Matter (Transactions of the All-Union Correspondence Institute of Mechanical Engineering, No. 29) [in Russian], VZMI (1977), p. 14.
[2]V. I. Domarkas and R.-P. Yu. Kazhis, Piezoelectric Transducers for Testing and Measurement [in Russian], MINTIS, Vilnius (1975).

Translated by J. S. Wood

Thermooptical generation of surface acoustic waves in a solid

V. V. Krylov and V. I. Pavlov

Physics Faculty, M. V. Lomonosov State University, Moscow

(Submitted February 26, 1981)

Akust. Zh. **28**, 836–837 (November–December 1982)

PACS numbers: 43.35.Pt, 78.20.Nv

The thermooptical generation of acoustic waves receives attention in connection with its numerous applications in various branches of experimental physics.[1-4] Experiments have been reported in which the generation of Rayleigh surface waves, along with longitudinal and transverse bulk waves, was observed when a focused high-intensity laser pulse was incident on the surface of metals.[4] The problem of the excitation of Rayleigh waves by an intensity-modulated narrow light beam is analyzed theoretically for the first time in the present article.

The basic equations are the equation of motion $\rho\ddot{u}_i = \tau_{ij,j}$ and the linearized equation of state with temperature effects included[5] $\sigma_{ij} = 2\mu^T\varepsilon_{ij} + [\lambda^T\varepsilon_{\alpha\alpha} - \gamma K(T-T_0)]\cdot\delta_{ij}$. Here ε_{ij} denotes the components of the linearized strain tensor, λ^T and μ^T are the isothermal Lamé constants, γ is the coefficient of thermal expansion, $K = \lambda^T + 2\mu^T/3$ is the bulk modulus, and T_0 is the initial temperature. We augment these equations with the linearized heat-balance equation, neglecting viscosity and heat-conduction effects, $\rho c_V\dot{T} = -\gamma K T_0\dot{\varepsilon}_{\alpha\alpha} - \partial[\beta I(x)f(t)e^{-\alpha z}]/\partial z$, where c_V is the specific heat at constant volume, β is the coefficient of transmission of optical radiation into the solid medium, I(x) is the intensity distribution of the incident radiation (the two-dimensional case is considered), α is the coefficient of light absorption in the medium, and f(t) is the light intensity modulation function. The field of the generated acoustic waves must also satisfy the conditions of zero net stress at the surface z = 0: $\sigma_{ij}n_j = 0$.

By means of the scalar Lamé potentials φ and ψ, which are related to the displacements u_i in the form $\dot{u}_x = \varphi_{,x} - \psi_{,z}$ and $\dot{u}_z = \varphi_{,z} + \psi_{,x}$, the given system of equations is reduced to two inhomogeneous equations in φ and ψ with two inhomogeneous mixed boundary conditions. The complete solution is written with the aid of surface and volume Green tensors[6,7] and represents Sommerfeld-type integrals with respect to the variable wave number k. In particular, the field of the excited Rayleigh waves, which is described by the contributions of the poles in the integrand, has the following form in the case of 100% harmonic modulation:

$$\varphi_R(x,z) = \frac{i\gamma\alpha\beta K\Phi(k_R)}{\rho c_V F'(k_R)}\left[\frac{2k_R^2-k_t^2}{\mu} - \frac{4k_R^2 s}{(\lambda+2\mu)(\alpha+q)}\right]\exp(ik_Rx - qz),$$

$$\psi_R(x,z) = \frac{2k_R\gamma\alpha\beta K\Phi(k_R)}{\rho c_V F'(k_R)}\left[\frac{q}{\mu} - \frac{2k_R^2-k_t^2}{(\lambda+2\mu)(\alpha+q)}\right]\exp(ik_Rx - sz),$$

where k_R is the wave number of the generated Rayleigh wave, λ and μ are the adiabatic Lamé constants, $F(k) = (2k^2 - k_t^2)^2 - 4k^2(k^2 - k_l^2)^{1/2}(k^2 - k_t^2)^{1/2}$ is the Rayleigh determinant, $\Phi(k_R) = \int_{-\infty}^{\infty} I(x)\exp(-ik_Rx)\,dx$ is the Fourier transform of I(x), $q = (k_R^2 - k_l^2)^{1/2}$, and $s = (k_R^2 - k_t^2)^{1/2}$. We note that the first terms in the brackets of the expressions for φ_R and ψ_R are attributable to surface forces, and the second terms to volume forces. It is seen at once that the influence of the volume forces is negligible in media that strongly absorb light $[\alpha \to \infty]$, for example, in metals. The factor $\Phi(k_R)$ characterizes the existence of optimal cross-sectional dimensions of the light beam such that the efficiency of surface-wave generation is a maximum. For example, in the case of a Gaussian beam with a characteristic width a, the optimum occurs for $k_Ra = \sqrt{2}$. In the optimal state the fraction of the power of the excited Rayleigh waves for strongly light-absorbing media with a Poisson ratio of 0.25 is ~67% of the total power of all the waves excited. The power fractions for longitudinal and transverse bulk waves are 7 and 26% respectively. With an increase in k_Ra the fractions of the radiated Rayleigh and transverse bulk waves drop rapidly to zero, and mainly longitudinal waves are radiated into the volume. This situation is entirely reasonable insofar as for light beams of infinite width the thermooptical generation of sound in a solid does not differ in principle from the case of a liquid.[1] The thermooptical generation efficiency η, defined as the ratio of the total power of the investigated wave mode to the power of the light beam, as in the case of a liquid, is proportional to the peak laser intensity I_0. An estimation of η for the generation of 30 MHz Rayleigh waves in aluminum by a CO_2 laser with a wavelength of 10.6 μm for $k_Ra = \sqrt{2}$ yields $\eta \sim 2\cdot 10^{-6}I_0$, where I_0 is evaluated in W/cm², i.e., the generation process is fairly efficient. The thermooptical generation of monochromatic Rayleigh waves can be enhanced by applying spatially periodic irradiation of the surface with a period equal to the Rayleigh wavelength (see Ref. 8). It follows directly from the expressions for φ_R and ψ_R that the amplitudes of the Rayleigh waves in this case increase (without regard for scattering by thermal inhomogeneities) directly as the number of illumination periods.

We note that these results agree satisfactorily with the experiments of Aindow and others.[9] In that work the generation of Rayleigh and bulk waves in aluminum by short laser pulses was investigated in greater detail than in Ref. 4. In particular, it was observed experimentally that the diameter of the laser spot is increased from 0.8 to 2 mm in correspondence with the above-stated resonance condition $k_R a = \sqrt{2}$. An estimation of the value of η according to the experimental data of Ref. 9 [with allowance for the resonant attenuation of the spectrum of the laser pulse $\sim\Phi(k_R)$ and typical conversion losses in a wedge] yields $\eta \sim 10^{-2}$, which agrees in order of magnitude with the value of η calculated for the observed resonance frequency ($f_0 \simeq 1$ MHz) according to the present theory.

[1]F. V. Bunkin and V. M. Komissarov, "Optical excitation of sound waves," Akust. Zh. 19, 305 (1973) [Sov. Phys. Acoust. 16, 203 (1973)].

[2]S. G. Kasoev and L. M. Lyamshev, "Theory of laser-pulse generation of sound in a liquid," Akust. Zh. 23, 890 (1977) [Sov. Phys. Acoust. 23, 510 (1977)].

[3]A. A. Karabutov, O. V. Rudenko, and E. B. Cherepetskaya, "Theory of the thermooptical generation of nonsteady acoustic fields," Akust. Zh. 25, 383 (1979) [Sov. Phys. Acoust. 25, 218 (1979)].

[4]H. M. Ledbetter and J. C. Moulder, "Laser induced Rayleigh waves in aluminum," J. Acoust. Soc. Am. 65, 840 (1979).

[5]L. D. Landau and E. M. Lifshitz, Theory of Elasticity, Addison – Wesley, Reading, MA (1959).

[6]E. R. Lapwood, "The disturbance due to a line source in a semi-infinite elastic medium," Philos. Trans. R. Soc. London Ser. A 242, 63 (1949).

[7]K. F. Graff, Wave Motion in Elastic Solids, Clarendon Press, Oxford (1975).

[8]E. A. Ash, E. Dieulesaint, and H. Rakouth, "Generation of surface acoustic waves by means of a c.w. laser," Electron. Lett. 16, 470 (1980).

[9]A. M. Aindow, R. J. Dewhurst, D. A. Hutchins, and S. B. Palmer, "Laser-generated ultrasonic pulses at free metal surfaces," J. Acoust. Soc. Am. 69, 440 (1981).

Translated by J. S. Wood