scanning the laser beam.

Depending on the method for recording the acoustic signal, photoacoustic microscopes are divided into microphone and piezoelectric transducer systems. There are also photoacoustic microscopes in which the useful signal is recorded employing an auxiliary laser beam or a photodetector.

In the microphone variant a sample is placed in an optoacoustic cell[156–158] (Fig. 30) which consists of a hermetically sealed gas- or air-filled chamber with a window transparent to the probe laser radiation, as well as a microphone and an object holder. Acoustic vibrations generated in this chamber by a laser beam interacting with the object are detected by the sensitive microphone. In a photoacoustic microscope with a piezoelectric detector (Fig. 31) an object is in direct contact with a piezoelectric transducer which acts as a detector of volume acoustic waves.[159,160] In a photoacoustic microscope with recording of an optoacoustic signal using an auxiliary beam (Fig. 32) either the change in the optical refractive index of the medium in the layer of the object or the acoustic vibrations of the object are detected. The latter variant is particularly convenient in studies of surfaces with steps and recesses.[161]

Applications of photoacoustic microscopes include nondestructive profile analysis, which gives the structure of inhomogeneous layer materials, investigation of microcircuits (Fig. 33), determination of the chemical composition of complex compounds, studies of changes in the crystal structure of semiconductors as a result of ion implantation, visualization of bulk or surface regions characterized by different thermal characteristics because of the inhomogeneity of the crystal structure,[162] direct control of laser annealing,[163] studies of phase transitions in crystals,[164] and measurements of the thickness as well as monitoring of the uniformity of films deposited anodically on semiconductor substrates. Researchers working on the development of photoacoustic microscopes are very hopeful of applications not only in electronic industry, but also in medicine and biology.[165]

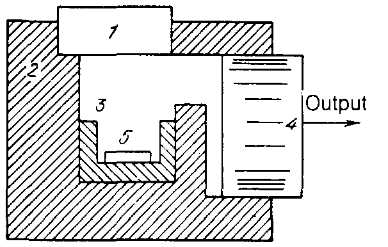

FIG. 30. Photoacoustic cell[155]: 1) entry window; 2) chamber wall; 3) sample holder; 4) microphone; 5) object.

The first reports on photoacoustic microscopy appeared about seven years ago. Intensive investigations are now proceeding at major laboratories throughout the world. The resolution of photoacoustic microscopes is inferior to that of optical and electron microscopes, but the images provide more information, since one can make visible details of the microstructure of objects which are opaque to photons and electrons, and this opens up new fields of application of microscopy which can greatly extend and supplement conventional methods of microscopic analysis.

Photoacoustic microscopes with electron excitation have been developed recently: in this case the role of a laser beam is performed by an electron beam.[166] Consideration has been given to the possibility of radiation-acoustic microscopy on the basis of the physical mechanisms of generation of acoustic, thermal, and other (for example, plasma) waves by beams of ionizing radiation.[167]

5.2. Optoacoustic sounding of an inhomogeneous condensed medium

A laser can excite acoustic signals of very large amplitude (up to tens or hundreds of atmospheres or more) in a condensed medium and, moreover, variation of laser radiation parameters can be used to control remotely the spatial, frequency-phase, and amplitude characteristics of acoustic fields generated in this way. Optical coherent methods have

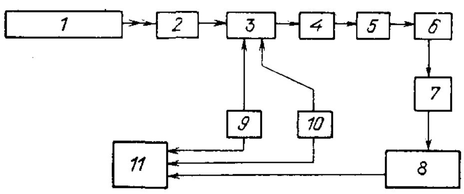

FIG. 29. Block diagram of a scanning photoacoustic microscope: 1) laser; 2) modulator; 3) scanning control system; 4) focusing system; 5) investigated object; 6) acoustic (thermal) transducer; 7) preamplifier; 8) lock-in detector (in the case of harmonically modulated laser radiation an amplitude- or phase-sensitive detector is used, whereas in the case of short pulses of optical radiation, a spectrum analyzer is required); 9), 10) oscillators controlling scanning and display; 11) visualization device.

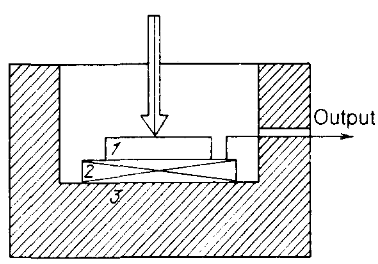

FIG. 31. Detection part of a photoacoustic microscope with a piezoelectric transducer[115]: 1) object; 2) transducer; 3) sample holder.

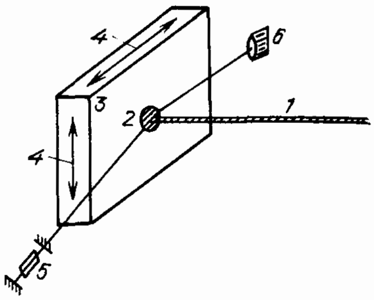

FIG. 32. Method for recording with the aid of an auxiliary laser beam[155]: 1) prob laser beam; 2) heated part of the object; 3) object; 4) directions of mechanical scanning; 5) auxiliary laser; 6) photodetector.

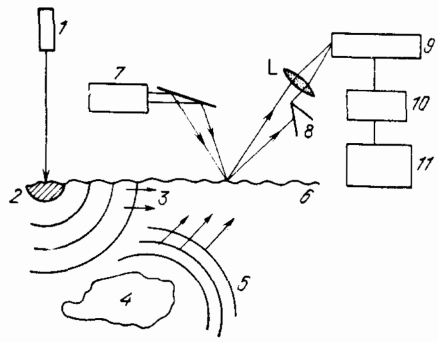

FIG. 34. Optoacoustic probing of an inhomogeneous condensed medium: 1) laser with a harmonically modulated intensity of the output radiation or pulsed laser; 2) optoacoustic antenna; 3) acoustic probe signal; 4) acoustic inhomogeneity of the medium; 5) acoustic waves scattered inhomogeneously; 6) boundary of the medium perturbed by the acoustic wave scattered by inhomogeneities in the medium; 7) laser; 8) edge of an opaque screen (knife edge); L is a lens; 9) photodetector; 10) amplifier filter; 11) indicator.

been developed for the study and detection of acoustic fields of very low amplitude. All this opens up the possibility of developing nontraditional optoacoustic or laser-acoustic methods for the sounding of inhomogeneous condensed media.

One of these methods[45] is illustrated in Fig. 34. A laser beam creates an acoustic signal in the investigated inhomogeneous medium and this signal is scattered by the inhomogeneities. Detection of the signal (scattered in the backward direction) is performed either by a second laser beam or by the beam used to excite the probe acoustic pulse. The detection or reception can be carried out by optical "readout" of the acoustic relief or acoustic vibrations of the surface of the investigated object. If this surface is subject to additional external perturbations and experiences relatively slow (compared with the frequency of sound) displacements, which are nevertheless large compared with the optical or acoustic wavelengths, the efficiency of detection can be retained and the immunity to external perturbations can be increased either by methods described in Refs. 68–70 or by utilizing self-diffraction of light and dynamics holography.[67,86–88,168]

Another optoacoustic method for probing inhomogeneous condensed media was proposed in Refs. 169 and 170. It is basically similar to photoacoustic microscopy with a piezoelectric transducer. Short pulses are generated by a probe laser beam. Variation of the spectrum of the acoustic signal recorded by a piezoelectric transducer and of the spectrum of the optical signal makes it possible to determine the spatial distribution of inhomogeneities in a medium. This method can be used to study the structure of a solid[171] or, more specifically, of a semiconductor.[172] The possibility of using this method in a study of thin boundary layers of water and air near the interface between the ocean and the atmosphere is considered in Ref. 173. The use of the optoacoustic method for probing inhomogeneous condensed media in the specific case of the hydrosphere was discussed in Ref. 45. The possibility of using the Bragg diffraction of coherent light by hypersonic waves created by thermal fluctuations in a liquid in the determination of the temperature and velocity of sound in surface layers of the ocean was pointed out in Ref. 46.

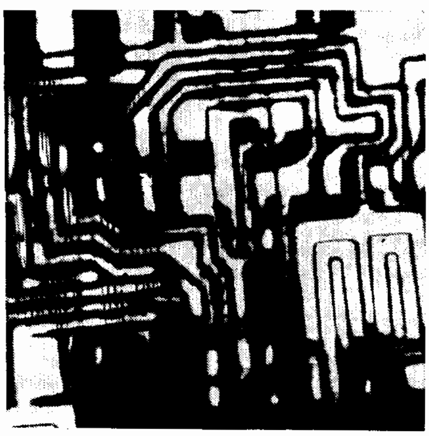

FIG. 33. Optoacoustic image of an integrated circuit.[155] An argon laser of 0.1 W power was employed, the frequency of modulation of the intensity of light was 1 kHz, and the resolution of the microscope was 5 μm.

5.3. Laser-acoustic effects on physicochemical properties and structure of solids

We shall now consider one other application of laser-acoustic technology. Interaction with laser radiation can alter the properties of a solid (in its interior) even if the solid is opaque. This is due to the transfer of laser radiation energy absorbed by the surface layer to the interior of a solid. Such transfer occurs mainly by thermal and mechanical mechanisms. The thermophysical aspects of the interaction of laser radiation with a condensed medium have been investigated in considerable detail and provide the basis of laser technology (Ref. 174). The thermal action of laser radiation on, for example, metals has opened up a wide range of applications; they include laser cutting, welding, tempering, drilling, and thermochemical treatments.

An extensive series of theoretical and experimental investigations of the laser excitation of sound has been carried out in the last decade and considerable progress has also been made in the understanding of the nature and characteristics of a "mechanical" field created by laser radiation. It has been established in particular that for certain parameters of laser radiation pulses (these parameters include the wavelength of light, pulse duration, and power) a "mechanical field" becomes the main carrier of the laser radiation energy into the interior of the body being irradiated. Giant laser radiation pulses acting on a condensed medium excite acoustic waves of finite amplitude which are then transformed

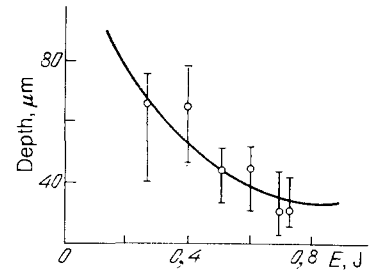

FIG. 35. Dependence of the depth of a maximum of the density of defects on the laser pulse energy.[180] The continuous curve is a theoretical dependence of the depth of formation of a shock wave by a laser beam.

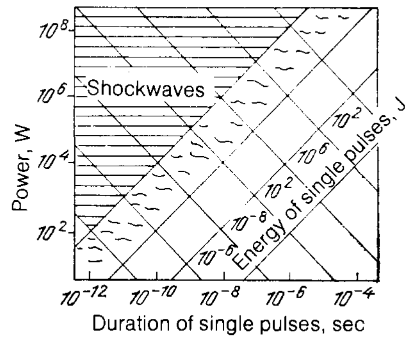

FIG. 36. Diagram showing parameters of lasers used for the purpose of laser-acoustic modification of physicochemical properties of materials (semiconductors).[178]

into shock waves.[175-177] Studies of changes in the physicochemical properties of solids under the action of laser radiation have shown that the formation of defects in a light-absorbing material as a result of pulsed laser irradiation, initially regarded as anomalous, is well correlated with the formation of shock waves by laser radiation. A phonon mechanism of dislocation-free laser generation of point defects in a solid has been proposed. It has been shown that laser-generated shock waves are scattered by inhomogeneities in a solid (including impurities, physical defects, and thermal fluctuations) and cause local damage to the crystal lattice.[178-180] Figure 35 shows the dependence of the depth of the positions of maxima of the concentration of point defects on the energy of laser radiation interacting with the surface of a molybdenum crystal.[180] The continuous curve is the theoretical dependence of the depth of formation of a shock wave. As expected, an increase in the laser pulse energy increases the amplitude of an acoustic wave and an increase in this amplitude reduces the distance in which a finite-amplitude acoustic wave is converted into a shock wave. In other words, it reduces the depth of formation of a shock wave. We can see that the agreement between the calculated depth of penetration of a laser shock wave agrees satisfactorily with the position of the maximum of the concentration of point defects formed under the action of giant laser pulses. It should be noted that a high concentration of point defects in a material after the passage of shock waves is mentioned also in Ref. 181.

The action of a laser-generated shock wave on a solid results in practically instantaneous generation of point defects in a concentration many orders of magnitude higher than the equilibrium concentration at the irradiation temperature. The high mobility of these defects makes it possible to establish ordered states which cannot be produced or can be generated only with difficulty by other "nonlaser" methods. The ability to create highly mobile defects by laser shock waves opens up an opportunity for initiating crystallochemical reactions.[182]

The use of nonlinear acoustic waves and changes in the conditions of focusing of laser radiation make it possible to create limited regions inside a solid which are enriched with point defects, i.e., it is possible to affect the concentration profile of mixtures in, for example, semiconductors. This method has been used to form a deep p-n junction in silicon.[183] The concept of phonon formation of defects and a theory of optical generation of acoustic waves of finite amplitude and their conversion into shock waves can be used to identify the parameters of laser sources which are needed to alter physicochemical properties of solids by laser radiation. Such a diagram is shown in Fig. 36. The part of the diagram relating to shock waves represents the range of parameters of laser radiation typical of the laser-acoustic modification of the characteristics of solids.

It should be pointed out that the thermophysical effect of high-power laser radiation on matter can also be regarded as in a sense laser-acoustic. For example, interaction of high-power laser pulses with semiconductor crystals that absorb light strongly results in pulsed laser annealing. The work carried out in the last 3–5 years has shown that rapid laser-induced phase transitions in surface layers of semiconductors (melting and solidification, conversion of an amorphous solid into a crystal and of a crystal into an amorphous solid) occur in the nanosecond, picosecond, and even subpicosecond range of pulse durations. A detailed explanation of these effects involves fundamental problems of the nature and rates of electron, electron-phonon, and phonon-phonon relaxation processes, as well as the question of stages of melting of a semiconductor crystal in a strong laser field when this crystal contains a dense hot electron-hole plasma: such melting can be due to direct transfer of the excess energy of free carriers to the lattice vibrations or it may be mediated by plasma-induced soft phonon modes, etc. (see Ref. 184).

We shall conclude this section by drawing attention to the possibility of "combining" laser and ultrasonic technologies, which we mentioned at the beginning of the section. In a narrow sense, laser technology is based on the thermal effects of laser radiation, whereas ultrasonic technology is based on the vibrational (mechanical) action. However, in a wider sense we know that laser radiation produces thermal and mechanical effects in a condensed medium. Apart from the applications of lasers, we know that irradiation with ultrasound simultaneous with thermal cycling can alter the structure of materials. In particular, it is shown in Ref. 185 that treatment of Kh16N11MZ steel by thermal cycling followed by ultrasonic irradiation can increase both the yield stress and the microhardness, whereas ultrasonic irradiation followed by thermal cycling increases the yield stress and reduces the microhardness. Suitable selection of the laser radiation parameters makes it possible to perform both these types of treatment and this opens up a fundamentally new opportunity of using such technology remotely to treat materials.

6. COHERENT OPTICAL ANALYSIS OF SIGNALS IN ACOUSTIC DATA SYSTEMS

Coherent optical processing of signals is an independent subject and it is part of an extremely wide field of optical processing of data and optical computing. Optical processing methods have made major progress in the last 20 years. Optical spectrum analyzers of electrical signals and images, apparatus for the formation of images with aperture synthesis, correlators, devices for calculation of convolutions, optical character readers, and other systems have been developed. There is a fairly extensive literature on the optical processing of data and its applications (see, for example, special issues of the Proceedings of the IEEE[186–187] and monographs[70,188–192]).

We shall simply mention here coherent optical processing because otherwise a review on applications of lasers in acoustics would be logically incomplete. There is a trend for *an increase in the number of channels in modern acoustic* systems. An example is a system for acoustic tomography of the ocean[193] and hydroacoustic systems for detection of ultrahigh-energy neutrino and muons in the ocean (DUMAND project).[194] The number of channels (separate hydrophones) in the latter case can reach 10^4. We shall mention also acoustic systems for nondestructive quality control and ultrasonic tomography,[195] as well as scanning laser-acoustic microscopy.[155,196] As a rule, information at the output of a system is in the form of an image and it should be analyzed in real time.

Modern computers are consecutively acting systems not designed for parallel analysis of large amounts of data. Even in the case of very fast computers the time needed for an analysis of a signal in the form of an image may be hundreds of minutes or even many hours. Obviously, the development of devices capable of operating in real time using conventional computers would be a very difficult task. It is therefore necessary to develop new computing devices capable of parallel processing of batches of data. Development work is proceeding on computers operating in parallel. However, such computers are as yet very complex and expensive, and their wide use depends on progress in microelectronics and microcomputer technology. Computing devices based on the principles of optical processing of data are naturally suited to parallel analysis of large batches of data presented in the form of images.

The main operations in the optical analysis of data are the Fourier transformation (spectral analysis) and the operations of convolution and correlation (correlation analysis); there are also certain other operations. A special feature of coherent optical processing methods is that two basic operations (Fourier transformation and complex multiplication) can be used to perform a wide class of linear operations, which include differentiation and integration of functions of a complex variable, calculations of the convolution and correlation, etc. All the operations are carried out on two-dimensional batches of data practically instantaneously (at the velocity of light) and this is the reason for the high speed of coherent optical processing methods and of computing devices based on them. It is usual to employ in such devices optical methods of analog calculation, which are based on diffraction, interference, polarization, and other properties of optical waves.

One should mention here that the application of coherent optical methods for spectral analysis is based on the fundamental property of a spherical lens focusing the image of an object, which is illuminated with coherent light: the *focusing can be accompanied simultaneously by the Fourier* transformation which is realized in the form of an amplitude distribution of light in the intermediate plane between the object and image planes (Fig. 37). This effect is used as the basis of optical spatial filtering (two-dimensional spatial spectral analysis). If a spatial filter mask (usually called transparency) is placed in the spatial frequency plane, it is possible to carry out filtering or change the amplitude or phase of the initial spectrum or both these parameters, so that the output signal (in the image plane) is transformed in accordance with the required mathematical operations.

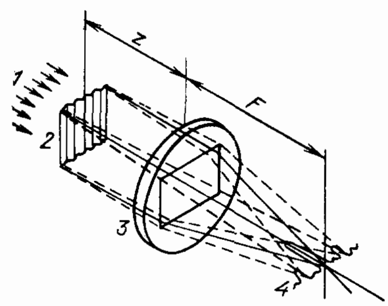

FIG. 37. Optical system for spectral analysis: 1) plane wave of monochromatic light; 2) object plane (sinusoidal optical signal); 3) spherical lens; 4) spatial frequency plane.

The spectrum of a one-dimensional temporal signal can be determined by converting the signal to a spatial one. Acoustooptic cells are used for this purpose and they allow introduction of a temporal signal into an optical data processing device. The action of an optoacoustic cell (ultrasonic modulator) is based on the diffraction of light by ultrasound. An ultrasonic wave is generated by an ultrasonic transducer and spatial phase modulation of light is induced in an acoustic channel which is transparent to light.

Figure 38 shows schematically a system for acoustooptic processing of signals, which can be used for analysis of the temporal signals. An acoustooptic modulator of light is an acoustic channel transparent to light with ultrasonic transducers at the ends of the channel. The application to one of these transducers of an electric signal to be analyzed excites an ultrasonic wave which travels along the channel. It creates spatial phase modulation of light. The coherent light flux leaving the modulator reaches the first Fourier-transformation lens and then a spatial filter mask which suppresses the constant component in the spatial frequency spectrum. The second Fourier-transformation lens converts the phase-modulated distribution of light at the output of the modulator into an amplitude distribution in the image plane. If a reference electrical signal is applied simultaneously to

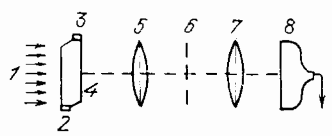

FIG. 38. Acoustooptic system for signal processing: 1) light flux; 2) input signal; 3) reference signal; 4) ultrasonic light modulator; 5) first Fourier transformation lens; 6) spatial filter (spatial frequency plane); 7) second lens performing Fourier transformation; 8) photodetector.

the second ultrasonic transducer attached to the opposite end of the acoustic channel, a correlation analysis of signals becomes possible.

An important step in the optical processing was made in Refs. 197 and 198 where holographic methods for the filtering of images were proposed. The use of a hologram as a transparency has opened up extensive opportunities for optical processing of signals (involving correlation of images, convolution, etc.) and has made it possible to progress in image recognition and the adaptation in optical data and lidar systems.[192] Transparencies are usually spatial light modulators, constructed from photorefractive and liquid crystals and electrooptic cells.[192,199]

We shall not consider details but simply point out recent suggestions of the use of lasers, fiber-optic sound detectors, fiber-optic communication lines, and optical processing methods not only in acoustic nondestructive quality control, ultrasonic tomography, etc., but also in hydroacoustics. For example, a passive hydroacoustic system ("optical sonar") is described in Ref. 200. In this system the components of a linear hydroacoustic antenna are fiber-optic sound detectors; use is also made of acoustooptic devices for the formation of the directionality characteristic of the antenna and for scanning; finally, the signals are processed optically.

An optical sonar system is shown schematically in Fig. 39. Acoustic waves in water reach fiber-optic sound detectors 1 forming a linear hydroacoustic antenna. Light rays are modulated by acoustic signals applied to these detectors and the output signals from the detectors are transmitted along fiber-optic lines 2 to a unit for the acquisition of signal data and channel multiplexing 3 and then the data are transmitted in the multiplexed form along a fiber-optic communication line 4 to the input of a system for channel demultiplexing 5 and conversion of optical signals back into electrical ones. Electrical signals carrying information on the amplitude and phase of acoustic signals arriving from water are applied to light-emitting diodes 6, the number of which is the same as the number of fiber-optic sound detectors in the antenna. The diodes 6, a perforated screen mask 7, an ultrasonic transducer 8, all attached to an optically transparent acoustic channel in the form of a quartz cube 9, form an acoustooptic cell 10 which acts as a signal delay device. This is done as follows. Light-emitting diodes are attached to one of the faces of the cube and their distribution repeats, on a suitable scale, the distribution of fiber-optic sound detectors in the antenna. On the opposite side of the acoustic channel there is a perforated screen mask, i.e., a transparent screen with apertures which have centers located exactly opposite the light-emitting diodes. In the absence of an ultrasonic wave inside the acoustic channel the light rays created by these diodes are not distorted and pass through the apertures in the screen mask reaching a converging lens 11 which focuses light on a photodiode 12. This photodiode sums the optical signals carrying acoustic information from the fiber-optic sound detectors. If a plane acoustic wave in water is incident normally on the linear antenna, then signals from the fiber-optic sound detectors reaching the photodiode are summed in phase. When a plane acoustic wave is incident at an angle, the signals are characterized by a phase shift. This shift can be removed by an ultrasonic transducer which excites, in the ultrasonic channel, acoustic vibrations of such a frequency that the Doppler effect in the course of propagation of light in the acoustooptic cell compensates the phase shift so that the signals from the fiber-optic sound detectors are added in phase at the photodiode. The acoustooptic cell 10, the converging lens 11, the photodiode 12, and an ultrasonic oscillator 13 represent a system 14, which determines the directionality characteristic of the antenna ("acoustic ray") and performs scanning. The signal from the photodiode reaches a balanced demodulator 15 and then a unit 16 for the acquisition and storage of data. The data storage process is relatively slow and it is determined by the rate of scanning of an acoustic ray in water. On the other hand, the retrieval and processing of data is a fast process. Data are applied to the light-emitting diodes in a system for optical processing and display of data. The number of these diodes is determined by the nature of data processing and display. For example, signals from these diodes can reach a target track plotter (recorder) 17, a correlator functioning as a target detector 18, and other optical data processing and display devices 19. Naturally, this system is simply an illustration of the possibilities in hydroacoustics.

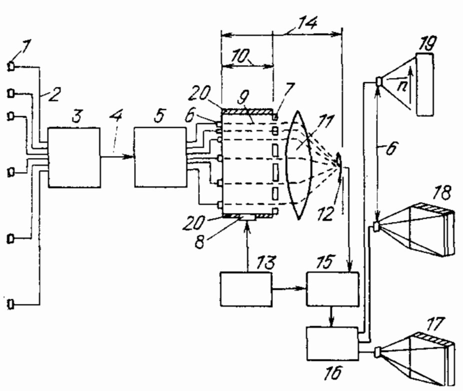

FIG. 39. Schematic diagram of an "optical" passive hydroacoustic system[200]: 1) fiber-optic sound detectors; 2) fiber-optic lines; 3) system for acquisition of signal data and channel multiplexing; 4) fiber-optic connecting line; 5) system for separation of channels and conversion; 6) light-emitting diodes; 7) perforated mask screen; 8) ultrasonic transducer; 9) light-transparent acoustic channel; 10) acoustooptic cell; 11) converging lens; 12) photodiode; 13) ultrasonic oscillator; 14) system for the formation of an "acoustic beam" and scanning; 15) balanced single-band demodulator; 16) cell for data collection and information storage; 17) track recorder; 18) correlator; 19) additional devices for optical treatment and imaging of data; 20) sound absorber.

The optical sonar system described above suffers from certain shortcomings. For example, the delay system does not introduce distortions only in the case of a hydro-acoustic signal which has a very narrow bandwidth.

However, if we bear in mind that the components of a data-handling acoustic system can be integrated, this makes the applications of lasers in acoustic systems even more attractive, because of the possibility of a strong reduction in the weight, dimensions, and power consumption. We shall conclude by noting that the "optical sonar" system described above can provide the basis of a laser-acoustic system for nondestructive quality control in which acoustic emission signals are detected and analyzed.

7. CONCLUSIONS

It follows from the above review that recent years have seen considerable progress in the theory of optical generation of sound which describes quite satisfactorily this effect under conditions when the action of optical radiation does not alter the aggregate state of a condensed medium. Studies have been made of the optical generation of sound in liquids under pulsed and cw laser operating conditions. The main laws governing the formation of acoustic signals have been determined and the relationships between the characteristics of these signals, on the one hand, and the parameters of optical radiation, as well as thermodynamic, optical, and acoustic properties of the liquid, on the other, have been established. Theoretical studies have been made of the influence of a "wavy" surface of a liquid on the optical generation of sound. The optimal conditions for laser generation of sound have been established. Characteristic features of the generation of sound have been determined for a laser beam moving along the surface of a liquid at subsonic, sonic, and supersonic velocities when the beam is intensity-modulated in any manner. Studies have been made of the influence of optical, thermodynamic, and acoustic inhomogeneities of a medium on the optical generation of sound. It has been shown that it is possible to induce optoacoustic sources of sound or optoacoustic emitting antennas in a liquid and these can operate in a wide range of frequencies from acoustic to hypersonic. Variation of the parameters of a laser (or a laser beam) makes it possible to control remotely the frequency, directionality, and intensity of sound emitted by an optoacoustic source.

The role of thermodynamic and hydrodynamic nonlinear effects in the optical generation of sound is discussed under conditions when the density of the optical energy released in the liquid is considerable but still small compared with the thermal evaporation of the liquid. One of the new possibilities is the construction of parametric optoacoustic sources of sound. A series of investigations has been made of thermooptic excitation of sound in solids.[201-205]

The theory of the optical generation of sound in the case when the thermal mechanism plays the dominant role is supported convincingly by the results of experiments, so that it is possible to select in a systematic manner the appropriate lasers for tackling a number of practical problems in the laser generation of sound both in liquids and solids.

Summarizing, we can say that theoretical and experimental investigations of the optical generation of sound have led to considerable progress in the case of the thermal mechanism.

In contrast, systematic purposeful investigations of the laser generation of sound in condensed media under the conditions of surface evaporation, explosive boiling, and optical breakdown have been far fewer. Considerable experimental data have now been accumulated, but only a few theoretical calculations (numerical and analytic) have been made and relatively simple models of the processes of the laser excitation of sound have been used. Many problems have not yet been solved. Examples of such problems are as follows: instability of the evaporation front and appearance of metastable states of an overheated liquid under surface evaporation conditions; the relative role of the bulk boiling and surface evaporation under the action of laser radiation on the free surface of a liquid; the role of spontaneously generated instabilities of the surface relief, creating periodic surface structures. Formation of such structures is related to spatially inhomogeneous heating of the surface of a material and the inhomogeneous field causing the heating is the result of interference between an incident laser wave and a field formed as a result of the scattering (diffraction) of this wave by instabilities of the surface in the form of surface acoustic waves, capillary waves, and interference instability of the evaporation process.[99,184]

The nature of the processes which occur in a surface layer of a liquid under the action of laser radiation determines largely the efficiency of conversion of the optical energy into sound and the nature of the evolution of an acoustic signal in the course of its excitation and propagation. The above theoretical and numerical estimates of the level of sound and of the efficiency of the conversion of optical energy into acoustic energy in the interaction of high-power laser radiation with matter have been obtained on the basis of very simple models. Nevertheless, these estimates are often in agreement with experimental results. This means that the models described above reflect the fundamental features of the phenomena. Summarizing, we can say that the current status of the study of nonequilibrium states and phase transitions induced by high-power laser fields is characterized by an understanding of the important and decisive role of the nonlinear response of matter. Therefore, a rigorous analysis of laser excitation of sound under phase transition conditions can be based only on numerical solution of time-dependent nonlinear equations of hydrodynamics, optics, and evaporation kinetics. We shall mention here interesting investigations[206,207] where calculations have been made of the specific recoil momentum and the processes of formation of a shock wave and its propagation into matter as a function of the intensity of laser radiation. The results of numerical integration of time-dependent equations of hydrodynamics, carried out without simplifying assumptions, are given in Refs. 207 and 208. The theoretical dependence of the specific recoil momentum on the intensity of laser radiation is in good agreement with numerous experimental data for metals.

We have ignored above the role of electrostriction in laser excitation of sound. This problem is discussed in a recent review.[29] We have not considered either the mechanism of generation of sound as a result of stimulated Brillouin scattering. Equally interesting are the optoacoustic effects in the case of resonant interaction of coherent optical radiation with matter. This last topic is treated separately in another review.[184]

Optical methods for the investigation and generation of acoustic fields and vibrations have been known well before the appearance of lasers. However, only the sources of coherent light with controlled spatial-frequency and time characteristics have made it possible to develop new methods, such as holographic interferometry. It has become possible to improve traditional methods. One of the examples is the work on the improvements in the shadow method by use of holographic focusing of an optical beam.[196] It has become possible to achieve record sensitivities in the determination of the amplitudes of displacements of a vibrating surface. It is reported in Ref. 66 that displacements of 10^{-16} m amplitude were detected under laboratory conditions at 15 kHz and the sensitivity of the optical system was limited by the photodetector noise rather than the photon noise. The photodetector noise was $3\times10^{-7}\ \mathrm{W\cdot Hz^{-1/2}}$, which was three orders of magnitude stronger than the photon noise. The authors of Ref. 66 pointed out that the use of two-photon resonances and a highly stable laser in their measurement system, together with utilization of narrow optical resonances, should make it possible to increase the sensitivity to 10^{-22} m! This sensitivity is fantastic and it raises the problem of the fundamental limit to the sensitivity, i.e., of limitations imposed on the maximum sensitivity by quantum effects. The answer is not yet known. The problem has been discussed recently in connection with a theoretical prediction of the existence of so-called "squeezed" states of optical radiation.[209,210] These squeezed states make it possible (at least in theory) to increase the signal/noise ratio in optical laser (measuring) systems.[211] It should be pointed out that squeezed states retain their unusual properties for any arbitrarily large number of photons, i.e., they represent a macroscopic quantum effect. Intensive studies are proceeding of the generation of squeezed states.[210,212] An attempt has been made recently to realize such states experimentally by four-wave degenerate mixing of optical waves in an optically nonlinear medium.[212] The quantum-mechanical nature of the noise in optical interferometers has been investigated.[213]

The ultimate sensitivity of remote coherent optical methods for the determination of acoustic fields and vibrations may be seriously limited by the influence of the medium in the propagation path. The problem can be solve by using nonlinear self-diffraction of light (dynamic holography) and wavefront reversal in a nonlinear optical medium.[86] In all probability it should be possible to construct adaptive highly sensitive remote optical methods for recording acoustic fields and vibrations. This applies equally well to the possibility of improvements in fiber-optic sound detectors, particularly those employing not just single-mode but also multimode fiber lightguides. In the latter case an important factor, which limits the detector sensitivity, is the existence of the mode noise and the speckle noise, the characteristics of which have been investigated.[214,215]

It is worth noting in this connection the work on the construction of lightguide stimulated Raman and Brillouin scattering lasers,[216,217] and the suggestion to use an injection laser (which is currently the main source of light in fiber-optic communication lines) as a detector of amplitude-modulated radiation. This opens up the possibility of constructing reversible fiber-optic communication lines (fiber-optic sound detectors) in which the transmitter and receiver are identical semiconductor lasers.[218]

We have discussed above an important field of application of lasers in acoustics: laser-acoustic technology. One should mention a branch of such technology which is laser-acoustic spectroscopy of gaseous and condensed media. In a sense, it represents a development of optoacoustic spectroscopy, which has been in use before the appearance of coherent light sources. Lasers have stimulated further development of optoacoustic spectroscopy and have made it possible to construct laser-acoustic spectrometers with record characteristics.[219] Optoacoustic Raman scattering spectroscopy has also been suggested. Theoretical and experimental investigations of the advantages and shortcomings of a new nonlinear optoacoustic Raman spectroscopy method were published recently.[220] The author suggested a counterpropagating geometry for the interaction of light beams in a spectrometer, which makes it possible to increase considerably (by at least an order of magnitude) the recorded signal compared with the unidirectional interaction of light employed earlier.[221,222] It has been shown experimentally that the proposed method has a high sensitivity and selectivity when investigations are made of pure molecular gases and their mixtures.

Two laser pulses coinciding in time can be used to excite a transient diffraction grating in a medium which can then be employed to determine the physical parameters of liquids and solids. Spatially periodic distributions of the intensity of light can, in particular, produce similar distributions of excited electron states in matter, which alter the optical properties of a material and thus create a diffraction grating. Studies of changes in the diffraction properties with time can provide information on dynamic characteristics of the investigated physical system.

Such transient gratings have been used experimentally in determination of the following: the transfer of energy and momentum from excited electron states, the rate of carrier capture, the rate of relaxation of hot electrons, the quantum efficiency of fluorescence, the orientational relaxation time, the rate of diffusion of heat and mass, the coherence time of picosecond lasar pulses, etc.

The dynamic properties of an "induced" grating can be influenced also by an external acoustic field.

This opens up the possibility of recording an external acoustic field in matter and the effects of the interaction of this field with matter, including the optoacoustic interaction.

Coherent optical methods for the processing of multichannel data will play an important role in acoustics. However, they also suffer from certain disadvantages, such as the low precision of the calculations and difficulties encountered in changing calculation programs. These shortcomings can be removed by employing hybrid optical-electronic processing systems containing optical analog computing devices as well as digital computers. Recent years have seen the development of optical numerical processing methods, including those employing miniature sources of coherent light and fiber-optic lightguides.[223]

We shall conclude by noting that optoacoustic sources and fiber-optic sound detectors, or laser methods for remote determination of vibrations and the reception of sound do not replace completely the traditional sources and detectors, just as coherent optical systems for data processing have not superseded computers completely. However, there is no doubt that the use of lasers will have a major influence on the future development of physical and technical acoustics.

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