Laser excitation of surface acoustic waves: a new direction in opto-acoustic spectroscopy of a solid

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Studies in thermo-optic excitation of surface acoustic waves are reviewed. The excitation of periodic and pulse signals is discussed, using nonmoving and moving beams. Most attention is paid to application of this effect for purposes of opto-acoustic spectroscopy of a solid. The possibilities and promises of using opto-acoustic spectroscopy (OAS) employing surface acoustic waves (SAW) are analyzed.

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I. INTRODUCTION

The thermal action of optical radiation on a material underlies a wide class of opto-acoustic effects, since the process of nonstationary inhomogeneous heating of the medium is accompanied by emission of an acoustic wave due to thermal expansion of the medium. This effect was investigated by Bell, Tyndall, and Roñtgen as early as 1881. Only after the creation and perfection of lasers, however, did the possibility occur of extensive use of the opto-acoustic effect in various forms of spectroscopy (both of optical and acoustic characteristics of the medium).

The action of laser radiation usually leads to excitation of acoustic disturbances in the target material. Theoretical and experimental studies of these effects were started practically immediately after the creation of lasers.[1,2] There exist several mechanisms of sound excitation during the action of laser radiation on a medium (see, for example, the reviews of Refs. 3, 4): thermal, evaporative, breakdown, and striction. The thermal mechanism is related to nonstationary thermal expansion of the bulk of the medium, in which the light energy has been absorbed. The evaporative mechanism is due to the recoil momentum of the material vapors during its evaporation under the action of laser radiation, and the breakdown mechanism is due to formation of a strong shock wave during optical breakdown (in this case the extracted energy density is comparable with the internal pressures in the medium). The striction mechanism occurs in transparent media, and is related to the appearance of mechanical stresses in the material in the presence of an electric field.

The basic mechanism of sound excitation by laser radiation in light-absorbing media is (due to its lack of threshold) thermal. The dynamics of thermo-optical sound excitation is determined by the radiation parameters (the beam geometry, the time dependence of the intensity) and the physical characteristics of the medium (the light absorption coefficient, the thermal expansion coefficient β, the heat capacity c, the compressibility, etc.). Under optimal conditions of heat release the thermoelastic stresses generated can be estimated by the quantity $p' \sim (\beta c_0^2/2c)E_V$, where c_0 is the speed of sound, and E_V is the bulk density of the absorbed light energy. The dimensionless quantity $\beta c_0^2/c$ is related to the Grüneisen constant, and is of the order of unity. The fraction of thermal energy transformed into acoustic energy $\eta = E_{ac}/E_{li}$ is proportional to the bulk density of heat release $\eta \sim (\beta c_0^2/2c)^2 E_V/\rho_0 c_0^2$ (ρ_0 is the medium density). Since the starting threshold of evaporation is substantially smaller than the quantity $\rho_0 c_0^2$ of the condensed media, the effectiveness of thermo-optic sound excitation is usually low, $\eta \lesssim 10^{-4}$. However, the high density and rate of heat release makes it possible to achieve sufficiently intense sound pulses in a wide frequency range. At the present time laser excitation of bulk acoustic waves has been investigated extensively (see, for example, the reviews of Refs. 5, 6) and widely used in scientific studies and applications.[7,8]

Thermo-optic sound excitation occurs in the surface layer of the absorbing layer. Therefore, along with bulk acoustic waves in solids the thermo-optic mechanism makes it possible to excite Rayleigh waves as well. This effect lacks a threshold (unlike the effect of induced enhancement of a surface wave due to interaction with the scattered light wave[9]). Interest in thermo-optic excitation of surface acoustic waves (SAW) became substantial only in the recent 2–3 years, particularly in connection with problems of investi-

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gating surface layers of media. These studies provide a new direction of opto-acoustic spectroscopy (OAS) of a solid—OAS of Rayleigh waves. The present review is devoted to analysis of its state, and the possibilities and perspectives of its use.

2. LASER EXCITATION OF SURFACE ACOUSTIC WAVES

By means of laser radiation one can excite SAW of a wide region of frequencies with varying spatial characteristics. As in the case of laser excitation of bulk waves, the thermo-optic mechanism makes it possible to excite both periodic and pulse Rayleigh waves. The various variants of SAW excitation have been discussed in the literature.

Laser generation of SAW was first described in the study of R. E. Lee and R. M. White.[10] The Rayleigh wave excited by absorption of a single laser pulse with Q-factor modulation in an aluminum film, deposited on the investigated surface. Various materials were used as sublayers, ceramics, crystalline and fused quartz. The laser radiation was focused in a narrow rectilinear band, and therefore the SAW front was nearly plane. However, the restricted bandwidth of Rayleigh wave receivers did not allow an adequate resolution of the time form of the wave. Therefore, one practically recorded the amplitude of the SAW spectral component at the fundamental resonance frequency of the receiver.

The following study devoted to laser generation of SAW appeared only 11 years later,[11] in 1979. Its authors used contactless laser excitation of acoustic waves (laser radiation with Q-factor modulation was focused by a cylindrical lens on the butt end of a plane face in a narrow band near an edge; Fig. 1) for simultaneous measurement of the velocities of longitudinal, shear, and Rayleigh waves. They were determined by the arrival time delays of pulses (L, T, and R, respectively, in Fig. 1), related to wave propagation along the free boundary plane. The quantities obtained coincide with measurements by other methods. This method is a variation of pulse methods of measuring the speed of sound, and is subject to errors of the same order as traditional methods. In proposing this method, the authors indicate its following advantages: the possibility of performing measurements with samples of small sizes and simple shapes over a wide range of temperatures and pressures, the operational aspect of obtaining data, and the simultaneity of measuring the velocities of all three types of waves.

Wideband videopulse Rayleigh waves were excited in Refs. 10, 11. The method of laser generation of periodic SAW was first suggested in Ref. 12. A harmonically modulated laser beam was directed at the investigated surface, which absorbed the radiation through a periodic mask. A sharp peak of effectiveness of SAW excitation was observed (Fig. 2) at the modulation frequency, corresponding to a Rayleigh wavelength equal to the mask period. The frequency dependence of the relative excitation effectiveness coincided with the spatial spectrum of the mask, measured by means of piezoelectric SAW excitation. Measurements of directivity diagrams of an opto-acoustic excitation antenna gave results in good agreement with theoretical results for a lattice of linear antennae (Fig. 3). Estimates of SAW amplitudes coincided in order of magnitude with experimental measurements.

It is necessary to note that the use of a periodic mask for excitation of periodic SAW is not mandatory. Harmonic modulation of radiation intensity and its focussing are sufficient (in this case the frequency characteristic of the opto-acoustic radiator will be wideband). This excitation variant was realized later in Refs. 13, 16.

A series of experimental and theoretical studies[13–24] appeared in 1982–1983, in which different variants of SAW laser excitation were investigated. The excitation of periodic

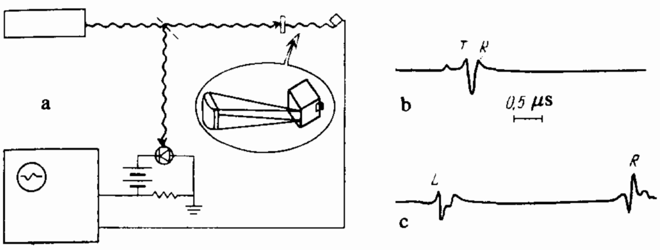

FIG. 1. Scheme of the experiment of Ref. 11 (a) and pulse oscillograms of transverse (b) and longitudinal (c) waves.

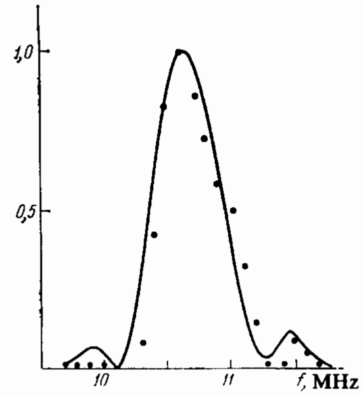

FIG. 2. Dependence of the SAW amplitude on the light modulation frequency and on the mask characteristics, measured traditionally (continuous line).[12]

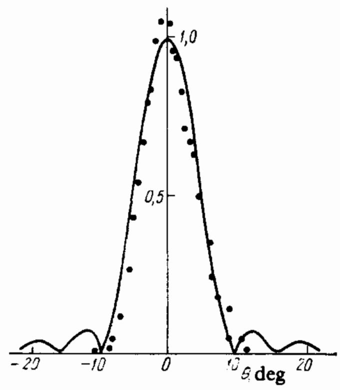

FIG. 3. Calculated (solid line) and experimental (circles) characteristic of the directivity of an opto-acoustic SAW antenna.[12]

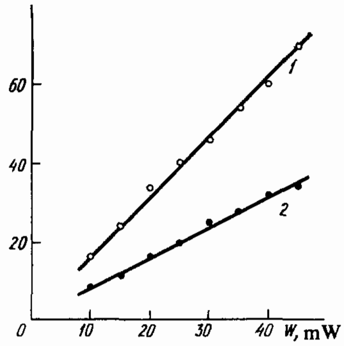

FIG. 4. The SAW signal amplitude as a function of the laser radiation intensity[13] in the continuous regime; 1) radiation focused by a cylindrical lens, 2) by a spherical lens.

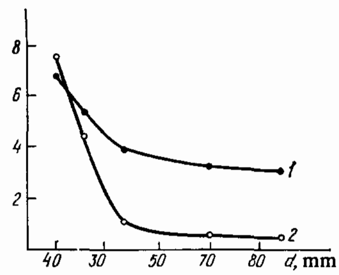

FIG. 5. The wave amplitude as a function of separation between the area of excitation and the receiver; 1) for a Rayleigh wave, 2) for bulk waves.[23]

Rayleigh waves is described in Refs. 13, 16; generation of pulse SAW was discussed in Refs. 14, 18, 23; SAW excitation during scanning of a laser beam over the surface of a medium is proposed in Refs. 21, 22.

A dye laser operating in the regime of mode synchronization was used in Refs. 13, 16 to excite periodic SAW. The radiation was absorbed in a colored film, drawn on the surface investigated. The laser beam was focused by a spherical or cylindrical lens. SAW registration was realized by counter-stub transformers, tuned at a frequency of laser pulses ~ 76.4 MHz. It was established in Ref. 13 that the acoustic signal is proportional to the light intensity (Fig. 4). A comparison of the results of Ref. 13 with theoretical calculations was carried out later in Ref. 24. The calculated SAW amplitudes coincided with the measured ones. This scheme was used in Ref. 16 for opto-acoustic microscopy of the light absorption coefficient based on a SAW. A laser spot of diameter $\sim 5\mu$ was moved over the investigated surface, and the signal was synchronously drawn on a plotter. The sensitivity of the method is comparable to that provided by traditional opto-acoustic microscopy. The scheme used is generally close to the traditional, and, apparently, has no substantial advantages.

In experiments of exciting SAW pulses[14,18,20] a basic difficulty is the registration of a wideband Rayleigh wave. The studies 14, 23 are a development of the studies 10, 11, while the problem of resolving the shape of a SAW videopulse was not solved in them. An experimental scheme was used in Ref. 14, similar to that described in Ref. 10,—the Rayleigh wave was excited on the surface of a metallic block, and the laser spot had the shape of a band. The registration was realized by a piezo-transformer with a resonance frequency of 3 MHz. The oscillation amplitude of the surface was in fact registered at the resonance frequency of the transformer. The directivity diagram of the opto-acoustic radiator of Rayleigh waves was investigated for various spot sizes. The velocity of Rayleigh waves was determined from the width of directivity diagram. Apparently, the accuracy of these measurements is not high due to the indefiniteness in the spot sizes.

A study of the dependence of the surface oscillation amplitude on the diameter of the light spot, the pumping intensity, and the transient wave scattering was carried out in Ref. 23. The SAW amplitude was proportional to the energy of laser pulses up to intensities of the order of 10^8 W/cm^2. The falling-off of the Rayleigh wave amplitude with distance approximately corresponds to the law $r^{-1/2}$ (Fig. 5), as would be expected from the cylindrical nature of the wave. Control experiments (the presence of a fluid layer, of surface imperfections in the path of the propagating wave) have shown that a surface wave is indeed observed. The duration of the SAW pulse was proportional to the diameter of the laser spot. Unfortunately, this dependence is not discussed in that study.

Laser generation of Rayleigh waves as a new OAS method of investigating surface layers was first discussed in Ref. 18. The SAW was excited by absorption of laser radiation by a dye on the surface of a quartz substrate (a substrate of lithium niobate was also used). The radiation was focused by a cylindrical lens in a spot of size $30\mu \times 2$ cm. The absorption occurred in a film of dye R590, remaining on the substrate after its flushing. The registration of the excited SAW videopulses was carried out by an end piezo-transformer having a bandwidth of 50 MHz. Light absorption spectra by the film were investigated in the wavelength range of 490–540 nm, with their variation in time and under the action of optic radiation. The OAS method using SAW is quite a bit more sensitive to the nature of coupling of the absorbing film with the substrate than are other methods (in particular, ordinary absorption). It was observed that addition of polystyrene to the dye enhances the optical stability of the film by approximately a factor of 4 (see Fig. 6—the rate of fall of the SAW signal decreases with the addition of polystyrene). The limiting sensitivity of the method was determined by the signal/noise ratio reached; according to estimates it corresponds to absorption in a monomolecular layer to the dye.

It can be stated that the method of the experiments of Ref. 18 is the most effective of all those described above. In particular, in that study the first successful resolution occurred of the shape of SAW videopulses, excited thermooptically. The pulse profile obtained for a Rayleigh wave is given in Fig. 7.

The studies of Refs. 21, 22 are devoted to investigating SAW excitation during motion of a laser beam over the surface of a solid with a velocity near that of a Rayleigh wave. the experimental[21] and theoretical[22] results are in good

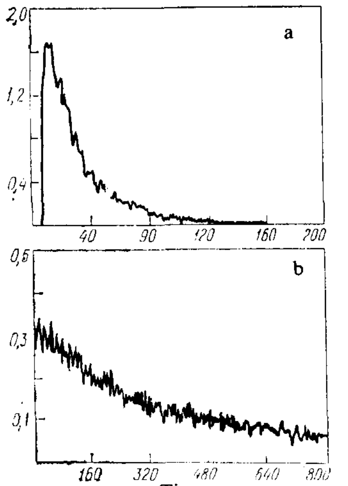

FIG. 6. Damping of the SAW signal in the R590 dye under the action of optical radiation (a)[18]; $\lambda = 510$ nm, the pulse repetition frequency is 10 Hz, and the energy density is 0.4 J/cm^2; b) dye diluted by polystyrene.

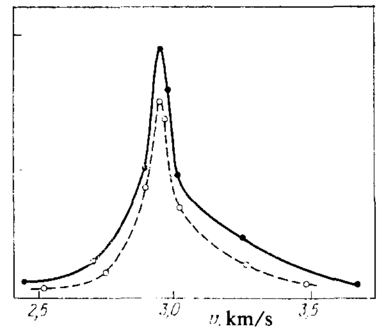

FIG. 8. The amplitude of a Rayleigh wave at the end of the scanning route as a function of velocity of a moving focus[21] (relative units).

agreement with each other. As in the case of bulk waves, a sharp (resonance) increase in the effectiveness of SAW excitation is observed when the velocity of beam motion approaches that of a Rayleigh wave (Fig. 8). The resonance width is determined by the spot size a and by the length of scanning sweep L. In the presence of a velocity difference δv from the resonance value c_R the amplitude growth takes place as long as the SAW and the beam do not diverge by a distance $\sim a$. Thus, the resonance width is estimated by the quantity $\delta v \sim c_R a/L$, which corresponds to the experimental data. With increasing tracking length the resonance curve narrows down (Fig. 9), while the wave amplitude increases. The deviation of the dependence of wave amplitude on distance from linearity is, apparently, related to SAW diffraction.

The surface displacement amplitude in the scanning regime can reach substantial values (in the experiment of Ref. 21—up to 0.1 μ) with quite weak surface heating ($\lesssim 3$ K). Nevertheless, it remains proportional to the intensity of laser radiation. Estimates of the displacement[22] are in good agreement with measurement data.[21] The problem of excitation of SAW by a moving laser beam in the form of a band was solved in Ref. 22. For exact coincidence of the scanning velocity with the velocity of the Rayleigh wave the latter increases linearly with time, and the component of the oscillation velocity normal to the surface reproduces the light intensity distribution over the cross section of the spot. The relative volume change during deformation of aluminum is of the order of $7 \cdot 10^{-12}$ cm^2/W $I_0 L/a$ (I_0 is the light intensity). Among the advantages of the scanning regime one can also include the possibility of purely mechanical action on the surface of the material without heating it substantially.

The theoretical analysis of laser SAW excitation was carried out on the basis of the linear problem of thermoelasticity.[17,19,20,24] The restriction to the linear acoustic approximation, as in the case of thermo-optic generation of bulk waves, appears to be quite justified. Due to the linearity of the problem it was sufficient to consider excitation of a monochromatic wave. All the studies mentioned are restricted to the case of a plane monochromatic Rayleigh wave, for which the theoretical analysis is substantially simplified.

The results of Refs. 17, 19, 20 are difficult to compare, since they were obtained under various simplifying approximations, not always stated sufficiently clearly. Practically the issue is the relation between three quantities, the beam width a, the depth of light absorption α^{-1}, and the wavelength $(\chi/\omega)^{1/2}$ (χ is the temperature conductivity of the medium, and ω is the wave frequency). The most developed theory is presented in Ref. 24, where, however, excitation of a plane monochromatic Rayleigh wave is considered in a nonheatconducting medium.

Laser SAW excitation in a nonheatconducting medium is analyzed in Ref. 17; the model used corresponds to the case $a, \alpha^{-1} \gg (\chi/\omega)^{1/2}$. Most attention is paid to the relative effectiveness of exciting various types of waves (longitudi-

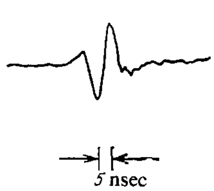

FIG. 7. The shape of an SAW videopulse, excited thermo-optically.[18] Front of a plane wave, spot width $\sim 30\,\mu$m duration of laser pulse 7 nsec.

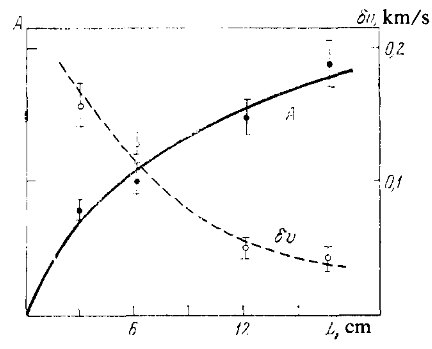

FIG. 9. The amplitude of a Rayleigh wave at resonance A and the resonance half-width δv as a function of the length of the scanning route[21].

nal, shear, and Rayleigh) as a function of the quantity $k_R a$, where $k_R = \omega/c_R$ is the wave vector of the Rayleigh wave. It has been established that for $k_R a \sim 1$ most of the intensity of all types of acoustic waves ($\sim 67\%$) is associated with the Rayleigh wave, while the bulk waves account for much less (26% for transverse, and 7% for longitudinal waves). With increasing $k_R a$ the fraction of the longitudinal wave intensity increases quickly and becomes dominant. This is explained by the fact that only a longitudinal wave is excited during thermal expansion of the medium, while a transverse wave appears upon its reflection from the boundary. Therefore, for thermo-optic excitation of high-frequency SAW one requires sharp focusing of the laser beam. In particular, this condition was satisfied in the experiments of Refs. 13, 18.

Analysis of thermo-optic SAW excitation with the thermal conductivity of the medium taken into account was carried out in Refs. 19, 20. The calculation in Ref. 19 was performed for the case of surface irradiation through a periodic mask, while the SAW excitation was realized on the surface of a piezoelectric. In Ref. 20 light absorption was assumed to occur at the surface, with the beam being infinitely thin (the thermal wavelength is much larger than the spot size and the light penetration depth—the low-frequency case). We note that the presence of a gas medium above the surface of a solid has no substantial effect on laser SAW excitation.

A comparative estimate of the effectiness of laser excitation of acoustic waves in semiconductors due to two different mechanisms, thermal and deformational, was provided in Ref. 15. An interference pattern is considered, created by two beams incident on the surface at an angle to each other. The light frequency exceeds the width of the forbidden band. The deformation mechanism is related to the occurrence of lattice deformation due to modulation of electron and hole concentrations generated by laser radiation. The thermal and deformation mechanisms have a different frequency dependence of the excitation effectiveness by an acoustic wave. By the estimates of Ref. 15 the deformation mechanism dominates at low frequencies; for gallium arsenide the frequency at which the effectiveness of these mechanism is comparable is of the order of 1 GHz.

In summary it can be said that up to the present time one has carried out, largely at a simply demonstration level, experiments in laser SAW excitation in the pulse, continuous, and scanning regimes. These studies show the advantages of the thermo-optic excitation mechanism of Rayleigh waves, its contactless and wideband features, universality, and possibility of remote tuning of wave direction. The inverse problem, opto-acoustic SAW spectroscopy, has been little investigated. However, the first experiments[18] show the promise of the new OAS variant. Its further development also requires further theoretical analysis.

3. SPECTRAL CHARACTERISTICS OF THERMO-OPTIC SOURCES OF SURFACE ACOUSTIC WAVES

For a theoretical analysis of thermo-optic excitation of a Rayleigh wave it is sufficient to restrict oneself (as in the case of exciting bulk waves) to the linear acoustic approximation. This is related to the fact that even at the threshold of material melting the acoustic Mach number M (the ratio of the oscillation velocity to the wave velocity) is small, less than 10^{-2}, and nonlinear acoustic effects are weak. They accumulate only during the wave propagation process at distances $\sim \Lambda/M$, where Λ is the wavelength, while at the same time the wavelength Λ is comparable with the size of the heat release region.

It is useful to take the equations of the nonstationary problem of thermoelasticity in terms of potentials[25] (since the equations for the displacement components are not separable):

$$c_l^{-2}\frac{\partial^2\varphi}{\partial t^2}-\Delta\varphi=-\left(1-\frac{4}{3}\frac{c_t^2}{c_l^2}\right)\beta\frac{\partial T}{\partial t}, \qquad (1)$$

$$c_t^2\frac{\partial^2\psi}{\partial t^2}-\Delta\psi=0. \qquad (2)$$

Here φ and ψ are the potentials of the displacement velocity of the particles of the medium,

$$\frac{\partial \mathbf{u}}{\partial t}=\operatorname{grad}\varphi+\operatorname{rot}\psi, \qquad (3)$$

u is the particle displacement vector, c_t and c_l are the velocities of transverse and longitudinal acoustic waves, β is the thermal expansion coefficient of the medium (assumed to be isotropic), and T is the temperature increment of the medium. The temperature change of the medium is determined by the absorbed energy, the thermal conductivity, and the dilatation. However, for frequencies up to 10 GHz, for the overwhelming majority of solid media the coupling of thermal and acoustic waves can be neglected.[25] At these frequencies sound propagation occurs adiabatically: during an oscillation period heat does not have time to diffuse over a distance of the order of a wavelength $\omega < \omega_T = c_l^2/\chi$, where χ is the temperature conductivity; in other words, the thermal wavelength is much smaller than the acoustic wavelength. In this approximation of the uncoupled problem of thermo-elasticity the temperature increment can be assumed to be a known function of coordinates and time $T(t,\mathbf{r})$, determined by external heat sources. Therefore one can solve the problem (1), (2) of SAW excitation by a nonstationary temperature field T, not specifying for the time being the nature of its generation.

Consider a homogeneous, isotropic, elastic half-space, whose boundary is chosen to be the xy plane, with the z-axis directed into the medium (Fig. 10). The conditions of ab-

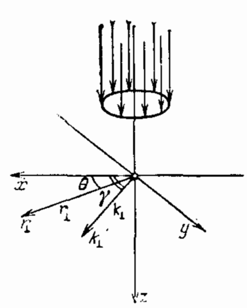

FIG. 10. Geometry of the problem and coordinate system used.

sence of stresses at the free surface $z = 0$ can be written in the form (the light pressure force does not practically need to be taken into account).

$$2\frac{\partial^2\varphi}{\partial z\,\partial x}+\frac{\partial^2\psi_z}{\partial z\,\partial y}=\frac{\partial^2\psi_y}{\partial z^2}-\frac{\partial^2\psi_y}{\partial x^2}+\frac{\partial^2\psi_x}{\partial x\,\partial y}, \tag{4}$$

$$2\frac{\partial^2\varphi}{\partial z\,\partial y}-\frac{\partial^2\psi_z}{\partial z\,\partial x}=\frac{\partial^2\psi_x}{\partial y^2}-\frac{\partial^2\psi_x}{\partial z^2}-\frac{\partial^2\psi_y}{\partial x\,\partial y}, \tag{5}$$

$$\Delta\varphi-2s^2\Delta_\perp\varphi+2s^2\left(\frac{\partial\psi_y}{\partial z\,\partial x}-\frac{\partial\psi_x}{\partial z\,\partial y}\right)=\left(1-\frac{4}{3}s^2\right)\beta\frac{\partial T}{\partial t}. \tag{6}$$

Here $s = c_t/c_l$, $\Delta_\perp = \partial^2/\partial x^2 + \partial^2/\partial y^2$ is the Laplace operator in transverse coordinates, and ψ_x, ψ_y, and ψ_z are, respectively, the components of the vector ψ. The condition of full determination of the system (1), (2), (4)–(6) is that the vector ψ be solenoidal:

$$\operatorname{div}\psi=0. \tag{7}$$

The system written down is quite awkward, and Eqs. (1), (2) are coupled through the boundary conditions (4)–(6). It is useful to introduce new variables

$$A=\frac{\partial\psi_y}{\partial x}-\frac{\partial\psi_x}{\partial y}, \tag{8}$$

$$B=\frac{\partial\psi_x}{\partial x}+\frac{\partial\psi_y}{\partial y}. \tag{9}$$

The quantity A has the meaning of the z-component of the divergence-free component of $\dot{u}$. The variables A and B satisfy a homogeneous equation similar to (2):

$$c_t^{-2}\frac{\partial^2(A,B)}{\partial t^2}-\Delta(A,B)=0. \tag{10}$$

In the variables φ, A, ψ_z, and B the boundary conditions (4)–(6) and condition (7) can be reduced to the form

$$z=0,\quad\left\{\begin{aligned}
&\frac{\partial}{\partial z}(\Delta_\perp\varphi)=\left(\frac{1}{2c_t^2}\frac{\partial^2}{\partial t^2}-\Delta_\perp\right)A, &(11)\\
&\frac{\partial A}{\partial z}=-\left(\frac{1}{2c_t^2}\frac{\partial^2}{\partial t^2}-\Delta_\perp\right)\varphi, &(12)\\
&\frac{\partial B}{\partial z}=-\left(\frac{1}{c_t^2}\frac{\partial^2}{\partial t^2}-\Delta_\perp\right)\psi_z, &(13)\\
&\Delta_\perp\frac{\partial\psi_z}{\partial z}=\left(\frac{1}{2c_t^2}\frac{\partial^2}{\partial z^2}-\Delta_\perp\right)B. &(14)
\end{aligned}\right.$$

The equations for these quantities remain independent. Therefore the problem decomposes into two pairs of independent equations for (φ, A) and (ψ_z, B), coupled in pairs through the boundary conditions. Since Eqs. (10) for ψ_z and B are homogeneous, then, obviously.

$$\psi_z=B\equiv 0 \tag{15}$$

(the initial conditions are, naturally, assumed to be homogeneous).

Thus, thermo-optic sound excitation in a homogeneous, isotropic, elastic half-space is described by two scalar equations for φ, Eq. (1), and for A, Eq. (10), coupled by the boundary conditions (11), (12). These equations describe the excitation of both bulk and Rayleigh waves. Thermoelastic stresses affect only the scalar potential φ, while shear stresses occur due to transverse inhomogeneities of the field φ at the boundary of the medium. Therefore, in the absence of sharp gradients of φ at the surface (both transverse and longitudinal) the excitation of shear, and, consequently, Rayleigh waves occurs ineffectively.

The solution of problem (1), (10), (12) is conveniently sought in spectral form. We introduce the Fourier transform in time and in transverse coordinates $\mathbf{r}_\perp = \{x,y\}$ (we denote the transformed functions by the sign "$\sim$" over them) and the Laplace transform in z:

$$\hat{T}(\omega,\mathbf{k}_\perp,p)=\int_0^\infty dz\iiint_{-\infty}^{+\infty}dt\,d\mathbf{r}_\perp\exp[i\omega t-i(\mathbf{k}_\perp\mathbf{r}_\perp)-pz]\,T(t,\mathbf{r}_\perp,z) \tag{16}$$

(the sign "$\wedge$" denotes the total transform of a function), and $\hat{\varphi}(\omega,\mathbf{k}_\perp,p)$, $\hat{A}(\omega,\mathbf{k}_\perp,p)$ are the similar spectral components of the fields $\varphi(t,\mathbf{r}_\perp,z)$ and $A(t,\mathbf{r}_\perp,z)$. In this case Eqs. (1) and (10) reduce to algebraic equations:

$$(k_l^2-k_\perp^2+p^2)\hat{\varphi}+\frac{d\tilde{\varphi}}{dz}\Big|_0+p\tilde{\varphi}|_0=-i\omega\left(1-\frac{4s^2}{3}\right)\beta\hat{T},$$

$$(k_t^2-k_\perp^2+p^2)\hat{A}+\frac{d\tilde{A}}{dz}\Big|_0+p\tilde{A}|_0=0,$$

where $k_l = \omega/c_l$, $k_t = \omega/c_t$, while

$$\tilde{\varphi}(\omega,\mathbf{k}_\perp,z)=\iiint_{-\infty}^{+\infty}dt\,d\mathbf{r}_\perp\exp[i\omega t-i(\mathbf{k}_\perp\mathbf{r}_\perp)]\,\varphi(t,\mathbf{r}_\perp,z)$$

(similarly for $\tilde{A}$), and $\tilde{\varphi}|_0$, $d\tilde{\varphi}/dz|_0$, $\tilde{A}|_0$, $d\tilde{A}/dz|_0$ are the Fourier components of the corresponding functions at $z = 0$.

From the condition that φ and A tend to zero for $z\to+\infty$ follows the absence of poles for the functions φ and A in the right half-plane $\mathrm{Re}\,p > 0$. Therefore, from the transformed equations follow relations for the spectra $\tilde{\varphi}|_0$ and $\tilde{A}|_0$ on the surface $z = 0$.

$$\frac{d\tilde{A}}{dz}\Big|_0+(k_\perp^2-k_t^2)^{1/2}\tilde{A}|_0=0, \tag{17}$$

$$\frac{d\tilde{\varphi}}{dz}\Big|_0+(k_\perp^2-k_l^2)^{1/2}\tilde{\varphi}_0\Big|=-i\omega\left(1-\frac{4s^2}{3}\right)\beta\hat{T}(\omega,\mathbf{k}_\perp,(k_\perp^2-k_l^2)^{1/2}). \tag{18}$$

The boundary conditions (11), (12) in the transformed coordinates are

$$\frac{k_\perp^2\,d\tilde{\varphi}}{dz}\Big|_0=-(k_\perp^2-k_2^2)\tilde{A}|_0, \tag{19}$$

$$\frac{d\tilde{A}}{dz}\Big|_0=-(k_\perp^2-k_2^2)\tilde{\varphi}|_0, \tag{20}$$

where $k_2 = \omega/\sqrt{2}c_t$.

For SAW the potentials φ and A separately do not have a physical meaning. Most of the interest for Rayleigh waves is in the normal component of the vibrational velocity $w(t,\mathbf{r}_\perp)$ at the surface of the medium $z = 0$. Its spectral component $\tilde{w}(\omega,\mathbf{k}_\perp)$ can be represented as follows in terms of the potentials:

$$\tilde{w}(\omega,\mathbf{k}_\perp)=\frac{d\tilde{\varphi}}{dz}\Big|_0+\tilde{A}|_0. \tag{21}$$

Expressing the quantities in the right-hand side of Eq. (21) by means of (17)–(20), the following expression can be obtained:

$$\tilde{w} = -i\omega\beta\left(1-\frac{4s^2}{3}\right)\frac{k_2^2(k_\perp^2-k_2^2)}{k_\perp^2(k_\perp^2-k_l^2)^{1/2}(k_\perp^2-k_t^2)^{1/2}-(k_\perp^2-k_2^2)^2} \times \hat{T}(\omega,\ \mathbf{k}_\perp,\ (k_\perp^2-k_l^2)^{1/2}), \tag{22}$$

where $k_\perp$ is the absolute value of the vector $\mathbf{k}_\perp$. Equation (22) provides the spectral component of the surface disturbance under the action of a nonstationary temperature field.

To the Rayleigh waves in solution (22) correspond the poles

$$k_\perp = \mp\frac{\omega}{c_R} = \mp k_R,$$

corresponding to the roots of the Rayleigh determinant:

$$k_R^2(k_R^2-k_t^2)^{1/2}(k_R^2-k_l^2)^{1/2}-(k_R^2-k_2^2)^2=0.$$

Performing the inverse Fourier transform over frequency and wave vectors, one obtains the coordinate and time dependence of the surface vibrational velocity:

$$w(t,\ r_\perp) = (2\pi^2)^{-1}F\beta\left(1-\frac{4s^2}{3}\right)\int_{-\infty}^{+\infty}d\omega\int_0^{2\pi}d\gamma\,\frac{\omega^3}{c_R^2} \times \exp\left\{-i\omega\left[t-\frac{r_\perp}{c_R}\cos(\theta-\gamma)\right]\right\} \times \hat{T}\left(\omega,\ \frac{\omega}{c_R},\ \gamma,\ |\omega|(c_R^{-2}-c_l^{-2})^{1/2}\right), \tag{23}$$

where the dimensionless factor

$$F=\frac{1}{4}\left(\frac{c_R}{c_t}\right)^2\left[2-\left(\frac{c_R}{c_t}\right)^2\right] \times\left\{\left[2+\left(1-\frac{c_R^2}{c_l^2}\right)^{-1}+\left(1-\frac{c_R^2}{c_t^2}\right)^{-1}\right]-8\right\}^{-1} \tag{24}$$

is determined only by the elastic properties of the medium (and is of the order of 0.1). Cylindrical coordinates were used in Eq. (23) (see Fig. 10). The physical meaning of the solution (23) is simple, it is the expansion of the SAW field in traveling plane monochromatic waves. The spectral field density is determined by the spectral component of the temperature field at frequency ω, its corresponding spatial frequency ω/c_R, and the SAW damping coefficient $|\omega|(c_R^{-2}-c_l^{-2})^{1/2}$.

The structure of the temperature field is determined by the light intensity distribution over the beam cross section and by the depth dependence of the light absorption coefficient. We assume that a laser beam with intensity

$$I = I_0F(t,\ \mathbf{r}_\perp) \tag{25}$$

is incident normally on the surface of the solid. The temperature increment is then described by the equation

$$\frac{\partial T}{\partial t}-\chi\Delta T=-\frac{bI_0}{\rho c}F(t,\ \mathbf{r}_\perp)\frac{df}{dz}, \tag{26}$$

where χ is the temperature conductivity, c is the specific heat capacity of the medium, b is the fraction of the light intensity entering into the medium, the function

$$f(z)=\exp\left(-\int_0^z\alpha(z)\,dz\right) \tag{27}$$

describes the depth dependence of the light intensity, and $\alpha(z)$ is the distribution of the light absorption coefficient. The condition of absence of thermal flux at the boundary of the medium is

$$\left.\frac{\partial T}{\partial z}\right|_0=0. \tag{28}$$

The solution of the problem (26),(28) is also conveniently sought in the spectral form (16). Taking into account the condition $T(z\to+\infty)\to0$, the solution is written in the form

$$\hat{T}(\omega,\ \mathbf{k}_\perp,\ p) = \frac{bI_0}{\rho c\chi}\tilde{F}(\omega,\ \mathbf{k}_\perp)\frac{(k_\perp^2-ik_\theta^2)^{1/2}\hat{f}(p)-p\hat{f}((k_\perp^2-ik_\theta^2)^{1/2})}{(k_\perp^2-ik_\theta^2)^{1/2}(p^2-k_\perp^2+ik_\theta^2)}, \tag{29}$$

where

$$\tilde{F}(\omega,\ \mathbf{k}_\perp)=\iiint_{-\infty}^{+\infty}\exp[i\omega t-i(\mathbf{k}_\perp\mathbf{r}_\perp)]F(t,\ \mathbf{r}_\perp)]\,dt\,d\mathbf{r}_\perp,$$

$$\hat{f}(p)=\int_0^\infty e^{-pz}\frac{df}{dz}\,dz,$$

and $\mathrm{Re}(k_\perp^2-ik_\theta^2)^{1/2}>0$, $k_\theta^2=\omega/\chi$ is the square of the wave vector of the thermal wave.

Expression (29) is quite cumbersome, but in many practical cases it can be simplified. Table I shows the values of k_R, k_θ, and $(k_R^2-k_l^2)^{1/2}$ for several media. For frequencies lower than 3 GHz (as well as for media with a small thermal conductivity, and for higher frequencies) the thermal wavelength remains smaller than the Rayleigh wavelength. Therefore, in Eq. (29) it can be assumed that $k_\perp^2\ll k_\theta^2$, as well as $p^2\ll k_\theta^2$. Equation (29) correspondingly reduces to the following:

$$\hat{T}(\omega,\ \mathbf{k}_\perp,\ p)=-\frac{i}{\omega}\frac{bI_0}{\rho c}\tilde{F}(\omega,\ \mathbf{k}_\perp)\hat{f}(p). \tag{30}$$

In fact this is the approximation of a nonheatconducting medium.

Equations (29) and (30) provide the solution of the

TABLE I. Rayleigh k_R and thermal k_θ wave vectors, and the SAW decrement coefficient $p=(k_R^2-k_l^2)^{1/2}$ $(\mu m)^{-1}$.

Frequency	Aluminum	Copper	Silicon	Melted quartz	Lithium niobate
0,1 GHz	p, 0,2	0,26	0,10	0,16	0,16
	k_R, 0,22	0,3	0,13	0,19	0,18
	k_θ, 2,7	2,3	3,0	9,6	20
1 GHz	p, 2,0	2,6	1,0	1,6	1,6
	k_R, 2,2	3,0	1,3	1,9	1,8
	k_θ, 8,6	7,4	9,4	30	63
10 GHz	p, 20	26	10	16	16
	k_R, 22	30	23	19	18
	k_θ, 27	23	30	96	198

laser SAW excitation problem:

$$w(t,\mathbf{r}_\perp)=\beta\left(1-\frac{4s^2}{3}\right)\frac{bI_0F}{\rho c}\times\int_{-\infty}^{+\infty}d\omega\int_0^{2\pi}d\gamma\left(-i\frac{\omega^2}{c_R^2}\right)\times\exp\left\{-i\omega\left[t-\frac{r_\perp}{c_R}\cos(\theta-\gamma)\right]\right\}\times\widetilde{F}\left(\omega,\frac{\omega}{c_R},\gamma\right)\hat{f}\left(|\omega|(c_R^{-2}-c_l^{-2})^{1/2}\right). \quad (31)$$

The expression obtained is fundamental for the OAS problem of SAW, it relates the Rayleigh wave spectrum to the spectra of light emission intensities and with intensity distributions over depth. This makes it possible, in principle, to determine the distribution of the absorption coefficient over depth for known light intensity distributions over a cross section, and inversely, to determine the distribution of absorption over the beam cross section from the known absorption distribution over depth.

It is useful to distinguish two cases, a resting and moving beam (the case of a resting beam correspond to velocities of its motion, much lower than the velocity of the Rayleigh wave). Since for problems of OAS based on SAW the scanning regime with nearly sonic beam velocity is not of substantial interest, it will be assumed in what follows that the SAW is excited by a resting (or slowly moving) beam. In this case the spatial and temporal source spectra $\widetilde{F}(\omega\mathbf{k}_\perp)$ are factorized:

$$\widetilde{F}(\omega,\mathbf{k}_\perp)=\widetilde{F}_t(\omega)\,\widetilde{F}_r(\mathbf{k}_\perp).$$

This makes it possible to introduce the concept of a transfer function, in analogy with laser excitation of bulk waves.[26,27]

Consider initially the one-dimensional source distribution:

$$F_r(\mathbf{r}_\perp)=F_r(x)$$

(the beam represents a band extended along the y-axis). Their spatial spectrum is then $\widetilde{F}_r(\mathbf{k}_\perp)=2\pi\delta(k_\perp\sin\gamma)\times\widetilde{F}_r(k_\perp\cos\gamma)$. Retaining in the solution (31) only the wave traveling toward increasing x, we find for the surface displacement velocity:

$$\omega\left(\tau=t-\frac{x}{c_R}\right)=\frac{F\beta}{\pi}\left(1-\frac{4s^2}{3}\right)\frac{bI_0}{\rho c}\int_{-\infty}^{+\infty}i\frac{\omega}{c_R}e^{-i\omega\tau}\widetilde{F}_r\left(\frac{\omega}{c_R}\right)\times\hat{f}\left(|\omega|(c_R^{-2}-c_l^{-2})^{1/2}\right)\widetilde{F}_t(\omega)\,d\omega. \quad (32)$$

Expression (32) can be obtained from the solutions in Ref. 17. The function

$$K_1(\omega)=i\frac{\omega}{c_R}\widetilde{F}_r\left(\frac{\omega}{c_R}\right)\hat{f}\left(|\omega|(c_R^{-2}-c_l^{-2})^{1/2}\right) \quad (33)$$

can be called the transfer function of laser SAW sources in plane geometry, since it relates the spectrum of a traveling Rayleigh wave with the temporal light intensity spectrum. Therefore, for effective SAW excitation at some frequency it is necessary that the spectral component of the intensity distribution not be small; in other words, that the beam satisfy the condition $k_R a\lesssim 1$. Besides, the light absorption coefficient must be quite large: $\alpha\gtrsim k_R$ (the width of the absorbing layer must be smaller than the Rayleigh wavelength). We note that the source transfer function, determined by the mask geometry, was, in fact, measured in Ref. 12 (see Fig. 2).

The result (32) is in qualitative agreement with experiments.[18] Indeed, for a short laser pulse and surface absorption the SAW pulse is proportional to the derivative of the intensity envelope. This is also observed experimentally (see Fig. 7). Besides, an increase in spot size leads to a proportional increase in the duration of SAW pulse, as observed experimentally.[23] It is necessary, however, to take into account that the restricted nature of the transformer bandwidth affected the pulse shape, therefore quantitative comparison with available experimental data is difficult.

The transfer function of laser SAW sources can also be introduced in the more general case. For this it is necessary to separate out only the propagating wave in the solution (31). It is formed outside the heat release region, therefore for $\omega r_\perp/c_R\gg 1$ and in the far wave zone Eq. (31) reduces to

$$w(t,r_\perp,\theta)=F\beta\left(1-\frac{4s^2}{3}\right)\frac{bI_0}{2\pi\rho c}\int_{-\infty}^{+\infty}\frac{\omega^2}{c_R^2}\left(\frac{c_R}{\pi|\omega|r_\perp}\right)^{1/2}\times\exp\left[-i\omega\left(t-\frac{r_\perp}{c_R}\right)-i\frac{\pi}{4}\right]\times\widetilde{F}_r\left(\frac{\omega}{c_R},\theta\right)\hat{f}\left(|\omega|(c_R^{-2}-c_l^{-2})^{1/2}\right)\widetilde{F}_t(\omega)\,d\omega. \quad (34)$$

Equation (34) provides an expansion of SAW in diverging plane waves in the far wave zone. As could be expected, the angular dependence of the SAW is determined only by the light intensity distribution over the spot cross section. In particular, for an axially symmetric laser beam the SAW will also be axially symmetric. Its amplitude decreases with distance as $r^{-1/2}$, as in the case for a cylindrical wave. This is in qualitative agreement with experimental results.[23]

The function

$$K_2(\omega,\theta)=|\omega|^{3/2}\widetilde{F}_r\left(\frac{\omega}{c_R},\theta\right)\hat{f}\left(|\omega|(c_R^{-2}-c_l^{-2})^{1/2}\right) \quad (35)$$

can also be called a transfer function. However, unlike the case of a plane wave, it contains a dependence on the observation angle θ (the same also occurs in the case of excitation of bulk waves[27]). Equation (35) can be used to analyze optoacoustic spectrograms on SAW.

We determine the amplitude of the vibrational velocity of the surface. For monochromatic modulation of light intensity of a narrow beam $\omega a/c_R\lesssim 1$ and strong absorption $\omega/c_R\lesssim\alpha$ it becomes

$$w_0\sim 2F\beta\left(1-\frac{4s^2}{3}\right)\frac{bI_0a}{\rho c c_R}$$

for a plane wave, and

$$w_0\sim F\beta\left(1-\frac{4s^2}{3}\right)\frac{bW}{\rho c}\frac{\omega^2}{c_R^2}\left(\frac{c_R}{\pi\omega r_\perp}\right)^{1/2}$$

in the cylindrically symmetric case (W is the laser radiation intensity). For aluminum, for example, it amounts to

$$w_0 \sim 3.8 \cdot 10^{-6}\ \mathrm{cm}^3/\mathrm{J} \quad (bI_0),$$

and is $(a/r_\perp)^{1/2}$ times lower in the second case. These estimates give for the transformation effectiveness $I_{\mathrm{SAW}}/I_0 \sim 6 \cdot 10^{-12}\ \mathrm{cm}^2/W(bI_0)$.

The SAW amplitude, excited thermo-optically, is directly proprotional to the laser radiation intensity. Correspondingly, the effectiveness of energy transformation is also directly proportional to the light intensity. These laws are common for the thermo-optic excitation mechanism of any type of acoustic waves.

If the thermo-optic SAW excitation is carried out by short, $c_R \tau_l \ll a$ laser pulses in a strongly light-absorbing medium, the pulse shape of the Rayleigh wave will be determined by the light intensity distribution over the spot cross section. The amplitude of the surface displacement velocity can be determined by the equation

$$w_0 \sim 2F\beta \left(1 - \frac{4s^2}{3}\right) \frac{bE_0 c_R}{\rho c a}$$

in the plane case and will be lower by the factor $(a/r_\perp)^{1/2}$ for cylindrical beam geometry, where E_0 is the surface density of the incident energy. For aluminum these estimates give in planar geometry

$$w_0 \sim (1\mathrm{cm/s}) \left(\frac{bE_0}{a}\ \mathrm{cm}^3/\mathrm{J}\right).$$

If the light penetration depth is large: $\alpha c_R \tau_l \ll 1$ and $\alpha a \ll 1$, then the SAW shape is determined only by the light absorption distribution over depth. The spectral representation is in this case most convenient for analysis.

4. POSSIBILITIES OF OPTO-ACOUSTIC SPECTROSCOPY USING RAYLEIGH WAVES AND ITS POTENTIAL APPLICATIONS

The advantages and possible uses of OAS using SAW can be brought out by comparison with traditional OAS methods for a solid using bulk waves. First it is necessary to note that, as in the case of OAS using bulk waves, in OAS using SAW a serious difficulty in the wideband regime is related to recording of acoustic videopulses. Therefore, more satisfactory is the use of periodic or pulse-periodic intensity modulation of laser radiation. This makes it advisable to use as light sources dye lasers with mode synchronization. The pulse-periodic regime is more effective from an energy point of view (the transformation effectiveness is proportional to the power or to the light intensity). On the whole OAS using SAW retains the main advantages of OAS using bulk waves; in particular, only the absorbed part of the energy is recorded by its means.

The spectral characteristics of SAW during thermo-optic excitation are formed by the frequency and spatial spectra of the light intensity distribution. The main difference from thermo-optic excitation of bulk waves consists of the following: the SAW spectrum is proportional to the Laplace component of the intensity distribution over depth, while the spectrum of bulk waves is proportional to the Fourier component of this distribution. Therefore, OAS using SAW can be particularly useful for studies of properties of near-surface layers with sizes of the order of the Rayleigh wavelength; the energy absorbed at large depths practically does not affect SAW excitation. This has already been verified by the first experiments.[18]

The presence of single-valued connection (32) or (34) of the SAW spectrum with the spectrum of the light intensity distribution over depth makes it possible to reconstruct adequately the distribution of the light absorption coefficient. In this case the spot dimensions must be smaller than the penetration depth of light (otherwise the SAW spectrum will be determined by the transverse intensity distribution), therefore the diagnostics is naturally local. In this case the main fraction of energy of acoustic distrubances is associated with the Rayleigh wave,[17] therefore this method is more effective than OAS using bulk waves. For these reasons the determination of the transverse distribution of the light absorption coefficient of OAS using SAW can have several advantages over OAS using bulk waves. The definite technical advantage of OAS using SAW is the possibility of contactless optical wave recording on the same plane on which it is excited.

Equations (32), (34) make it possible to estimate the resolving capability of the method. To find the spectral component of $\hat{f}(p)$ over the SAW spectrum it is necessary that the spectral component of the transverse intensity distribution $\tilde{F}_r(p/[1-(c_R^2/c_l^2)]^{1/2}$ and the component at the modulation frequency $\tilde{F}_t(pc_R/[1-(c_R^2/c_l^2)]^{1/2})$ not be small. The first restriction is the stronger one. The size of the light spot can be of the order of the light wave length λ. Correspondingly, the spatial resolution of the OAS method using SAW is restricted to a level of the order of $\lambda/2[1-(c_R^2/c_l^2)]^{1/2} \sim 0.3$–$1\ \mu$m. This corresponds the modulation frequencies $\nu \sim c_R/\pi\lambda \sim 1$–$3$ GHz. As seen from Table I, in this region the approximation of a nonheatconducting medium is still valid. It is also obvious that resolution in depth and in the transverse direction are practically equivalent. The required frequency modulations are achieved in lasers with mode synchronization (as harmonics of the pulse repetition frequency). To enhance the resolving power it is entirely possible to use other kinds of penetrating radiation, which produce sharper beam focusing.

The OAS method using SAW appears to be quite promising as a control means of technological processes in microelectronics, as a method of surface diagnostics. The discussion of other possibilities of the method described, such as local measurements of elastic constants, is premature due to shortage of experimental data. Besides, the thermo-optic method is extremely convenient and flexible for excitation of intense, high-frequency Rayleigh waves (for example, for light intensities $I_0 \sim 10^8\ \mathrm{W/cm}^2$ the achievable Mach numbers of the wave are $\sim 10^{-4}$). It can be useful in many problems of acousto-electronics. Its various advantages and features have been discussed above (see Section 2).

On the whole it can be repeated that OAS using SAW, possessing distinct advantages over OAS using bulk waves (being contactless, localized, highly sensitive to the absorbed energy) can be most useful in investigating near-surface layers of different media. It is precisely this feature which determines the possibilities of its applications.

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