Propagation of acoustic surface waves in periodic structures

Yu. V. Gulyaev and V. P. Plesskiĭ

Institute of Radio Engineering and Electronics, Academy of Sciences of the USSR, Moscow
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This review covers the propagation of acoustic surface waves (ASW) in periodic structures. The authors discuss the main types of ASW: Rayleigh waves, Gulyaev-Bleustein waves, Love waves. Shear surface waves which can propagate along a periodically uneven surface of an elastic solid are described in detail. The authors rigorously treat the Bragg reflection of ASW from periodic arrays of grooves on the substrate for the cases of normal, oblique, and side incidence. Reciprocal conversion effects between bulk and surface waves in an array whose period is close to the ASW wavelength are discussed, together with such related effects as the interaction between Rayleigh waves and Lamb modes, acoustic wave transmission through a gap in a piezoelectric material, etc. Laser excitation of ASW and magnetostatic wave propagation in periodic structures are also reviewed.

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1. INTRODUCTION

A century has passed since 1885, when Rayleigh first described acoustic surface waves in an elastic solid.[1] For a long time this outstanding scientific discovery was not sufficiently appreciated because Rayleigh waves appeared to have few applications, primarily in seismology and nondestructive product testing. A quarter of a century ago, however, it was pointed out that ASW can effectively interact with electrons in piezoelectric materials and layered piezoelectric-semiconductor structures.[2] After the discovery of an efficient method of exciting high-frequency ASW waves in piezoelectrics using interdigital transducers (IDT)[3] it became clear that ASW can furnish the physical mechanism for a large number of analog signal-processing devices. Thereafter the volume of research into surface waves grew precipitously. Today the number of papers published on this topic probably exceeds 10^4. Surface waves attract such interest because they possess a number of unique properties: their propagation speed is low; they can be influenced externally in the course of propagation; they can be excited in piezoelectrics with low losses. These and other advantages of ASW allowed researchers and designers to develop a number of devices—filters (bandwidth, conjugate, dispersion), resonators, delay lines, spectrum analyzers—whose performance is a marked improvement on analogous devices based on other physical mechanisms.

A large class of ASW-employing devices is based on periodic arrays of elements located along the propagation path. In order to achieve the desired device characteristics one should be able to control the propagation of the wave by means of low-loss reflection, scattering, conversion of bulk waves into surface waves, etc. As a rule, due to the complexity of ASW structure these operations cannot be performed by a single local element; rather, a large number of periodically (or quasiperiodically) located inhomogeneities on the surface of the acoustic medium provide the necessary control over wave propagation. Separating the excitation and reception of ASW (via IDT) from the design of device characteristics (using reflecting structures) also affords a number of advantages. Currently, reflecting structures are being employed to produce resonators and dispersive delay lines with unique parameters.

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The great practical importance of acoustic surface wave propagation in periodic structures has drawn many researchers to this problem. This review covers the propagation of various types of acoustic waves in substrates with periodic arrays on the surface, since practical applications often exploit periodic structures (for example, arrays of grooves). We omit the problem of "electrical" periodic disturbances, like thin conducting stripes on the piezoelectric surface. These are less common in real applications than arrays of grooves and they are properly treated in the theory of IDT transducers, which requires a different mathematical formalism.

Both the properties of surface waves and the utilization of ASW in signal-processing devices are discussed in a large number of reviews[3–5] and monographs.[6–18] Consequently, in this review we shall describe only the fundamental characteristics of Rayleigh waves, shear ASW in piezoelectrics, and several other types of ASW. Instead, we shall discuss in detail the studies which focus on the propagation of ASW along surfaces with single or periodic inhomogeneities.

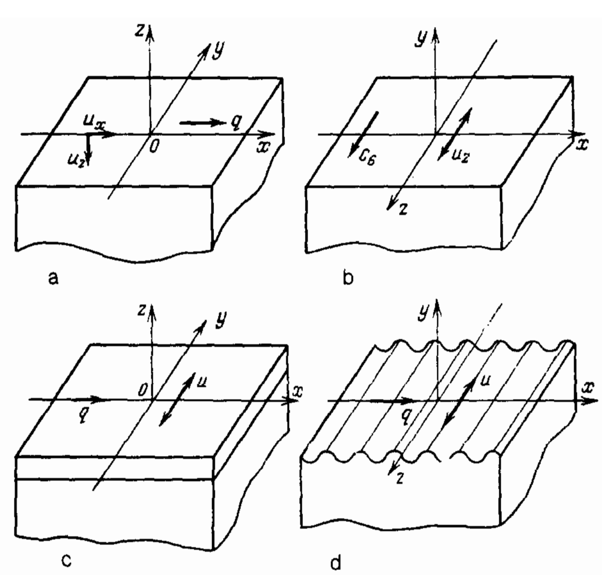

FIG. 1. a—Rayleigh waves. b—Shear surface electroacoustic waves. c—Love waves. d—Shear ASW on a corrugated surface.

2. RAYLEIGH WAVES, SHEAR ACOUSTIC SURFACE WAVES IN PIEZOELECTRICS, AND OTHER TYPES OF ASW. NEAR-SURFACE WAVES

In describing Rayleigh waves propagating along the surface of an isotropic, elastic semiinfinite space (Fig. 1), the displacement **u** can be conveniently expressed via a combination of a scalar φ and vector Ψ potentials:[12]

$$\mathbf{u} = \operatorname{grad} \varphi + \operatorname{curl} \psi \tag{1}$$

This representation can accommodate any spatial structure of the wave field by decomposing the wave into its compression (φ) and shear (Ψ) components (see Refs. 18–20). The equations for φ and Ψ are independent and can be written as:

$$\begin{aligned} &\ddot{\varphi} - c_l^2 \Delta\varphi = 0, \\ &\ddot{\psi} - c_t^2 \Delta\psi = 0, \end{aligned} \tag{2}$$

where Δ is the Laplacian; c_l and c_t are the longitudinal and transverse acoustic velocities respectively. When the wave propagates along the OX axis (see Fig. 1,a) and the displacement vector lies in the sagittal (X,Z) plane, the vector potential has only one non-zero component Ψ_y. In this case the displacements u_x and u_z are described by the formulae

$$u_x = \frac{\partial\varphi}{\partial x} - \frac{\partial\psi}{\partial z}, \quad u_z = \frac{\partial\varphi}{\partial z} + \frac{\partial\psi}{\partial x}. \tag{3}$$

The solutions to equations (2), which describe a surface wave, have the following form:

$$\begin{aligned} \varphi &= \varphi_0 \exp\,[pz + i\,(qx - \omega t)], \\ \psi &= \psi_0 \exp\,[sz + i\,(qx - \omega t)], \end{aligned} \tag{4}$$

where ω and q are the frequency and wavenumber; φ_0 and Ψ_0 are the amplitudes of the two wave components; p and s are the coefficients which describe the attenuation of compression and shear waves moving into the bulk of the substrate. It follows from the equations of motion (2) that

$$\begin{aligned} &p^2 = q^2 - k_l^2, \\ &s^2 = q^2 - k_t^2, \quad \operatorname{Re} p,\ s > 0, \end{aligned}$$

where $k_l = \omega/c_l$, $k_t = \omega/c_t$ are the wavenumbers of longitudinal and shear bulk waves.

At the free surface of the half-space $z = 0$ the stress-free conditions $\sigma_{zz} = \sigma_{xz} = 0$ must be fulfilled, hence the Rayleigh equation:

$$D\ (q,\ \omega) = (q^2 + s^2)^2 - 4q^2ps = 0. \tag{5}$$

Introducing the Rayleigh propagation speed v_R ($q = \omega/v_R$), we see that v_R is independent of frequency, i.e. in a classical elastic solid Rayleigh waves are nondispersive and the ratio v_R/c_t is determined by the ratio

$$\frac{c_l}{c_t} = \left(\frac{2-2\sigma}{1-2\sigma}\right)^{1/2}$$

and depends only on the Poisson coefficient σ. The Rayleigh equation is usually solved numerically.[12] In Fig. 2 we plot the dependence of the quantity $q_R/k_t = c_t/v_R$ on the Poisson coefficient. The value of the derivative of the Rayleigh determinant $D'_q(\omega,q)|_{q=q_R}$ enters into a number of expressions that govern the decay and excitation of Rayleigh waves—in Fig. 3 we plot the dependence of the corresponding dimensionless quantity

$$\Delta'_R \equiv -\frac{D'_q}{k_t^3}.$$

The amplitudes φ_0 and Ψ_0 are linearly dependent; accordingly, solutions of (4) can be represented as

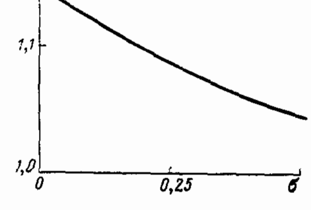

FIG. 2. Rayleigh wave propagation velocity as a function of the Poisson ratio.

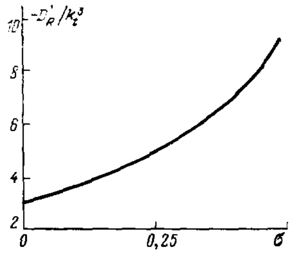

FIG. 3. The quantity $-D'_R/k_t^3$ as a function of the Poisson ratio.

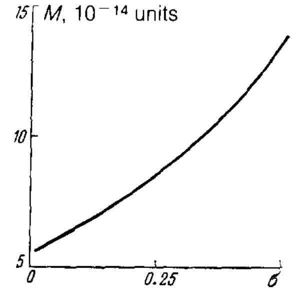

FIG. 4.

$$\varphi = \varphi_0 \exp[pz + i(q_R x - \omega t)],$$
$$\psi = \frac{2iq_R p}{q_R^2 + s^2}\varphi_0 \exp[sz + i(q_R x - \omega t)]. \tag{6}$$

The displacements u_x and u_z are computed from formulae (3). In particular, for the displacement amplitude u_z at the $z = 0$ surface we have

$$u_z = -\frac{pk_t^2}{q_R^2 + s^2}\varphi_0; \tag{7}$$

accordingly $u_x|_{z=0}$ is given by the formula

$$u_x = i\frac{k_t^2}{2q_R}\varphi_0. \tag{8}$$

From these expressions we find that the particles of the acoustic medium move in ellipses as the Rayleigh wave passes: at the "crest" of the wave the particles move in the opposite direction to the wave propagation vector. (If the wave is propagating in the negative OX direction Ψ in (6) and u_x in (8) change sign.)

The energy flux of a Rayleigh wave per unit width of the acoustic wavefront W is given by the formula[18]

$$\mathcal{P}_R = -\int_{\infty}^{0} \langle \sigma_{1k}\dot{u}_k\rangle \, dz = \frac{1}{2}\,\mathrm{Re}\int_{-\infty}^{0} i\omega\sigma_{1k}u_k^* \, dz \tag{9}$$

(u_k^* is the complex conjugate of u_k). Substituting into (6) we obtain

$$\mathcal{P}_R = \frac{\rho\omega^3}{2}\,\frac{-D'_R}{8q_R^2 s}\,|\varphi_0|^2, \tag{10}$$

If in this last expression φ_0 is expressed via (7) in terms of displacement u_z normal to the surface, we find

$$\mathcal{P}_R = \frac{\pi(-\Delta'_R)}{2(z^2-a^2)^{1/2}}\, f\rho v_t^2 |u_z|^2, \quad z = \frac{q}{k_t}, \quad a^2 = \left(\frac{u_t}{v_l}\right)^2. \tag{11}$$

For numerical estimates it is convenient to express the energy flux $\mathcal{P}_R$ in W/cm, the frequency $f = \omega/2\pi$ in GHz, the density ρ in g/cm^3, the amplitude u_z in Å: then (11) can be rewritten as

$$\mathcal{P}_R = M f u_z^2 v_t^2 \rho, \tag{12}$$

where $M(\sigma)$ is a function of the Poisson coefficient which is plotted in Fig. 4.

Note that the proportionality of the energy flux to the characteristic determinant D'_q is no accident, but rather has profound physical origins.[21,22]

The above-discussed relations allow us to calculate all the essential properties of Rayleigh waves in an isotropic solid. In analytic calculations of Rayleigh waves the Rayleigh equation (5), together with the expressions for the attenuation constants p and s, form a peculiar "Rayleigh trigonometry". Accordingly, physically equivalent expressions can take on different explicit forms, which often happens in research papers. An example of this is the equation

$$p - s = \frac{k_t^4}{4q^2 s}, \tag{13}$$

which is equivalent to the Rayleigh equation (5).

Although in practice most ASW-employing devices are fabricated on anisotropic crystalline substrates, theoretical investigations of ASW physics usually focus on the isotropic model of an elastic solid. The reasons for this are several. First, an analytic description of Rayleigh waves in crystals is hindered by the complexity of resulting equations and usually cannot be carried out in closed form. Second, real devices often make use of symmetrical crystal cuts and wave propagation vectors because anisotropic effects (for example, deviation of ASW energy flux vector from its wavevector) are usually undesirable. In actual use, nonsymmetric cuts and directions are usually the "penalty" paid in exchange for improved wave characteristics, such as enhanced thermal stability. For a number of frequently used cuts and crystal symmetry directions (for example, YZ-$LiNbO_3$) the Rayleigh wave structure is similar to its isotropic counterpart. Such waves are called Rayleigh-type waves. When comparing theoretical results derived for the isotropic solid with experimental ASW in crystals, the Poisson coefficient σ is used as a fitting parameter.[23,24]

In general, the existence of Rayleigh waves in an arbitrary section of an anisotropic crystal given an arbitrary propagation direction constitutes a distinct and rather difficult mathematical problem. A large number of studies have focused on this question[25-30]; a complete description is available in the monograph by Balakirev and Gilinskiĭ.[17] For symmetrical directions in cubic, hexagonal and some other types of crystals the dispersion relation of ASW has been obtained analytically.[17,31-34] Normally the dispersion relation is considerably more complex than (5) and is solved numerically.

Efficient numerical methods have been developed for computing the velocities and structures of ASW wave fields in crystals (including piezoelectrics)[28,35] and an extensive reference literature is available.[36,37]

We have omitted a number of important questions, such as the acoustoelectronic interaction of Rayleigh waves, ASW excitation, Rayleigh waves in layered structures and waveguides, waves on curved and randomly rough surfaces, and numerous applications of Rayleigh waves in acoustoelectronic devices. An exhaustive bibliography on these subjects can be found in the above-cited reviews and monographs.[2-18]

Electroacoustic shear surface waves in piezoelectrics constitute the second important type of surface acoustic waves.[38-39] Like Rayleigh waves, these waves can exist on a free surface of a solid, but unlike Rayleigh waves they can only propagate on particular cuts and in particular directions in piezoelectric crystals.[17,40]

If the propagating acoustic wave in a solid gives rise to associated electric and magnetic fields, these fields will be invariably distorted near the solid surface, and this can generate mechanical stresses on the surface. In this case the bulk acoustic wave solution no longer satisfies the boundary conditions and the bulk wave can be transformed into a surface wave.[74] Purely mechanical perturbations of the boundary conditions are also possible. These can be caused by mass loading, viscosity of the medium, or corrugation of the surface.

First let us consider a wave propagating along a piezoelectric in the simplest geometry, which was first described by Gulyaev[38] and Bleustein[39] (GBW). That is, consider a class C_{6v} with the hexagonal axis OZ (Fig. 1,b) lying in the plane of the sound-guide surface. The resulting wave has a displacement **u** only along the OZ axis and propagates in the OX direction.

In the general case the piezoacoustic equations have the form[18,41]

$$\begin{aligned} \sigma_{ij} &= c_{ijkl}u_{kl} - e_{kij}E_k, \\ D_i &= \varepsilon_{ij}E_j + e_{ijk}u_{jk}, \end{aligned} \tag{14}$$

where σ_{ij} is the stress tensor; C_{ijkl} is the elastic tensor; e_{ijk} are the piezomoduli; **E** is the electric field vector; D_i is the displacement component; and ε_{ij} is the permittivity tensor. Here we work in SI units because in reference handbooks the piezomoduli e_{ijk} are usually stated in SI units. Note that in CGS units equations (14) appear as[42]

$$\begin{aligned} \sigma_{ik} &= C_{iklm}u_{lm} + \tilde{e}_{lik}E_l, \\ D_i &= \varepsilon_{ik}E_k - 4\pi\tilde{e}_{ikl}u_{kl}, \end{aligned} \tag{14'}$$

i.e., the piezomoduli differ not only in magnitude, but also in sign. Occasionally, for the sake of convenience, the sign before the piezomoduli in equations (14') is defined the same as in the SI convention.[12,17]

In the chosen problem geometry, the equations of motion $\rho\ddot{u}_i = \partial\sigma_{ik}/\partial x_k$ take the form

$$\rho\ddot{u} = C_{44}\Delta u + e_{15}\Delta\varphi \tag{15}$$

where ρ is the density of the crystal. Further, Poisson's equation div $\mathbf{D} = 0$ can be rewritten as

$$-\varepsilon\Delta\varphi + e_{15}\Delta u = 0, \quad \Delta \equiv \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}. \tag{16}$$

Finally, in the $y > 0$ region, where the medium has permittivity ε_d, potential φ_d must satisfy the Laplace equation $\Delta\varphi_d = 0$. The solution of equations (15)–(16) can be represented as a surface wave:

$$\begin{aligned} u &= u_0 \exp[\varkappa y + i(qx - \omega t)], \\ \varphi &= \varphi_0 \exp[\varkappa y + i(qx - \omega t)], \end{aligned} \tag{17}$$

where u_0, φ_0 are the amplitude coefficients; the constant κ characterizes the attenuation of oscillations moving into the bulk of the substrate (Re$\{\varkappa\} > 0$); q is the wavenumber. Substituting (17) into equations of motion (15)–(16) we find that the full solution consists of a sum of two partial solutions with

$$\varkappa_1^2 = q^2, \quad \varkappa^2 = q^2 - \frac{k_0^2}{1+\eta},$$

where $k_0^2 = \rho\omega^2/C_{44}$, and $\eta = e_{15}/\varepsilon C_{44}$ is the electromechanical coupling constant:

$$\begin{aligned} u &= u_0 \exp(\varkappa y + iqx), \\ \varphi &= \varphi_0 \exp(qy + iqx) + \frac{e_{15}}{\varepsilon} u_0 \exp(\varkappa y + iqx). \end{aligned} \tag{18}$$

In the $y > 0$ region

$$\varphi_d = \Phi_0 \exp(-qy + iqx)$$

(we assume that the wave propagates along OX and Re$\{q\} > 0$; in order to have $\varkappa > 0$ the condition $q > k_0(1+\eta)^{-1/2}$ must be satisfied, i.e., the wave must propagate slower than bulk shear waves of the same polarization). From the free surface condition

$$\sigma_{23}|_{y=0} = 0,$$

and the continuity of the potential and the normal component of **D** we obtain the dispersion relation of GBW

$$D(q, \omega) = \varkappa - \frac{\eta}{1+\eta}\,\frac{\varepsilon_d}{\varepsilon+\varepsilon_d}\,q = 0. \tag{19}$$

Hence we find that the penetration depth of oscillations into the substrate $\varkappa^{-1}$ is inversely proportional to the electromechanical coupling constant η (which is usually much smaller than unity) and depends on the permittivity of the medium adjoing the piezoelectric. The greatest localization of the wave occurs when the surface is metallic ($\varepsilon_d \to \infty$). Then

$$d = \varkappa^{-1} \sim \frac{\lambda}{2\pi\eta}.$$

For most piezoelectrics $d \gg \lambda$, but in very strong piezoelectrics (for instance, $LiIO_3$) the localization depth can be smaller than the wavelength. The GBW velocity

$$v = c_t\left[1 - \left(\frac{\eta}{1+\eta}\,\frac{\varepsilon_d}{\varepsilon+\varepsilon_d}\right)^2\right]^{1/2} \tag{20}$$

is smaller by a quantity $\sim\eta^2 \ll 1$ than the velocity of the bulk shear wave c_t of the same polarization propagating in the same direction. The energy carried by GBW per unit time is given by the expression[17]

$$\begin{aligned} P &= C_{44}(1+\eta)\,\omega\,(1-\delta^2)\,\frac{|u_0|^2}{4\delta}\,W \\ &= C_{44}(1+\eta)\,\omega\,(D_q')\,\frac{|u_0|^2}{4}\,W, \\ \delta &= \frac{\varkappa}{q}, \end{aligned} \tag{21}$$

where W is the wave aperture. Given a fixed displacement amplitude u_0 the energy flux is inversely proportional to η, i.e. proportional to the localization depth of the wave.

The great localization depth and the energy flux of GBW that exceeds that of Rayleigh waves make the former less sensitive to single imperfections on the surface. At the same time, the surface structure of GBW is determined by the distortion of electric field near the piezoelectric boundary (for example, the wave structure changes strongly with ε_d). Consequently, if the boundary condition perturbations are periodic and extend over many wavelengths the characteristics of GBW can be significantly affected.

Electroacoustic shear surface waves were experimentally investigated in a number of studies.[43-47] Currently, together with near-surface bulk acoustic waves (see below), GBW are widely used in acoustoelectronic devices. Since their discovery in 1968–69, the question of GBW existence in crystals of different symmetry classes has been studied extensively.[40,48-51] As a result, it has been discovered that these waves can exist in a great many materials, including such frequently used ones as quartz.[52-54] Also, it was demonstrated that GBW can propagate in isotropic dielectrics placed in an electric field.[55,56,66] In this case, electrostriction inside the dielectric "induces" a piezoelectric effect.[57,58] The resulting material possesses $C_{\infty v}$ symmetry, which allows for the existence of GBW. A number of theoretical[50,56] and experimental[43,44,59,60] studies investigated the acoustoelectronic amplification of GBW in piezoelectric semiconductors and layered piezoelectric-semiconductor structures. It was experimentally demonstrated that in strong piezoelectrics ($LiIO_3$) GBW amplification can exceed Rayleigh ASW amplification.[59] An important contribution to our understanding of GBW excitation mechanisms appeared in Refs. 61–63. In particular, it was demonstrated that "deeper" waves are more difficult to excite at the crystal surface because bulk shear waves are excited in addition to the surface wave. Although the amplitude of these bulk waves decays with distance, it may nonetheless exceed the GBW amplitude at great distances $\sim\lambda/\eta^2$.

Waves that can propagate along the interface of two piezoelectrics constitute a further generalization of electroacoustic shear waves. If the two materials are in mechanical contact the shear wave, whose oscillations decay in both directions away from the interface, can propagate either along the interface between two piezoelectrics whose mechanical parameters are similar[64] or between two identical piezoelectrics whose polar axes C_6 are antiparallel. In the latter case the interface is equivalent to a domain wall in a ferroelectric.[65] In this geometry shear ASW can also exist in nonpiezoelectric materials that are placed in an electric field whose intensity vector is parallel to the interface between the materials.[55,56,57] If two adjacent piezoelectrics are separated by a small gap, the interaction of electric fields also alters the structure of GBW propagating along the gap edges and leads to the formation of coupled modes. These piezoelectric gap waves were first described in Refs. 55, 68–70. Gap modes of Rayleigh waves were exhaustively studied in Ref. 71; previously they had been employed to transmit Rayleigh waves from one substrate to another without mechanical contact.[72]

Waves analogous to piezoelectric ASW can also exist in semiconductors due to the acoustoelectronic interaction mediated by the deformation potential,[73,74] in magnetic materials due to magnetostatic interactions,[75,76] and in metals placed in a magnetic field due to Lorentz forces.[77,78] These interactions are significantly weaker than the piezoelectric effect (in strong piezoelectrics) and consequently shear ASW engendered by these interaction mechanisms are weakly inhomogenous and penetrate deeply into the substrate. In practice this means that such waves are difficult to excite selectively (without an admixture of bulk waves), because the ASW formation length becomes extremely large.[61,62]

In piezoelectrics shear ASW result from a particular instability[12,74] of the bulk shear wave which can propagate along the free surface of an isotropic elastic solid or along some crystal directions in certain crystals. These shear waves have found application in various devices (discussed in the next section).

A classic example of mechanical surface exitation which produces shear ASW is the Love wave in a semi-infinite medium–layer system (see Fig. 1,c).[12,19] If the speed of bulk shear waves in the layer is lower than in the semi-infinite medium, the shear waves in this system are described by the following expressions:

$$u_1 = u_0 \exp[s_1 z + i(qx - \omega t)],$$
$$u_2 = u_0 \frac{\cos[s_2(z-h)]}{\cos s_2 h} \exp[i(qx - \omega t)], \tag{22}$$

where u_1, u_2 are the displacements in the medium and the layer; h is the layer thickness; $s_1 = q^2 - k_1^2$, $s_2 = k_2^2 - q^2$ (k_1 and k_2 are the wavenumbers of bulk shear waves in the medium and the layer). The wavenumber q is fixed by the dispersion relation

$$\mathrm{tg}\, s_2 h = \frac{\mu_1 s_1}{\mu_2 s_2}. \tag{23}$$

A thin layer $k_2 h \ll 1$ supports a single Love mode, but as the parameter $k_2 h$ increases several Love modes can appear. The energy flux carried by a Love wave is

$$\mathcal{P} = \frac{1}{2} \mu_1 \omega A |u|^2, \tag{24}$$

where

$$A = -D'_q,$$
$$D(q, \omega) = \frac{\mu_2}{\mu_1} s_2 \,\mathrm{tg}\, s_2 h - s_1.$$

Love waves have found some practical applications in laboratory research.[78,79] In theory these waves often provide the simplest model of surface waves, because the calculations are much simpler than in the case of Rayleigh waves.[80,81]

Weakly inhomogenous Love waves can also exist in an elastic semi-infinite medium with an inhomogenous surface.[82] In this case the near-surface region of the substrate plays the role of a layer where wave propagation is slower than in the rest of the medium.

Another type of a perturbed boundary condition is a corrugated substrate surface (see Fig. 1,d). The near-surface stiffness of such a system is reduced by the grooves, leading to the excitation of surface shear waves (SSW).[83-84] The propagation speed in the near-surface region is reduced because the wave must travel a longer distance following the surface undulations. The equations of motion for the displacement vector **u** and the stress-free boundary condition on the corrugated surface of the substrate are equivalent[83,84] to the equations for H-polarized electromagnetic waves in a delay line. Consequently, SSW on periodically uneven surfaces are analogous to surface electromagentic waves travelling in "corrugated" delay lines. The propagation of SSW is currently well understood. Different studies addressed the cases of weak corrugation[85-86] and finite substrate thickness,[87,88] and the effect of corrugated surface combined with mass loading by a thin layer.[89] The propagation of SSW in quartz and berlinite have been studied in Refs. 88, 90. This attention to shear surface waves is explained by the fact that SSW retain the attractive characteristics of near-surface bulk waves (see below) but nonetheless remain true surface waves, i.e., there is no diffractive energy loss into the substrate bulk. For this reason the implementation of delay lines based on SSW results in a significant (~ 20 dB) loss reduction.[91,92] In principle, SSW can be employed in resonator design;[87,88,93–95] moreover, SSW can be reflected by the same periodic surface profile that produces the wave itself.[90,95]

The boundary conditions can also be perturbed by another mechanism: the surface can be in contact with a liquid (or gaseous) medium. The propagation of Rayleigh waves in the acoustic medium–liquid and acoustic medium–liquid layer systems is fairly well understood.[12] Since the speed of sound in liquids is usually lower than in solids, Rayleigh wave propagation along the interface is accompanied by sound radiation into the liquid and the resulting Rayleigh wave attenuation. At low frequences ($\lesssim$ 100 MHz) this attenuation mechanism can dominate the intrinsic absorption in the material and hence limit the quality of ASW resonators.[96] Much later, the effect of viscous loading on the substrate surface was examined by Plesskiĭ and Ten.[97] It turned out that this perturbation of the boundary conditions also produces a special "viscous" ASW which decays as it propagates because viscosity unavoidably leads to energy losses. (The possibility of Love-type waves existing in a substrate–viscous liquid–substrate system was mentioned earlier in Ref. 98, but no supporting calculations were appended.)

The preceeding brief discussion in no way exhausts the variety of surface waves and waves propagating in bounded substrates. Let us also mention Stonelee and Sezawa waves[12] which can propagate in solids, edge acoustic waves which can propagate along the edge of an elastic wedge, and various type of diverging (loss) waves.[12,100]

An important role in the reflection of bulk waves from piezoelectric interfaces is played by the so-called associated surface oscillations (ASO).[101–103] These surface oscillations do not constitute eigenmodes of the piezoelectric substrate. The appearance of SSW on piezoelectric interfaces is a general phenomenon related to the fact that the Laplace equation $\Delta\varphi = 0$ has no "bulk" solution of the form $\exp[iqx]$, but rather "surface" solutions of the form $\exp[qy + iqx]$.

Other types of waves are also described in the literature (for example. shear ASW generated by spatial dispersion of the medium[104]) but we shall omit these because practical devices with periodic structures are usually based on Rayleigh waves; shear ASW in piezoelectrics and SSW on uneven surfaces are used less frequently; Love waves have also found some application. Consequently this review will concentrate on the above waves.

In concluding this section let us review near-surface waves. Acoustic surface waves are inferior to acoustic bulk waves in some respects. They usually propagate more slowly than bulk waves by a factor of 1.5–2; the thermal stability of ASW time delays is also inferior to bulk shear waves on some cuts of quartz.

It is known that interdigital transducers excite parasytic bulk waves in ASW devices.[105] Several authors have proposed a new class of devices based on these near-surface waves.[106,107] These devices usually employ bulk shear waves with group velocity vectors parallel to the substrate surface.[108,109] Given an isotropic medium or certain orientations of some crystals, such a wave satisfies the boundary conditions and propagates without generating mechanical

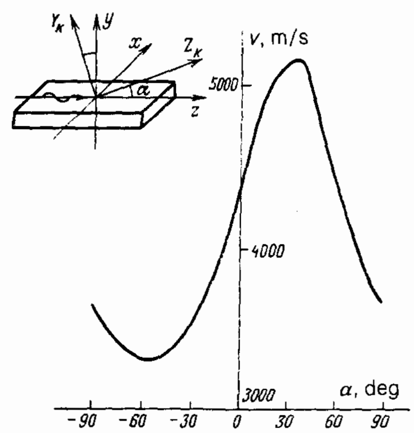

FIG. 5. Near-surface wave propagation velocity as a function of angle of the Y-cut in quartz.

stresses at the interface.[108] In addition, the crystal cut must satisfy the following criteria: the propagation speed of shear waves should be as high as possible; the thermal coefficient of the delay should be small or zero; the electromechanical coupling constant should be large for shear waves and zero for Rayleigh waves and other types of waves. Rotated Y-cut quartz meets these criteria and is therefore widely used in near-surface wave devices.[91,110] In this case the wave displacement falls along the OX axis (Fig. 5) and the wave propagates along the OZ axis. In Fig. 6 we plot the intersection of the Y,Z plane and the inverse velocity surface for shear waves in quartz (cut angle $\alpha = 0$). A near-surface wave is a bulk wave whose wavevector corresponds to point A on the inverse velocity surface. It is easy to demonstrate that a wave with this wavevector automatically satisfies the condition that no mechanical stresses appear at the $y = 0$ surface of the substrate ($\sigma_{xy} = 0$). In Fig. 5 we plot the dependence of near-surface acoustic wave velocity on the rotation angle of Y-cut quartz.

Near-surface waves can be excited and received using IDT. They combine the useful properties of ASW and bulk waves. Yet it should be emphasized that unlike, for example, Rayleigh waves, IDT-excited near-surface waves are not eigenmodes of the system, but rather wave-packets of bulk waves with slightly different wavevectors. In the course of propagation this wave-packet broadens and the wave amplitude at the surface decays according to a power law.[108,111] In

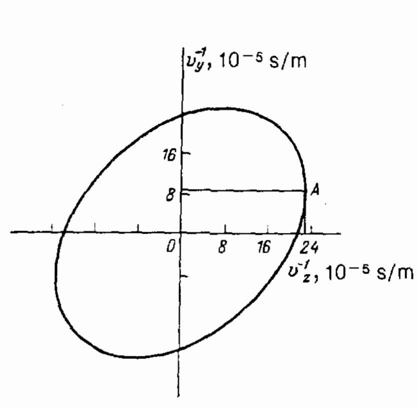

FIG. 6. Near-surface waves in Y-cut quartz.

order to minimize the losses intrinsic to this process, either the IDT's are positioned close to each other or the near-surface wave is transformed into SSW either by depositing a layer with lower wave velocities between the IDT's or by fabricating a periodic groove array.[83,87–94,111]

Another circumstance is worth noting. In piezoelectrics (which are invariably used in practical devices) the near-surface wave is accompanied by electric fields and this can lead to the result that no bulk wave solution might actually exist and at the near-surface wave can turn into a shear electroacoustic wave.[90,110–113] However, in piezoelectrics that are not too strong, such as the commonly used quartz, this distinction is unimportant, since the dimensions of the substrate are smaller than the GBW formation length.[61,62]

Near-surface waves have been employed in a number of highfrequency (higher than 1 GHz) devices: delay lines[91,112,114] and filters.[115] These elements are used mainly to stabilize the frequency of gigahertz band generators.[112,116]

In conclusion we note that in anisotropic substrates there may exist special bulk waves which satisfy the boundary conditions and yet are not purely shear waves.[117,118] There have been attempts to generate longitudinal near-surface waves.[119,120] Obviously, a plane bulk longitudinal wave cannot propagate along the surface of an elastic medium as it would not satisfy the boundary conditions. But the behavior of a wave-packet which is excited to propagate along an interface (which is easily accomplished experimentally) has not been thoroughly investigated to date.[121] The amplitude of longitudinal waves excited by a monochromatic point source should decay along the substrate surface as $\sim x^{-1.5}$.

3. SCATTERING OF SURFACE ACOUSTIC WAVES FROM A SINGLE SURFACE INHOMOGENEITY

3.1. Rayleigh wave reflection from a single groove

If an acoustic surface wave propagates over an inhomogeneity (groove, protrusion, strip of a different material, conducting layer on the piezoelectric surface, etc.) scattering occurs because the incident wave does not satisfy the boundary conditions in the inhomogenous region. A review of early research into Rayleigh wave scattering from single defects is available in Viktorov's monograph.[12] There we find a discussion of experiments in which a Rayleigh wave propagated over "strong" single defects, such as grooves with depth of the same order as the ASW wavelength. In this situation the wave is strongly reflected and scattered into the bulk, with the distribution of energy between the transmitted, reflected, and scattered waves depending on the geometry of the inhomogeneity and material parameters.[12] Strong defects are not employed in ASW devices, since ASW scattering from such defects cannot be controlled. On the other hand, arrays of weak defects, which reflect and scatter the wave weakly, have found wide practical application.[14,15] As we mentioned previously, if these defects are periodic one can achieve phase interference effects: for example, the reflected waves can be made to add in phase and the transmitted waves to cancel. In this fashion, shallow grooves provide the necessary means of controlling wave propagation.

Grooves are the most common type of surface inhomogeneity because the reflection coefficient can be tuned by varying the groove depth (Fig. 7). Grooves are technologically simple to fabricate within the required tolerances and do not degrade with time.[123,124] Arrays of strips made from a different material or metallic strips on the substrate surface have also found application.[125]

Rayleigh wave scattering from a single, linear inhomogeneity (groove) has been investigated theoretically in a number of studies.[23,126–144] Calculations of ASW reflection from a single groove are also cited as a specific case in studies devoted to ASW reflection from periodic arrays of inhomogeneities.[145–147] The results of this research can be summarized as follows.

In the inhomogenous region the incident wave exerts forces (in the first order proportional to the extent of the inhomogeneity) on the surface of the elastic medium. These forces, in turn, give rise to reflected and scattered fields concentrated in the vicinity of the inhomogeneity.

The reflection coefficient r of Rayleigh waves from a single groove of depth h is proportional to the ration h/λ, that is $r = C_1 h/\lambda$, where C_1 depends on the shape of the groove and on material parameters. For a single step whose width $l \ll \lambda$ the coefficent C_1 is independent of its shape and r can be derived as[133,147]

$$r = 2\pi \frac{k_t^4 (q^2 - k_t^2)^{1/2}}{(-D_R') q^2} \frac{h}{\lambda} = C_1 \frac{h}{\lambda}. \tag{25}$$

(The considerably more complex expressions given in Refs. 134, 135 reduce to the simple form above.)

For an "upward" step (Fig. 7,a) r is a positive real quantity and C_1 depends only on the Poisson coefficient of the material. This dependence is plotted in Fig. 8.

The phase of the reflection coefficient is important in the design of devices with reflecting arrays. Here the reflection coefficient is defined as the ratio of the scalar potentials of the incident and reflected waves $r = \varphi_{\rm ref}/\varphi_{\rm inc}$ $(x = 0)$ or as the equivalent ratio of normal (with respect to the substrate) displacements u_y of the reflected and incident waves at $x = 0$.

When an ASW is incident on a "downward" step (Fig. 7,b) r in formula (25) changes sign. When the reflection coefficient from the groove is calculated, its phase depends on the choice of the point at which the phases of the reflected and incident waves are compared. Thus, if the origin coincides with the left edge of a groove $\lambda/4$ in width, the reflection coefficient for a wave incident from the left is $R = -2r$, where r is the reflection coefficient from an "upward" step.

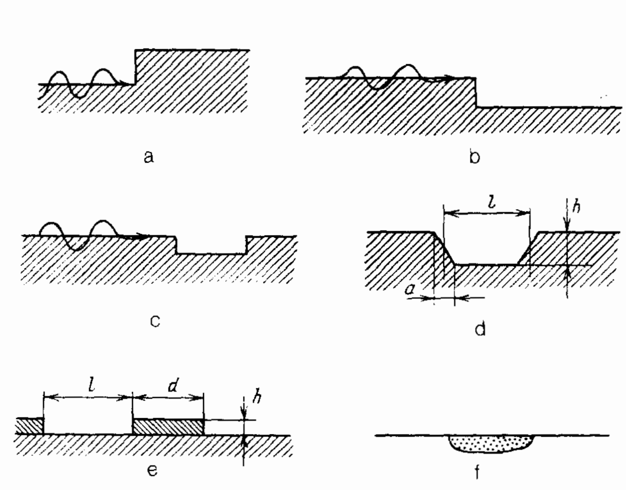

FIG. 7. Various types of ASW reflectors.

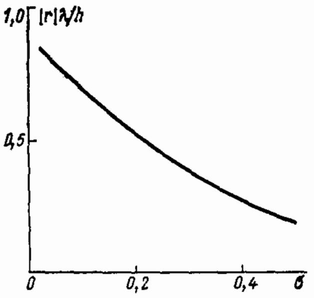

FIG. 8. Normalized ASW reflection coefficient as a function of the Poisson ratio.

If, on the other hand, the origin coincides with the center of the groove, $R = 2ir$.

Given a groove of arbitrary profile $y = f(x)$ expression (25) acquires a factor

$$G(q) = \int_{-\infty}^{+\infty} \frac{df}{dx} \exp(2iqx)\, dx\ ^{133}.$$

The values of $G(q)$ for several groove profiles are cited in Table I. These first order results are obtained in the Born approximation of perturbation theory. This approximation is valid when $h \ll \lambda$ and the slopes of the uneven regions are small.[148] Nonetheless, it turns out that the integral of the derivative of the groove profile, which enters into $G(q)$, is finite also for inhomogeneities with steep walls—for example, for rectangular grooves. When the width of a step is much smaller than the wavelength, the wave does not "feel" the details of the step profile.[134] The correctness of these theoretical results is consistently corroborated by experimental data on rectangular grooves. These questions are discussed in Ref. 137.

When a Rayleigh wave is incident on a single groove at an angle θ to the normal of the groove, the reflection coefficient can be obtained from the formula[133,134]

$$r = C_1 \frac{h}{\lambda} \left(1 - 4 \frac{C_t^2}{v_R^2} \sin^2 \theta\right) G(q \cos \theta). \tag{26}$$

The most interesting feature of this expression is the fact that r turns to zero at $\theta = \sin^{-1}(v_R/2v_t)$. This effect was first described in Refs. 133, 134, whose authors termed it to be the analogue of the Brewster angle for ASW. Subsequently this "Brewster angle" was discovered during research into the diagrams of Rayleigh wave scattering from local three-dimensional inhomogeneities.[149] A simple, intuitive explanation of this phenomenon is currently lacking. It is believed[133] that two types of stresses (normal and tangential) occur in the inhomogenous region and these give rise to coherent ASW. The phase shift between these ASW depends on their propagation vectors and can equal π. When a Rayleigh wave is incident on a strip made of a different material the reflection coefficient r becomes dependent on the material parameters of the strip.[140,141] In particular, depending on the material properties of the strip and the acoustic medium, ASW reflection can exhibit two, one or no "Brewster angles" where $r = 0$.

3.2. Second-order effects

In addition to the first-order (Born approximation) effects described above, more subtle second-order effects enter into the problem. For example, the local wave fields that appear in the vicinity of inhomogeneities accumulate wave energy and thus influence the scattering and transmission processes.

A number of difficulties hinders the consideration of second-order effects on the $\sim (h/\lambda)^2$ scale. First, perturbation theory calculations for a single groove become very complicated. Second, perturbation theory becomes inapplicable when the groove has steep walls.[148,150,151] Empirically it has been established that the reflection from a single "upward" step, taking into account second-order effects, can be expressed as

$$R = C_1 \frac{h}{\lambda} + iC_2 \left(\frac{h}{\lambda}\right)^2,$$

where the second term describes the phase accumulation in the uneven region of the surface. (When an infinitely thin, perfectly conducting layer is deposited on a piezoelectric material there also exists a $\Delta v/v$ effect arising from reflection due to the shorting of the wave electric fields which is independent of the metal thickness). In Refs. 152–154 this phase accumulation is related to the accumulation of energy near inhomogeneities. There also exists a purely geometric qualitative explanation of this effect: the wave requires more time to traverse an uneven region. In this approximation the transmission coefficient through a step can be written as

$$T = 1 - \frac{C_1^2}{2} \left(\frac{h}{\lambda}\right)^2 + iC_2 \left(\frac{h}{\lambda}\right)^2,$$

which corresponds to the wave's velocity changing by a quantity

$$\frac{\Delta v}{v} = -\frac{2}{\pi} C_2 \left(\frac{h}{\lambda}\right)^2.$$

Experimentally these shifts are measured on large arrays of grooves and the results are normalized to a single groove (step).[96-153] The constant C_2 depends strongly on the shape of the grooves. In particular, for a rectangular groove the perturbation theory result diverges logarithmically.[155-157] In experiments on very shallow grooves ($h/\lambda < 0.01$) the precision with which C_2 is determined falls to $\sim 50\%$,[96] which may indicate that the above formula becomes invalid as $h/\lambda \to 0$. Recently Biryukov has shown that, in the case of a rectangular step, the expressions for R and $\Delta v/v$ contain another term

TABLE I. Groove form factor (a–d—groove profiles in Fig. 7, a–d).

Inhomogeneity	a	b	c	d
$G(q)$	$+1$	-1	$2i \sin ql$	$2i \sin ql \dfrac{\sin qa}{qa}$

$$C_3\left(\ln\frac{h}{\lambda}\right)\left(\frac{h}{\lambda}\right)^2,$$

which may be significant at very small h/λ (in this case the total corrections to velocity are small, however).

The currently known values of C_1 and C_2 coefficients for normal and oblique incidence are collected in Table II.

3.3. Scattering into the bulk

The scattering of Rayleigh ASW into bulk waves from a single groove has been exhaustively examined in Refs. 129, 130, 132. The conversion coefficient (with respect to energy) of surface into bulk waves depends on the groove shape and elasticity parameters. For a rectangular groove of $\lambda/4$ width the conversion coefficient depends solely on the Poisson coefficient. If $\sigma = 0.31$ (the quantity usually cited for Y,Z-$LiNbO_3$ in the isotropic approximation) this coefficient becomes $\sim 10(h/\lambda)^2$.[182] Hence it follows that a single groove scatters an order of magnitude more energy into the bulk than it reflects. In periodic structures (see below) the situation can be quite different, however, because the waves scattered into the bulk by individual grooves interfere and can cancel.

3.4. Gulyaev-Bleustein wave reflection from a single inhomogeneity

Scattering of shear ASW from a single inhomogeneity in piezoelectrics has been studied less extensively than the scattering of Rayleigh waves. A number of authors have examined theoretically and experimentally the scattering of GBW when the wave traverses the edge of a conducting screen, i.e., when the wave moves from the free substrate surface to a metallized region and vice versa.[17,47,62,159-162] The resulting effects are quite strong as the wave structure is modified markedly. The transmission coefficient of a wave moving from a free to a metallized surface is described well by the following formula.[62,17,47]

$$T = \frac{u_M}{u_0} = \frac{2(\varepsilon+\varepsilon_0)}{\varepsilon+2\varepsilon_0}, \tag{27}$$

where u_M and u_0 are the displacement amplitudes of GBW on the metallized (transmitted wave) and free piezoelectric surfaces; ε and ε_0 are the permittivities of the piezoelectric and the adjoining medium.

In this scenario reflection is weak and the reflection coefficient is proportional to the square of the electromechanical coupling costant $\sim\eta^2$. In $LiIO_3$ the reflection coefficient of GBW from the edge of a conducting screen

TABLE II. Rayleigh wave reflection from a single inhomogeneity and reduction of propagation speed in a periodic array of inhomogeneities (s—metallization delay coefficient). Data from Refs. 124–158. In case of disagreement all conflicting data are cited.

Material	Cut and reflection angle	Type of inhomogeneity	Reflection coefficient $R = C_0 + C_1(h/\lambda) + iC_2(h/\lambda)^2$			Velocity reduction $-\Delta v/v = S(B_0 + B_1(h/\lambda)) + B_2(h/\lambda)^2$		
			C_0	C_1	C_2	B_0	B_1	B_2
lithium niobate	Y, Z, 180°	$\lambda/4$ groove		0,67	25; 42			13,4; 8.0
		shorted Al strips	0.018			0,024	0,2	
		unconnected Al strips	0,011					
		$\lambda/4$ Au strips				0,024	4	
	$Y, Z\rightarrow X$, 90°	upward step		0,51	4,5±0,4			5.5; system of grooves
		SiO_x strip		0,6±0,1			0,12	1,3
		$\lambda/2$ Al strip	0,018 0,027			0.024	0,4—0,56	
	Y, X, 180°	$\lambda/4$ groove		0,88				
	$Y, X\rightarrow Z$, 90°	Al strip				0,0078		
quartz	ST, 180°	$\lambda/4$ groove		0,50—0,02 0,54; 0,65	34; 32; 24—34			9—12; 10,3
		$\lambda/4$ Al grooves		0,5—0,1	25—32; 29			
		buried Al strips		0,2				
		Au strips		1,5				
	$STX\rightarrow\perp x$, 90°	Al strips				0,004	0,4	
		$\lambda/2$ Au strips		9,7				
	$Y, X\rightarrow z$, 90°	$\lambda/2$ groove		1,67±0,05				
		Al strips		1,1±0,2		0,009		
		Cu strips		6,1∓0,8				
BGO	(001), (110), 90°	$\lambda/2$ groove		0,46				
	(100), (011), 180°	$\lambda/2$ Al strip	0,011					
$Li_2B_4O_7$	45°$x\rightarrow z$, 180°	step		0,23				
		shorted Al strips	0,006	2				
		shorted Au strips	0,006	4				
PZT-4	180°	$\lambda/4$ Al strip	0,04	−0,5				
		$\lambda/4$ Au strip	0,04	0,5				

amounts to $r \sim 6 \cdot 10^{-3}$ (in amplitude).[17,62] When a GBW, propagating along a metallized surface of lithium iodate, is converted into an antisymmetric gap mode the wave amplitude is reduced by a factor of two.[47,163]

The reflection of GBW from a single groove has been addressed in Ref. 164. The reflection coefficient is given by the formula

$$R = -2i \frac{\eta}{1+2\eta} \frac{h}{a} \sin \frac{2\pi l}{\lambda} \cdot \sin \frac{2\pi a}{\lambda}, \tag{28}$$

where λ is the wavelength; h, l, and a are the parameters of a trapezoidal groove (see Fig. 7,d). Consequently, $r \sim \eta h/\lambda$ and in piezoelectrics with weak electromechanical coupling GBW waves experience much weaker reflection than Rayleigh waves in the same geometry. But in strong piezoelectrics (like $LiIO_3$) reflection can be significant: $r \approx 1.65 h/\lambda$ for $LiIO_3$, which is much higher than the reflection coefficient of a Rayleigh wave in Y,Z-$LiIO_3$ from a rectangular step with the same h/λ ratio.

4. SHEAR SURFACE WAVES (SSW) ON A CORRUGATED SURFACE ($\lambda \gg 1$)

The scattering of ASW from a periodic array of inhomogeneities is largely determined by the interference of waves scattered by individual array elements and, consequently, depends significantly on the ratio between the array period and the wavelength. The phase-matching condition for vectors $q + nQ = k_p$ (q is the ASW wavenumber; $Q = 2\pi/l$ is the wavenumber of the periodic structure; k_p is the wavenumber of the scattered wave; $n = \pm 1, \ldots$) is conveniently illustrated by the diagrams in Fig. 9. When an ASW propagates along a periodically uneven surface it generates surface stresses with wavenumbers $q + nQ$. If one of the surface stress harmonics has a wavenumber equal or nearly equal to one of the wave eigenmodes of the system, the corresponding wave is resonantly excited. In Fig. 9,a we have $\lambda > 2l$ ($q < Q/2$), in which case the wavenumbers $q \pm Q$, $q \pm 2Q$, etc., have moduli that are too large to excite waves in the system. Consequently, when $\lambda > 2l$ ASW propagation along a periodically uneven surface does not generate scattered waves. The $q + nQ$ wavenumber harmonics then become near-surface oscillations whose amplitude is much smaller than the ASW amplitude as long as the surface corrugation is weak. The existence of these near-surface oscillations has the effect of slightly slowing Rayleigh wave propagation. This phenomenon is not particularly interesting and the propagation of Rayleigh waves over arrays with period $l < \lambda/2$ has attracted little study.

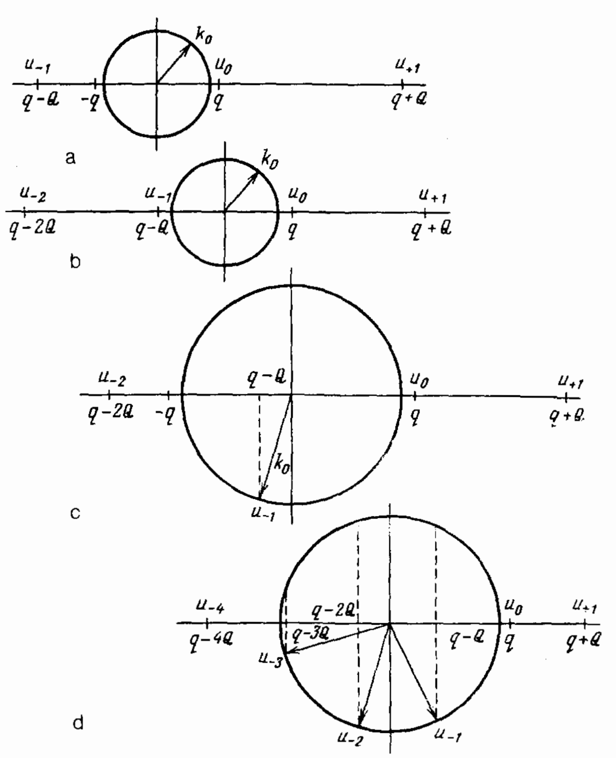

FIG. 9. ASW scattering diagram at different relative values of ASW wavevector **k** and lattice wavenumber Q.

The influence of periodic arrays of inhomogeneities on the propagation of shear waves is markedly different. As we have already observed (see Sec. 2), a periodically uneven substrate surface localizes bulk shear waves and converts them into surface shear waves (SSW).[83-84] In this case the wave field consists of a surface wave

$$u = u_0 \exp(\varkappa y + iqx),$$

with a series of small-amplitude harmonics ($u_n \ll u_0$) of wavenumber $q + nQ$. For a rectangular grating the attenuation coefficient $\varkappa$ and the propagation speed $c = \omega/q$ are given by the expressions

$$\varkappa = \frac{d}{l} k \,\mathrm{tg}\, kh, \tag{29}$$

$$c = \frac{v_t}{\{1 + [(d/l)\,\mathrm{tg}\, kh]^2\}^{1/2}}, \tag{30}$$

where l, d, and h are the dimensions of the grating (see Fig. 7,e). In the case of a smooth (sinusoidal) corrugation of the surface the quantity $\varkappa$ becomes proportional to h^2:[85,86]

$$\varkappa = \frac{h_0^2 q^2 Q}{2} \tag{31}$$

($y = -h_0 \sin Qx$ is the functional form of the corrugation). As an example we take grooves on ST-cut quartz of depth $2h_0 = 0.4$ μm and period $l = 10$ μm. Then $\mathrm{Re}\{\varkappa l\} = 370(h_0/\lambda)^2$, i.e., the attenuation depth $\varkappa^{-1}$ reaches $70l$ at $\lambda = 40\,\mu$m.[90]

Currently SSW have found wide application in high-frequency delay lines and filters.[89,91,92] These waves retain the attractive properties of surface waves but allow for significant reduction of losses. In weak piezoelectrics like quartz, arrays of inhomogeneities make it possible to reduce significantly the localization depth of GBW, which simplifies wave excitation and ultimately also leads to loss reduction. Earlier, in Sec. 2, we cited studies focussing on the detailed examination of SSW properties. The dispersion curves of SSW in isotropic media at frequencies $0 < \omega < \omega_0$ (where ω_0 is the Bragg frequency) have been numerically computed in Ref. 165. If the corrugation profile is sinusoidal the calculation is valid up to $h/\lambda < 0.6$. The width of the Bragg stopband is $\sim (h/\lambda)^2$. The authors incorrectly stated that the dispersion curves are symmetric about the Bragg frequency ω_0 (see below).

A number of authors have studied SSW in strong piezoelectrics ($LiNbO_3$, $LiTaO_3$) where the waves are localized at the surface by depositing a periodic array of conducting strips and causing the shorting of electric fields (the

$\Delta v/v$ effect).[166-168] In Ref. 168 the authors designed a resonator employing SSW in a strong piezoelectric. An advantage of this design is its simple fabrication technology, which does not require ion-etching of the substrate; a disadvantage is that the wave characteristics cannot be tuned.

5. BRAGG REFLECTION OF ASW ($\lambda \approx 2l$)

5.1. Bragg reflection of Rayleigh waves

We have seen that ASW scattering does not occur in arrays with $\lambda \gg l$. Such arrays have periods so small that the inhomogeneneities are averaged over many periods, i.e., the surface appears nearly smooth. Now let us consider higher frequencies at which the wavelength λ is comparable to the period of the array of inhomogeneities.

As the frequency is increased the "-1" surface stress harmonic, generated by an ASW propagating on a periodically uneven surface, comes to coincide with the wavenumber of an ASW propagating in the opposite direction $q - Q \approx -q$, $2q \approx Q$ (see Fig. 9,b). In this case a reflected wave is resonantly excited. The effect can be described as constructive interference of waves reflected by individual grooves. Indeed, from the condition $2q = Q$ it follows that $\lambda = 2l$. The incident wave gains a phase of π by traversing the distance $\lambda/2$ between the grooves. Accordingly, the wave reflected by a groove after travelling a distance of $\lambda/2$ in the opposite direction has the same phase ($\Delta\varphi = 2\pi$) as the wave reflected by the preceeding groove in the array. This effect, known as Bragg reflection, occurs in all physical systems of waves traveling through a periodic structure,[169] including x-rays whose diffraction in crystals was originally studied by Bragg.

If the number of reflecting elements N is large, Bragg reflection cannot be treated within the framework of the Born approximation. In fact, as the reflected waves are matched in phase, the total reflection coefficient $R = r\cdot N$ can exceed unity at large N, which is obviously unphysical. Therefore, if $N\cdot r > 1$ one must consider the decay of the incident wave amplitude as it propagates through the array and take into account multiple reflections. The ASW reflection coefficient of such a distributed reflector can be very close to unity. Clearly the penetration depth of the wave into the array is of the same order of magnitude as $|r|^{-1}$. In 1970 Ash proposed an ASW resonator based on distributed reflectors[316] and experimentally demonstrated the efficacy of such a resonator. The development of ASW resonators, which have a number of advantages over bulk resonators, proceeded extremely quickly and resonators with quality factors of $\sim 4\cdot 10^4$ became available by 1976.[5] This rapid success of experimental designs was due to the availability of proven photolithographic and ion-etching technologies, which made it possible to fabricate structures with desired properties.[14] Soon thereafter the quality factors of ASW resonators reached $\sim 10^5$, reaching the limit imposed by substrate imperfections.

The theoretical understanding of ASW Bragg reflection from arrays of grooves, strips, etc. proceeded in tandem with or even lagged behind the experimental work. First, the scattering of Rayleigh waves from a periodic array of grooves was described in terms of a mismatched transmission line.[125] It was shown that at the Bragg frequency the reflection coefficient is $|R| = \tanh(N\cdot|r|)$ and the effective penetration depth into the array is $L = \lambda/4|r|$. A review of research devoted to reflecting structures prior to 1976 is available in Refs. 124, 125. These simple models accurately described the basic properties of distributed Bragg reflectors, but they had several flaws. First, the models were purely one-dimensional and could not describe reflection at oblique incidence, scattering into the bulk, etc. Second, the coefficient r was introduced phenomenologically, neglecting second-order effects.

A step forward was furnished by Refs. 145, 170, in which Bragg reflection was described in terms of "coupled modes"—a method previously developed for problems in integrated optics[171] and for the theory of distributed feedback lasers.[172,173] The coupled mode analysis was based essentially on the fact that from the infinite number of wave harmonics of wavenumber $q + nQ$ in a periodic structure Bragg reflection selected only two (with $n = 0, -1$) whose amplitudes remained large. Other harmonics had amplitudes $\sim h/\lambda$ and could be discarded. A system of coupled mode equations could then be derived for the $n = 0, -1$ harmonics. These equation described the amplitude changes in the incident ($n = 0$) and reflected ($n = -1$) waves as a function of distance along the array due to reciprocal multiple reflections. In Refs. 145, 170 the coupled mode equations were postulated, rather than derived, while the coupling coefficient, determined by ASW reflection from a single groove, was calculated separately[145] or computed numerically from energy considerations.[170]

The full analytic solution of Bragg reflection from a periodic array of inhomogeneities was given in Refs. 134, 174 (for normal incidence) and Refs. 147, 175–177 (for oblique incidence). In these studies the distributed reflector characteristics were determined from "first principles" via the acoustic parameters of the substrate and the array geometry. Somewhat later these results were extended to large amplitude arrays (up to $h/\lambda \approx 0.5$)[178] but the edges of the grooves were taken to have finite slopes. Rayleigh wave reflection from an array of rectangular grooves was studied numerically.[179-181] It was shown that the analytic solution obtained to first order in perturbation theory remains valid for rectangular grooves as well.

Let us recall the fundamental characteristics of a distributed Bragg reflector. Such a structure usually contains 500–2000 small grooves ($5\cdot 10^{-3} < h/\lambda < 2.10^{-2}$):[96] the array has a period of $\lambda/2$ and the grooves are about $\lambda/4$ wide. The transmission coefficient for a wave at the central stop-band frequency is given by the expression

$$20 \lg T = 8.68\, N\, |r| - 6.02 \tag{32}$$

which is valid when $N\cdot|r| > 1$, where r is the reflection coefficient from a single groove. If losses to bulk scattering are ignored the reflection coefficient R at the central frequency is $\tanh(N\cdot r)$. Second-order effects play an important role in ASW resonators. The most important of these are scattering into the bulk and reduction in wave velocity in the vicinity of reflecting structures. Notably, scattering into the bulk is an "edge effect", because complete destructive interference of waves scattered into the bulk occurs everywhere except at the boundaries of the periodic array. These energy losses have been calculated in Refs. 145, 170, 182, where it was shown that as the number of scatterers N rises the amount of scattered energy quickly becomes independent of N (at

$N \gtrsim 20)$[182] and that the loss coefficient is $C_v(h/\lambda)^2$, where C_v is determined by material parameters. In an isotropic material with the Poisson ratio $\sigma = 0.31$ we have $C_v = 9 \pm 1$. With small corrections to wave field structure ASW scattering into the bulk can also be treated as the transformation of a wave which passes from a smooth to a periodically uneven surface region.[146] Scattering of ASW into the bulk can limit the quality factor of ASW resonators. In order to limit these losses there have been proposals to reduce the groove depth towards the boundaries of the groove array.[183,184] The stopband bandwidth, defined as the frequency separation between the first two zeroes (Fig. 10) is determined by the equation[96]

$$\frac{\Delta f}{f_0} = \frac{2}{\pi}|r|\left[1 + \left(\frac{\pi}{N|r|}\right)^2\right]^{1/2}, \tag{33}$$

where f_0 is the central stopband frequency $f_0 = v_G/2l$, and the ASW propagation speed v_G is somewhat lower in the array than on the free surface:

$$v_G = v_R\left[1 - K_v\left(\frac{h}{\lambda}\right)^2\right], \quad K_v = \frac{2}{\pi}C_2. \tag{34}$$

The reduction in propagation speed on an uneven surface quadratic in h/λ is sometimes labelled as an "energy accumulation effect".[152] As in the case of a single groove, this effect can be qualitatively explained by several physical mechanisms (reduction in the effective stiffness due to surface inhomogeneity, increase in the path length traversed by the wave, multiple wave reflection, and energy accumulation in near-surface oscillations near surface inhomogeneities). For smoothly-varying surface corrugation the effect has been computed by two different methods:[151,155] the theoretical values proved in adequate agreement with experimental data which, as we have already discussed, are known with poor ($\sim 50\%$)[155] precision when $h/\lambda < 0.005$. For rectangular grooves the theoretical methods[151,155] yield logarithmically divergent expressions for K_v. Recently Biryukov demonstrated that in this geometry formula (1.36) acquires another term of the form

$$\left(\ln\frac{h}{\lambda}\right)\left(\frac{h}{\lambda}\right)^2.$$

Quadratic effects at oblique incidence of the wave onto the array have been examined in Refs. 154, 185.

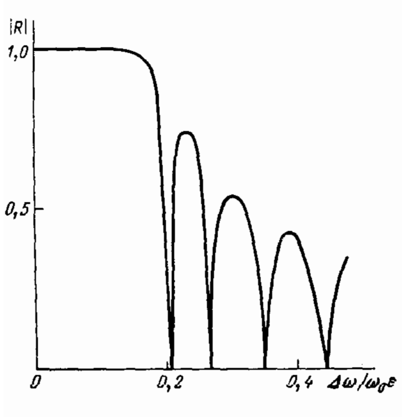

FIG. 10. Bragg array amplitude-frequency characteristic at normal incidence ($N = 200$).

5.2. Modulation of groove depth

Thus we find that a Bragg reflector array containing a large number N of small ($r \sim h/\lambda \ll 1$) grooves can reflect a wave with a coefficient close to unity (if $Nr \gg 1$) in a frequency stopband near the Bragg frequency determined by the $\lambda = 2l$ condition. Two requirements need be met in resonator design. First, the reflection coefficient R at the operating frequency should be as close to unity as possible. For sufficiently large N, when $Nr \gg 1$, one must take into account scattering into the bulk as the wave travels from a smooth to a periodically uneven surface region. This scattering is due to a small modification in the spatial wave structure as the wave propagates over the array. In order to reduce this wave field "mismatch" there have been proposals[183,184] to reduce the groove depth gradually to zero at the array boundaries on the cavity sides of the resonator.

The second important requirement is that the reflection coefficient $R(\Delta\omega)$ should be as small as possible away from the operating frequency in order to suppress additional resonances. A uniform array has a frequency characteristic $R(\Delta\omega)$ which contains side lobes whose height is only a few decibels below $R(0)$, which makes such an array unacceptable for a number of applications. It turns out that the $R(\Delta\omega)$ characteristic can be markedly improved by the same groove depth modulation technique.[186,187] If the reflection coefficient from each array element varies smoothly along the array $r(x)$, then the total reflection coefficient at the Bragg frequency, taking multiple reflections into account, has the form

$$|R| = \tanh\left(\int_0^L r(x)\,dx\right).$$

The side lobes in $R(\Delta\omega)$ are strongly suppressed if the groove depth is gradually reduced to zero at the array boundaries. Physically, at small r multiple reflections are of little importance away from the Bragg stopband. The amplitude of the reflected wave is determined by the sum of the amplitudes of the waves reflected by each groove with appropriate phase delays. In essence this process is analogous to transverse filtration. It then turns out that the functional shape of $R(\Delta\omega)$ is determined by the Fourier spectrum of $r(x)$ and that the ripple can be reduced by employing smoothly graded $r(x)$ functions that go to zero at the boundaries. The technology to vary groove depth along the array in a predetermined manner has existed for some time.[14] The characteristics of ASW Bragg reflectors can also be controlled by employing point reflector arrays,[188,189] where the local reflection coefficient can be tuned by varying the local density of metallic points.

5.3. Oblique incidence of ASW onto arrays

Reflector arrays are also employed in filters, where they can be used to control filter performance. Historically, reflector arrays have found their greatest application in filters used to form and process linearly frequency-modulated (LFM) signals.[190,191] Excellent results have been achieved in this field (for example, signal compression of better than 10^4, for reviews see Refs. 191–193), but we shall omit further discussion because structures employed in such devices are nonperiodic and hence fall outside the scope of this review.

Periodic reflecting arrays are employed in narrow-band

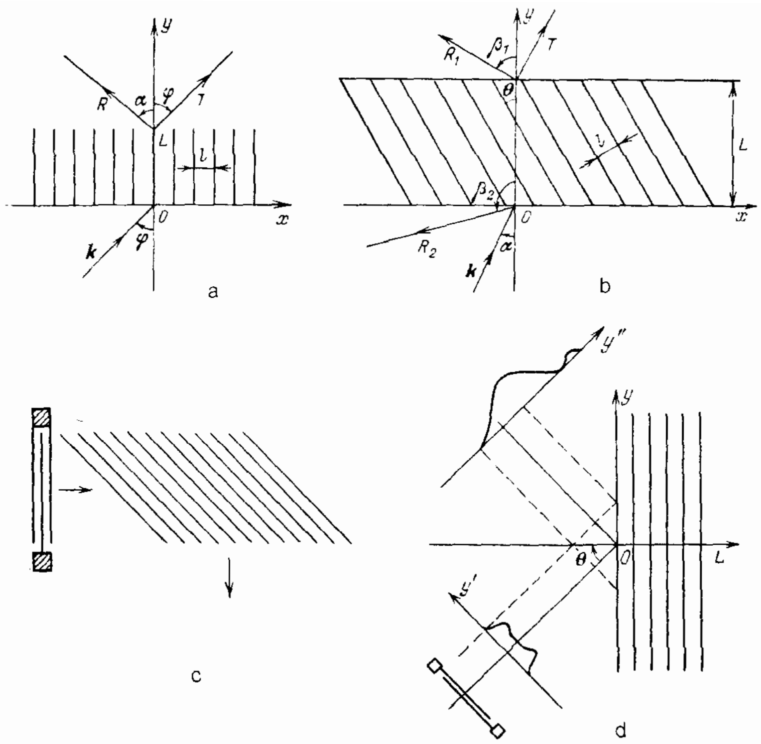

FIG. 11. Array reflectors.

ASW filters. Detailed calculations of the properties of such filters can be found in Ref. 194. The important advantages of reflecting array filters are that optimal IDT's can be used to excite ASW independently of array frequency characteristics, and that the level of spurious signals is low. Reflecting arrays have been used to design ring filters[195,196,197] with losses of only a few decibels.

In reflecting array filters the relevant geometry is often considerably more complex than the above-described cases of normal or oblique incidence of plane waves onto an array consisting of infinitely long grooves. Several of these geometries are schematically illustrated in Figs. 11 and 12. The finite extent of the arrays and finite wavefront apertures of ASW are important. In some simplest cases, such as grazing incidence onto an infinite array consisting of finite-length grooves (see Fig. 11,a,b) the solution can be found via the coupled wave method by considering the interaction of incident and reflected waves in the array.[198-200] The interaction varies depending on the exit point of the reflected wave. If the reflected wave propagates in the reverse direction ($\alpha + 2\theta > \pi/2$) the incident wave decays quickly as it moves into the array and the reflection coefficient increases with array width. If, on the other hand, the reflected wave propagates through the array in the forward direction, reflection from the array becomes analogous to the acousto-optic interaction in the Bragg regime.[201] The reflection coefficient then oscillates as a function of array width. In wide arrays the incident and reflected waves propagate as if channeled along the grooves and experience multiple reciprocal reflections.

5.4. Arrays of finite extent

In the above discussion we have assumed that the wave amplitude does not change along the array. This assumption is invalid if the reflected (or incident) wave propagates along the array (see Fig. 11,c). In practice this is usually achieved by having the wave propagation vector change by 900. The equations which determine the reciprocal multiple reflections in this geometry have been derived by various means in Refs. 194, 197, 202. The equations which govern the amplitudes of interacting waves have the form

$$\begin{aligned} &\frac{\partial u^+}{\partial x'} - \tilde{r} u^- = 0, \\ &\frac{\partial u^-}{\partial y'} + \tilde{r} u^+ = 0, \end{aligned} \tag{35}$$

where $\tilde{r} = \varepsilon F/D'$; $r = \tilde{r}\cdot\lambda$ is the reflection coefficient of a single groove. This system of equations (35) is completed by the appropriate boundary conditions which determine the presence (or absence) of waves incident on the array in directions of x' and y' axes. The Riemann method yields analytic solutions for these equations for several simple array configurations.[202,194] In particular, given an array occupying the rectangular region $x'Oy'$ (Fig. 12,b) and an incident wave at the central frequency ($\Delta\omega = 0$), the incident and reflected waves in the array are distributed as follows:

$$\begin{aligned} &u^+ = J_0\left(2\tilde{r}\,(x'y')^{1/2}\right), \\ &u^- = \left(\frac{y'}{x'}\right)^{1/2} J_1\left(2\tilde{r}\,(x'y')^{1/2}\right), \end{aligned} \tag{36}$$

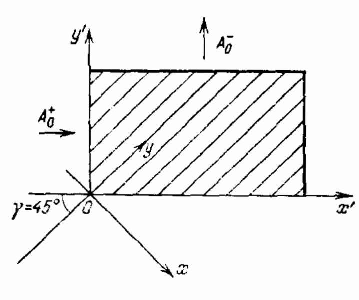

FIG. 12. Rayleigh ASW reflection by an array at oblique incidence.

where J_n are nth-order Bessel functions of the first type; the amplitude of the incident wave at $x' = 0$ is taken as unity.

If the array occupies a region of arbitrary shape, equations (35) are best solved numerically. A simple numerical algorithm results when the boundary conditions are imposed on a rectangle which bounds the array and a position-dependent reflection coefficient $r(x',y')$ is introduced.[197] We observe from equations (36) that reflection becomes significant when $r^2XY > 1$, where X and Y are the dimensions of the array (in wavelengths)—this is true for other array shapes as well.[203] Wave diffraction was neglected in deriving equations (35); diffraction can be taken into account[204,194] in real systems but ASW wave aperture is $\gtrsim 100\lambda$ and diffraction effects are small.

When a finite aperture beam is Bragg-reflected by an array the beam profile can change significantly (see Fig. 11,d) and a beam shift can occur.[205]

5.5. Bragg reflection of SSW

The Bragg reflection of SSW and shear ASW in piezoelectrics proceeds quite differently.[206,207,93] The very existence of shear ASW is due to surface corrugation. Consequently wave reflection at $\lambda = 2l$ and scattering into the bulk (when $\lambda < 2l$) are no longer small effects and can markedly alter the wave structure. Researchers have determined[85,93,90] that as the frequency approaches the Bragg value the penetration depth into the substrate $\varkappa_0^{-1}$ falls off and reaches its minimum at the left edge of the stopband. In the stopband the wavenumber of the incident wave becomes

$$q = \frac{Q}{2} + \delta,$$

where δ is a purely imaginary quantity. The Bragg stopband bandwidth is

$$2\,\frac{\Delta\omega}{\omega} \approx \varepsilon^2 \sim \left(\frac{h}{\lambda}\right)^2,$$

and the maximum attenuation coefficient along the array is

$$\operatorname{Im}\delta \sim \frac{\varepsilon^2}{2}\,\frac{Q}{2}.$$

Numerical calculations for an ST-quartz structure with period $l = 10\,\mu$m and groove depth $h = 0.4\,\mu$m are shown in Fig. 13. In the stopband $\operatorname{Re}\{\delta\} = 0$ and $\varkappa_0$ is the complex conjugate of $\varkappa_{-1}$. As the frequency increases and approaches the right edge of the stopband the localization depth of the wave increases sharply. At even higher frequencies the solutions yield $|\operatorname{Im}\{\varkappa_{0,-1}\}| > |\operatorname{Re}\{\varkappa_{0,-1}\}|$ and hencehave the form of inhomogenous bulk waves. In Fig. 14 we plot schematically a typical experimental curve[95] of loss vs frequency as the wave propagates through the array. Unlike the Rayleigh wave case, the curve is sharply asymmetric (see Fig. 10), because at frequencies above the Bragg value SSW are practically nonexistent.

The changes in the wave field structure lead to changes in the phase of the reflected wave as a function of frequency in the stopband. At the central stopband frequency the phase shift is $\pi/4$,[93] rather than 0 or π as in the case of Rayleigh waves. This fact should be heeded when designing SSW resonators, which have been discussed in Refs. 88, 94, 93 and experimentally realized in Ref. 95. Their advantages lie in the properties of near-surface waves and SSW—high frequency and thermal stability. Problems arise because of losses due to scattering into the bulk in the resonator cavity,

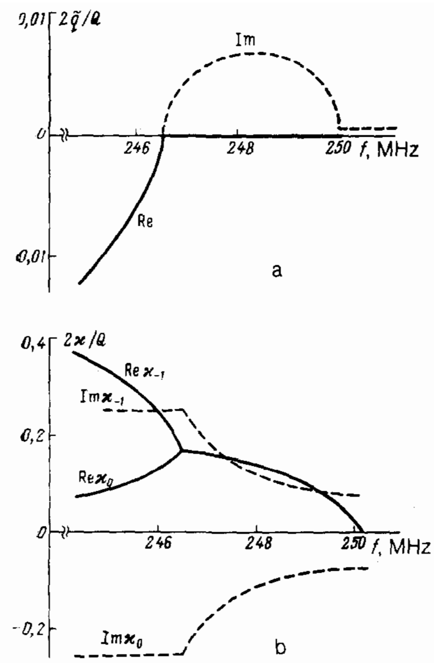

FIG. 13. SSW in ST-quartz. a—wavevector correction. b—inverse penetration depth.

since no SSW can exist on the smooth regions of the substrate. There has been a proposal[88] to fabricate an array of grooves with a different (smaller) period inside the cavity, which would support ASW of approximately matching structure but transmit the wave at the operating frequency. It follows from the above discussion that this wave-matching is unattainable because the quantities $\varkappa_{0,-1}$ are complex in the Bragg stopband. Consequently the most promising alternative is to reduce the distance between the array boundaries to the absolute minimum of $3\lambda/8$.[93]

In the case of Rayleigh waves, the central Bragg reflection frequency $f_0 = v_R/2l$ and the frequency f_p at which scattering into the bulk begins are quite different, because Rayleigh wave velocity is less than the velocity of the bulk shear wave. These frequencies do coincide, however, for SSW on a periodically corrugated surface given infinitely weak corrugation, and this leads to the above-described effects: changes in the wave structure, stopband asymmetry, etc. When SSW propagate in piezoelectrics we have an intermediate situation. Scattering into the bulk begins at a frequency which is only slightly greater than the Bragg value: $f_p - f_0 \sim \eta^2 f_0$, where η is the electromechanical coupling co-

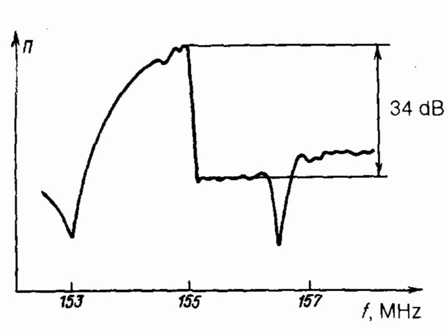

FIG. 14. SSW losses upon passing through a reflecting array.

efficient. Since the Bragg stopband bandwidth is determined by the corrugation ratio h/λ, it is possible that the frequency f_0 may fall into the Bragg stopband. Calculations show[207] that if $\varepsilon \ll \eta$ no such overlap occurs and the GBW structure is unaffected. Accordingly GBW reflection is the same as that of any "good" wave[208]—the Rayleigh wave, for example. The coefficient of exponential decay $\mathrm{Im}\{\delta\}$ as the wave propagates into the array is proportional to $\eta h/\lambda$ and therefore small. The decay coefficient per array element equals the GBW reflection coefficient from a single array element. Thus, when $\varepsilon > \eta$, the Bragg stopband merges with the frequency range of decay due to scattering into the bulk (Fig. 15,a), while the localization depth of GBW oscillations changes sharply (Fig. 15,b).[206,207,235]

6. RECIPROCAL CONVERSION OF BULK AND SURFACE WAVES ON PERIODIC STRUCTURES ($\lambda \approx l$)

As the frequency is increased above the Bragg value, beginning at some critical frequency $f_p = 2f_0 v_t/(v_t + v_l) > f_0$ (where v_t is the propagation speed of the bulk shear wave) surface inhomogeneities begin to scatter ASW into bulk waves (see diagram in Fig. 9,c). The back-scattered bulk shear wave appears first, then, as the frequency is increased, the longitudinal wave. At $\lambda = l$ scattered waves propagate normal to the surface. When the wavelength is further decreased (diagram in Fig. 9,d) several scattered waves appear.

6.1. ASW attenuation due to scattering into the bulk

Rayleigh wave attenuation due to scattering into the bulk was examined theoretically in a number of studies.[209-219] The pioneering role was played by Brekhovskikh[209] who evaluated the attenuation coefficient by the successive approximation technique. In the "zeroth" order approximation the Rayleigh wave is taken to have the same structure and velocity on the uneven surface as on the smooth regions and hence to propagate without attenuation. Such a wave does not fulfil the boundary conditions on the free surface $z = \zeta(x)$; one can evaluate the forces that act on the $z = 0$ plane and the amplitudes of bulk waves generated by these forces. The attenuation coefficient is defined as the ratio of the energy flux carried off by the bulk waves to the energy of the Rayleigh ASW. In the case of a one-dimensional sinusoidal corrugation $z = \zeta_0 \cos Qx$, when $q = Q$ one obtains the expression:[219,34]

$$\Gamma \equiv \mathrm{Im}\,\delta = \left(\frac{\zeta_0 Q}{2}\right)^2 k_t \frac{k_t s + k_l p}{Q^2 \Delta'_R}\,; \qquad (37)$$

where

$$s = (q^2 - k_t^2)^{1/2}, \quad p = (q^2 - k_l^2)^{1/2}, \quad \Delta'_R = -\frac{D'_q}{k_t^8},$$

D'_q is the derivative of Rayleigh determinant $(D,q,\omega) = (q^2 + s^2)^2 - 4q^2 ps$ with respect to g; $\zeta_0 Q = \varepsilon$ is the small corrugation parameter. Consequently, the attenuation coefficient can be put into the form

$$\Gamma = C(\sigma)\left(\frac{h}{\lambda}\right)^2,$$

where $C(\sigma)$ is a factor that depends only on the Poisson ratio and the groove profile. For sinusoidal grooves and $\sigma = 0.3$ we find $\Gamma = 0.06\varepsilon^2 q$. Attenuation due to scattering into the bulk is significantly weaker than attenuation along the array in the case of Bragg reflection ($\Gamma \sim h/\lambda \sim \varepsilon$), because scattering into the bulk involves the addition of scattered wave energies rather than amplitudes. The analysis of Brekhovskikh was repeated in Ref. 211 and experimentally verified in Ref. 210. Rayleigh ASW scattering into the bulk at oblique incidence onto the array was investigated in Refs. 182, 217–218. By varying the spacing between the grooves scattered bulk waves can be focused and scanned.[213] In Ref. 34 the Brekhovskikh method was used to calculate ASW attenuation with the wave propagating along a periodically uneven surface ($\lambda = l$) of cubic and hexagonal crystals. The analysis demonstrated that in almost all crystals of these symmetries longitudinal and transverse waves carry off approximately equal amounts of energy.

When the wavelength λ equals the array period l the $q - 2Q = -q$ condition is fulfilled (see diagram in Fig. 9,c), i.e., in addition to scattering into the bulk this scenario phase-matches double Bragg reflection or, equivalently, scattering from the second harmonic of the Fourier function $\zeta(x)$ which describes the uneven surface. This harmonic appears, for example, in the case when the width of the rectangular grooves is different from the distance between them. Since Bragg reflection is a stronger effect, it is this double reflection of ASW, rather than scattering into the bulk, that determines attenuation along the array.

6.2. Second-order effects

In Refs. 220, 219 the authors first pointed out that in the case of sinusoidal corrugation at $\lambda = l$ there can be significant wave reflection due to second-order effects, whose contribution to the attenuation along the array exceeds that of scattering into the bulk. Given sinusoidal corrugation $\zeta(x) = \zeta_0 \cos Qx$ ASW reflection of amplitude $\sim \zeta_0 Q = \varepsilon$ is absent, since the waves reflected by thé hill and valley of each sinusoidal period interfere destructively. However, there exist several coherent reflection mechanisms whereby each pe-

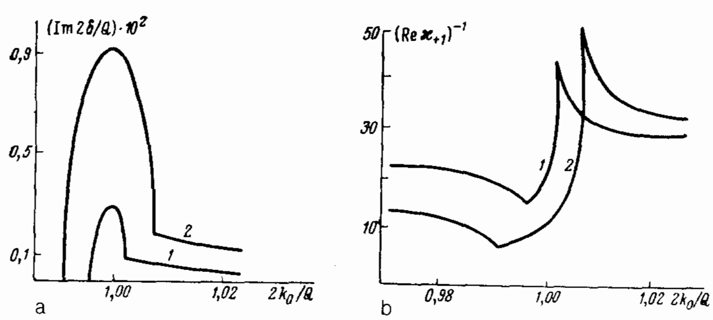

FIG. 15. GBW in periodic structures. a—wave attenuation. b—change in wave structure. 1—$h/l = 0.1$; 2—$h/l = 0.2$, CdS.

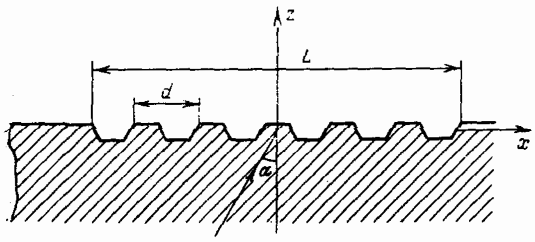

FIG. 16. Structural transducer "acoustic bulk waves ↔ ASW".

riod gives rise to a scattered amplitude $\sim\varepsilon_2$, including double scattering of bulk waves, incomplete destructive interference of waves reflected by the hill and valley, and effects of harmonics with wavenumbers nQ generated near the uneven surface.[219] Let us estimate the amplitude of the reflected wave given a sufficiently long reflecting array. Since the reflected waves are also attenuated by scattering into the bulk, the number of waves reaching a given point is $\sim\varepsilon^2$. Adding the amplitudes of these waves we obtain $u_{\rm ref} \sim\varepsilon^2 u_0 \varepsilon^{-2} = u_0$, i.e., at $\lambda = l$ the reflected wave can be comparable in amplitude to the incident wave. Scattering of the reflected wave into the bulk leads to a strong (several-fold) enhancement of the ASW attenuation coefficient at the resonant frequency.[219] In the case of nonsinusoidal corrugation with grooves in the shape of symmetrical trapezoids (a configuration which contains no harmonics with wavenumber $2Q$) reflection becomes a strong function of groove profile, increasing with the slope of the groove steps. It was shown experimentally that reflection from arrays at $\lambda = l$ is large[153,221] an description of second-order effects using "energy accumulation" near inhomogeneities for arrays with $\lambda = l$ [154,191] is not completely rigorous because this model does not incorporate scattering into the bulk.

6.3. Theory of the structural transducer

Interest in arrays with $\lambda\sim l$ is largely due to the opposite phenomenon—the possibility of transforming a bulk wave incident on an array into ASW. Such a transducer was first proposed in Ref. 222 and then numerically modeled at a 10 MHz frequency in Ref. 223. Subsequently it was demonstrated that this method can be used to excite ASW at 1 GHz frequency[224] in nonpiezoelectrics. In Fig. 16 we illustrate the "surface-structural" transducer due to Ash.[223] The phase-matching condition (see diagram in Fig. 17,a) has the form $k\sin\alpha \pm Q = \pm q$ or $q - Q = \mp k\sin\alpha$. Hence we obtain the resonant frequency

$$f = \frac{v_{\rm R}}{l}\left(1 \pm \frac{v_{\rm R}}{v}\sin\alpha\right).$$

Here " $-$ " corresponds to the excitation of ASW propagating forward along the OX axis and " $+$ " corresponds to ASW propagating in the opposite direction. At normal incidence ($\alpha = 0$) of a bulk wave onto the array two ASW waves are excited and these propagate in opposite directions. The order of magnitude of the generated ASW amplitude can be estimated as follows.[225] Let the incident bulk wave have amplitude A_0. The surface wave excited at every inhomogeneity will be of order εA_0. Given the phase-matching condition the surface waves add in phase. They also decay with attenuation coefficient $\sim\varepsilon^2 q$, however, and hence the number of waves reaching a given point in a long array is $N_{\rm eff}\sim\varepsilon^{-2}$, and their combined amplitude is

$$u \sim \varepsilon A_0 \varepsilon^{-2} = \frac{A_0}{\varepsilon} \gg A_0.$$

This estimate holds if the array length exceeds the attenuation length, i.e., $N > \varepsilon^{-2}$. In the opposite situation, which occurs when $\varepsilon\to 0$, we have $u\sim\varepsilon A_0 N\to 0$.

In comparison with the interdigital transducer, the surface-structural transducer has certain advantages at frequencies >300 MHz: *arrays are easier to fabricate than* IDT's;[14,15] bulk transducers based on ZnO films[13] are also quite efficient and work in the GHz range; unlike IDT the structural transducer is insensitive to local structural defects; the groove depth can be modulated, etc. The effectiveness of a structural transducer at normal incidence was demonstrated in Refs. 223, 224. Conversion losses were 5–10 dB. At the same time, if the attenuation of bulk signal is weak the amplitude-frequency characteristic of a transducer in steady state operation becomes distorted due to multiple reflections of the bulk wave.[226,227] Also, as we have seen already, at normal incidence there exists the possibility of double Bragg reflection from the second harmonic of the surface profile or due to second-order effects. These effects reduce the efficiency of structural transducers.[228,229] A detailed theory of the structural transducer at normal incidence, which takes into account second-order effects, is derived in Ref. 229 both for the ASW generation and reception (conversion into bulk waves). The optimal number of grooves in the array $N_{\rm opt}$ is $\sim\varepsilon^{-2}$, which is comparable to ASW attenuation length due to scattering into the bulk. Then the conversion efficiency into ASW of longitudinal bulk waves is $\eta_l\approx 0.2$ and of transverse waves is $\eta_t\approx 0.4$. The operating bandwidth of the transducer is $\Delta\omega/\omega\sim\varepsilon^2$.

Multiple reflections of the bulk wave are avoided in the case of oblique incidence.[228,230,231] In this geometry the phase-matching condition is first fulfilled at a frequency lower than v_R/l, generating a "backward" ASW ($\mathbf{k}_R\mathbf{k} < 0$), and then at a frequency higher than v_R/l, generating an ASW propagating "forward" along the OX axis (see Fig. 17). These regimes differ in that excitation of the forward-propagating wave is less efficient, since it is invariably accompanied by additional scattered waves (see diagram in

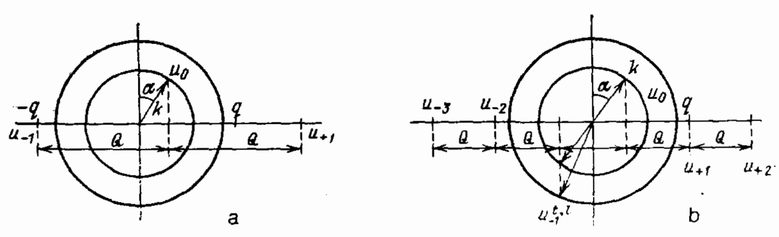

FIG. 17. Wavevector diagrams for conversion of bulk waves into ASW propagating backward (a) and forward (b).

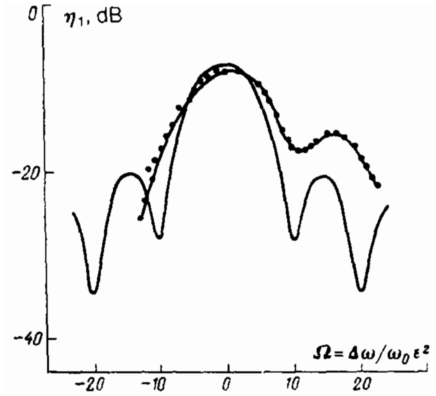

FIG. 18. Efficiency of ASW excitation for a longitudinal bulk wave incident at 45° as a function of normalized frequency mismatch. Theory—solid curve, experiment—dotted curve.

Fig. 17,b). Phase-matching at even higher frequencies is avoided for the same reason. A detailed theoretical analysis of ASW excitation at oblique incidence[216,230–232] indicates that excitation of backward-propagating ASW is most efficient, with conversion losses as low as 2–3 dB. The excitation of ASW at oblique incidence of bulk wave onto a periodic array of grooves on the substrate was first observed experimentally in Ref. 227. The losses for conversion of a longitudinal bulk wave into ASW at 320 MHz were 8 dB, in good agreement with the theoretical result (Fig. 18).[230,232]

6.4. Destructive interference of scattered bulk waves in ASW propagation over an array with $\lambda = l$

The effects discussed above for $\lambda = l$ (l being the period of a weak sinusoidal corrugation) exhibit additional features when shear ASW (Love and GBW) are involved.[220,233,80] Here the reflected wave generated by second-order phenomena is scattered into the bulk analogously to the incident ASW. In this situation it is possible that the scattered waves propagate in antiphase and destructively interfere with one another.[220] The exponential attenuation coefficient for propagation along the array then goes to zero (Fig. 19). This effect is nonexistent for Rayleigh waves because both types of waves (longitudinal and transverse) scatter into the bulk and simultaneous destructive interference is impossible.[219] A similar effect exists in integrated optics.[234] Detailed calculations[80] have shown that if $\mathrm{Im}\{\delta\} = 0$ the incident ASW still decays over an array of finite length, but linearly rather than exponentially. The reflected wave also grows linearly, while the waves scattered into the bulk are not completely canceled by interference and their amplitude is constant over the array. A structural transducer operating in this regime can convert up to 50% of the incident wave energy into bulk waves.[233,80] If a second harmonic is present in the nonsinusoidal function that describes surface corrugation, the wave experiences strong multiple Bragg reflection. The number N_{eff} of waves excited by individual inhomogeneities that add in phase is sharply reduced and the conversion efficiency of bulk waves into ASW deteriorates.[235] Such an array causes strong reflection and an incident ASW is reflected after propagating a distance $\sim\lambda/\varepsilon$, before it can scatter appreciably into the bulk. The attenuation of shear ASW (Love and GBW) and their excitation at oblique incidence of a bulk wave onto an array were investigated in detail by Lapin.[236–238] Second-order effects are insignificant in these processes and can be neglected (see also Refs. 239–241).

6.5. Resonance interaction of Rayleigh waves with Lamb modes

During experimental research into the attenuation of Rayleigh waves due to scattering into the bulk from groove arrays on the Y,Z-$\mathrm{LiBNO_3}$ surface at $l\approx\lambda$ several groups (Refs. 154, 242 and, independently, Refs. 226, 243, 244) discovered that Rayleigh waves interact with Lamb modes in a plane-parallel plate with a polished lower edge (Fig. 20). The effect manifests itself in the appearance of narrow and deep notches in the amplitude-frequency characteristic of a delay line. The authors of Refs. 242, 245 proposed a qualitative model which explained the effect in terms of Rayleigh ASW interacting with plate modes, the latter calculated in the parabolic approximation. The resulting monotonic behavior of notch parameters did not agree with experiment, however. Nonetheless, the model[242,245] gave a correct qualitative explanation of the different interaction properties at $f<f_0 = v_R/l$, when the excited Lamb modes propagate backwards and the incident ASW decays exponentially as it propagates over the array, and $f>f_0$, when the Rayleigh wave and the excited Lamb mode travel in the same direction and periodically exchange energy as they propagate over the array. In the isotropic approximation this interaction of Rayleigh ASW with Lamb modes due to surface corrugation was first described in Ref. 243 (see also Ref. 246), where the coupled mode analysis was employed to explain qualitatively all the experimentally observed properties and calculate the shape of stopband peaks. An accurate numerical calculation of resonance frequencies was carried out in Ref. 244, where the

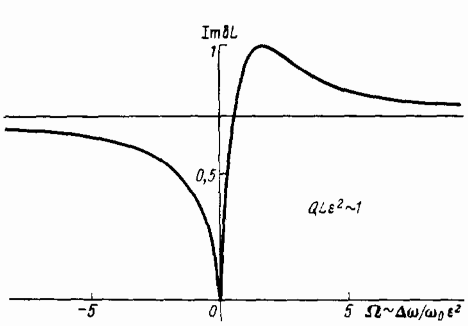

FIG. 19. Normalized attenuation coefficient for Love waves due to destructive interference of scattered waves.

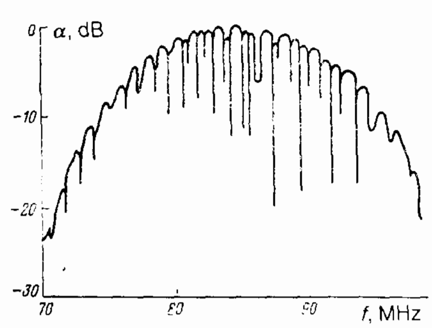

FIG. 20. Interaction of a Rayleigh wave with Lamb modes. Attenuation coefficient of a wave travelling over an array with $\lambda = l = 40\,\mu$m, $h = 0.5\,\mu$m, $N = 150$.

authors computed the dispersion curves of higher numbered Lamb modes ($N \sim 40$) in a lithium niobate plate. The agreement with experiment was good. It is worth noting that this calculation confirmed the presence of Lamb modes (low number) with negative group velocities in $LiNbO_3$.[247,248] Experiments carried out by the groups of Melngailis[245] and Grigor'evskii[232,243] demonstrated the possibility of "inverting" the notches, i.e. fabricating devices demonstrated the feasibility of designing narrow bandpass and stopband filters.

This phenomenon has also been observed in a plane-parallel plate of ST-quartz.[232] Essentially, the effect is due to the excitation of a high harmonic bulk plate resonance, with the array effectively pumping energy into the resonator. Consequently thick ($\gtrsim 1$ mm) plates can be used at high frequencies, which simplifies the fabrication technology. The uncertainty in material parameters and their change *from sample to sample make it difficult to obtain* resonances at a given frequency.

6.6. Transmission of a bulk wave through a gap with irregular edges

As we have seen earlier, the amplitude of ASW excited by conversion from bulk to surface waves on a sufficiently long array can exceed the incident wave amplitude by a factor of $\varepsilon^{-1} \gg 1$. In piezoelectrics this phenomenon can result in strong electric fields on the surface. A number of effects based on this generation of strong electric fields was proposed in Refs. 250, 251. In particular, if an identical second crystal is placed close to the piezoelectric surface of the first and both crystals have identically oriented arrays of surface grooves, the electric fields will generate ASW on the other side of the gap and these ASW will scatter into the bulk of the second crystal. Thus an incident bulk wave will, in effect, travel through a vacuum gap. Calculations show[252] that for shear waves the transmission from one crystal to another can be total. A necessary condition for total transmission is a sufficiently strong piezoelectric effect $\eta > \varepsilon$, such that the excited ASW transfer to the other side of the gap before they scatter into the bulk on the surface inhomogeneities of the first (source) crystal. In Fig. 21 we plot this effect in Rayleigh wave excitation.[253] The transmission losses of 4.5 dB are probably due to excitation of both longitudinal and transverse waves by Raleigh wave scattering, while only the longitudinal wave is recorded. Unlike the seepage of a bulk wave through a gap[103] related to the so-called attendant oscillations, this phenomenon depends resonantly on frequency and does not require grazing incidence of the bulk wave, as does the seepage effect described in Refs. 103, 254.

6.7. Bulk acoustic wave amplification upon reflection from a semiconductor interface

The electric field created on the surface can be used for electroacoustic amplification of bulk waves upon reflection.[225,255] To this end a semiconductor must be located adjacent to the corrugated piezoelectric surface. The electron drift velocity in the semiconductor should exceed ASW velocity, just as in an ordinary acoustoelectronic amplifier. (Other amplification mechanisms are examined in Refs. 256, 257.) Calculations show that the resulting amplification should be a strong, resonance phenomenon.[225] The nonresonant interaction occurring when a bulk wave is incident

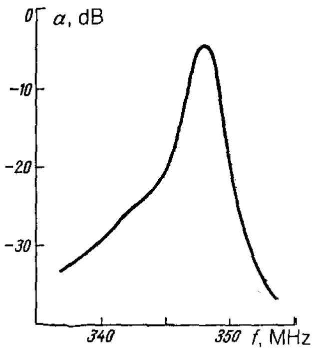

FIG. 21. Amplitude-frequency characteristic of the transmission coefficient.

on an array of period l which is several times smaller than wavelength λ is also of interest.[255] In this case the bulk wave is reflected without scattering and the surface oscillations with the same period as the array have a small amplitude ($\sim \varepsilon$) and contribute only slightly to the phase of the reflection coefficient. But the interaction of the electric fields that penetrate into the semiconductor with the drifting electrons can cause a weak enhancement $|R| - 1 \sim \varepsilon\eta$ of the reflected wave—the so-called "orotronic" effect. Interestingly, the drift velocity required for such amplification is smaller than ASW velocity by a factor of λ / l, which eases the thermal operation of this amplifier.

If the frequency is increased further above $f > v_R / l$ several scattered bulk waves are excited (the diffraction orders are shown in Fig. 9,d). When light is diffracted by diffracting structures—including diffraction by sound in acoustooptics[10,201]—this situation is common. However, light propagates through vacuum (air) and can be received or redirected at any point in space, even far away from the structure. Unfortunately, bulk acoustic waves are difficult to control and the dimensions of the acoustic medium are usually comparable to those of the diffracting structure. Consequently diffracting arrays that produce many scattered waves are rarely employed in acoustoelectronic devices.[258]

7. LASER EXCITATION OF ACOUSTIC SURFACE WAVES

In the two remaining sections of this review we will briefly discuss laser excitation of ASW, which frequently involves periodic irradiation of the surface, and the propagation of magnetostatic waves (MSW) in periodic structures.

The generation of acoustic waves due to absorption of laser radiation is well known.[259] At low laser intensities the main mechanism is the time-dependent thermal expansion; as the intensity is increased other mechanisms, like evaporation, come into play.[260,261]

Since laser radiation is usually absorbed near the surface laser excitation of ASW becomes possible. This phenomenon was first observed in 1968 by Lee and White.[262] In the last several years there has been much active research in laser excitation of ASW for two major reasons. First, the combination of laser ASW generation and the use of laser probes for ASW reception provides a contactless and fairly precise means of quality control, which is essential for mass production of ASW-employing devices. Second, laser excitation of ASW appears to hold promise in the fields of photo-acoustic spectroscopy[265] and microscopy.[266]

The advantages of laser ASW generation are the following: the technique is contactless; small samples of all acoustic media (nonpiezoelectric, metallic, etc.) can be studied; laser intensity and frequency can be varied over an extremely wide range; there is the unique possibility of creating a moving sound source; directions of ASW propagation can be quickly altered, etc.[264,267–268]

Several focusing techniques have been used experimentally. In Refs. 260–262, 264–265, 269–270 ASW were excited by amplitude modulated laser radiation focused onto a point[262,269,271] or a narrow strip.[260,261,264,265,270,271] This method allows for ASW generation over a wide frequency range. In another study[272] the authors focused laser radiation onto a ring and generated outgoing and incoming Rayleigh pulses. When the substrate surface is periodically irradiated through a mask[262,268] or by creating a diffraction grating of light and dark stripes,[267] the generated ASW have the same wavelength as the irradiation period. Others have fabricated periodic heat sources on the substrate by depositing a periodic array of strips of an optically absorbing material separated by a Rayleigh wavelength.[273] The sample can be scanned through a focused laser beam by means of a step motor drive.[266] Generation of ASW by a light spot running along the surface at ASW speed was proposed in Ref. 274 and experimentally realized in Ref. 275. Such synchoronous excitation of the substrate produces a linearly increasing ASW amplitude: fairly large displacements ($\sim 10^{-5}$ cm) have been observed even at low (<3 °K) substrate heating.

In most experiments the frequency of excited ASW is determined by our ability to modulate laser radiation and ranges from 3 MHz[261] to 130 MHz.[265] A record frequency of 830 MHz was obtained in Ref. 267. The intensity of continuously modulated laser irradiation usually falls in the 10–50 mW range (although $I = 2.5$ W has been reached in Ref. 264) and the magnitude of ASW signals received by IDT in a strong piezoelectric $LiNbO_3$ is of the order of 1 μV. The ASW generation efficiency on the surface of anti-reflection-coated $LiNbO_3$ by radiation focused onto a narrow strip reaches $V_{ASW}/I \approx 10^{-3}$ (μV/W·cm^{-2}). In addition to investigations focused on ASW generation we also note a study[267] in which Rayleigh wave excitation occurred as a secondary effect in the laser probing of a charge distribution created by inhomogenously irradiating a photoconducting semiconductor.

Laser generation of ASW has been discussed theoretically in a number of papers[273,274,277-284] which examined all the above-described geometries. In addition to laser excitation of Rayleigh waves in an isotropic solid, there have been attempts to take into account heat losses to the thermally conducting nonviscous medium adjacent to the semiconductor[279] and to calculate the excitation properties in a piezoelectric without neglecting the anisotropy of elasticity and permittivity constants.[281] In the case of monochromatic excitation the process is determined by three length scales: surface wavelength λ; "thermal wavelength" $l_T = (\varkappa/\rho c\omega)^{1/2}$ ($\varkappa$, ρ, c are respectively the thermal conductivity, density, and specific heat capacity of the acoustic medium); and the laser penetration depth into the acoustic medium γ^{-1}. Usually $l_T \ll \lambda$ and thermal conductivity can be neglected in calculations.[277] A number of other assumptions are usually employed but not specifically outlined in theoretical studies, making it difficult to compare the results obtained in Refs. 277–282. A consistent theory of laser ASW excitation by periodic irradiation with modulated laser light was developed in Refs. 283–284. Furthermore, the calculation was carried out within the framework of thermoelasticity theory,[20] i.e., taking into account not only sound generation due to temperature variations, but also the reverse process—sound-wave-induced temperature variations leading to thermoelastic light absorption. The relation between the quantities λ, l_T, γ^{-1} is taken to be arbitrary. The calculations have shown that ASW generation efficiency peaks when the radiation is absorbed at the surface. Also, the peak efficiency of converting laser energy into ASW occurs when the irradiatated region has the same length as the ASW attenuation length. The peak efficiency is $\sim \Delta T/T_0$, where ΔT is the amplitude of temperature variation.

Now let us cite some order of magnitude estimates of the amplitude of generated waves.[284] If the mean energy flux density I_0 is incident on 1 cm^2 in 1 s over a period of $2\pi/\omega$, the acoustic medium absorbs the energy $I_0 \cdot 2\pi/\omega$ which heats a layer of thickness l_T:

$$I_0 \frac{2\pi}{\omega} \approx l_T \rho c \, \Delta T.$$

Due to thermal expansion the surface shifts by a quantity $u \approx \alpha \Delta T l_T$, whence we have $u \approx \alpha I_0/\rho c\omega$.[268] Since the excited waves add in phase ($\lambda = l$) the resulting amplitude is

$$u = F(\sigma) \frac{\alpha I_0}{\rho c\omega} Lq, \tag{38}$$

where $F(\sigma)$ is a factor of order unity that depends only on the Poisson ratio σ.[284] This formula is valid as long as $L < L_a$, the attenuation length of ASW, which is usually the case. Since the amplitude u depends on the product $I_0 L$, the excitation efficiency is nearly the same regardless of whether the laser beam is focused onto a point or a single narrow $L \sim \lambda$ strip.

Undoubtedly precise and effective methods of measuring the velocity and attenuation of ASW will be developed based on laser excitation of ASW. An indication of this is provided by the first very successful investigations[264] in this direction.

8. MAGNETOSTATIC WAVES IN PERIODIC STRUCTURES

Modern signal processing systems must cope with ever-increasing signal bandwidths at ever higher central frequency. Fabrication of ASW-employing devices with bandwidth $\Delta f > 500$ MHz and central frequency above 1 GHz has met with daunting technological difficulties and physical limitations (for instance, rapidly increasing losses in the acoustic medium). For this reason magnetostatic waves (MSW), which were first discovered and theoretically analyzed in 1961–1965,[288,289] have attracted much scientific attention over the last decade.[285-287] Magnetostatic waves are spin waves whose propagation speed is much lower than the speed of light. Usually the MSW wavelength is sufficiently large for the exchange interaction to be ignored.[287] Research into MSW burgeoned after the development of the technology for fabricating high-quality yttrium-iron garnet (YIG) films on low-loss gallium-gadolinium garnet (GGG) substrates. The three principal MSW excitation geometries are shown schematically in Fig. 22, together with the dispersion

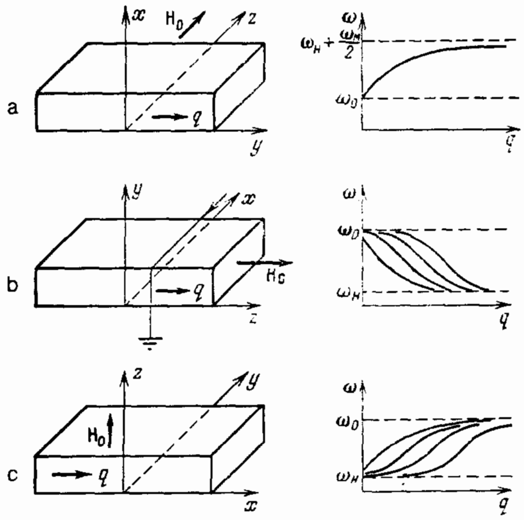

FIG. 22. Types of MSW: a—SMSW; b—backward bulk MSW; c—forward bulk MSW.

relations of the three types of waves that can propagate in these geometries. When film thickness is $\sim 10\,\mu$m the wave velocity lies in the $3\cdot10^5$–$3\cdot10^7$ cm/s range, with the wavelength falling between 1 μm and 1 mm.[290] Magnetostatic waves are easily excited with a single shorted conductor (see Fig. 22): the losses are low and the excitation band is quite wide (the wavelength must be greater than twice the sample thickness).

We therefore find that a number of properties—ease of excitation, possibility of altering the direction of propagation—make MSW the high-frequency analogs of ASW.[291] At higher velocities and lower attenuations in the 1–20 GHz range the dimensions and losses of MSW-employing devices are quite acceptable. Another advantage of MSW devices is the tunability of their parameters afforded by changing the magnetic field. Disadvantages of MSW devices include strong dispersion, high level of directly transmitted (inducing) signals and other spurious signals, and poor parameter stability. Methods of controlling MSW dispersion,[292] reducing parasitic wave reflections,[291] and improving device stability are currently under development. As in ASW-employing devices, reflecting arrays for MSW play an important role. These arrays are usually composed of small grooves or metallic strips.[293] The role of reflecting arrays is particularly crucial in the design of narrow-band devices, since the strong interaction between MSW and the exciting antenna (transducer) limits the possibility of tailoring the amplitude-frequency characteristic in transducers.

Periodic arrays have been employed to design MSW resonators[294] and LFM compression filters.[291] Although the central frequencies of these devices are high (3–5 MHz), other parameters (resonator quality factor, compression ratio and quadratic nature of phase-frequency (PF) chacteristics of LFM filters, thermal stability) so far remain greatly inferior to analogous ASW devices.

The scattering of all three MSW types from various periodic disturbances is well understood. The propagation of surface magnetostatic waves (SMSW) in periodic structures has been examined in Refs. 295–307. Tsutsumi and coworkers[296] obtained the dispersion relation for SMSW propagating through a plate with two periodically uneven edges; others[297] have investigated the case when the film and substrate are ferrites with different magnetizations and only one surface is uneven. These studies considered infinite periodic structures only. The scattering of SMSW from a finite array of grooves and from a single groove was evaluated numerically in Refs. 298, 303. But the frequency behavior of reflectors remained unclear and the reflection coefficient was calculated inaccurately by ignoring the reciprocity of SMSW propagation. These deficiencies were corrected in Ref. 307. Bragg reflection of SMSW has the same characteristic properties as the reflection of Rayleigh waves: a frequency stopband and exponential attenuation as the wave propagates along the array. At the same time, due to strong dispersion, the reflection coefficient from a single groove, the stopband, and other reflector characteristics are strongly dependent on wavenumber. As the SMSW wavelength is reduced the stopband shrinks exponentially because at lower wavelengths the interaction of the forward and backward waves propagating on the opposite surfaces of the YIG film is diminished. Simultaneously, the attenuation coefficient increases sharply because the group velocity falls off exponentially as qd is increased (d is the film thickness).

The reflection of SMSW from conducting strips was examined in Refs. 305, 313. In Ref. 305 the strip was taken as perfectly conducting and was positioned some distance from the top surface of the ferrite in order to reduce the image term. In Ref. 313 the conductivity of the metal was taken as finite and the strip thickness was assumed small compared to the skin depth. In that scenario it turned out that the periodic structure modulates wave absorption rather than wave velocity. Reflection was weak—even a semi-infinite array has $|R|\sim 0.1$.

The reflection of forward bulk magnetostatic waves (FBMSW) from periodic systems of inhomogeneities at normal and oblique incidence was studied in Refs. 306, 308. The reflection coefficient per period at normal incidence is found to be

$$|r|=\frac{\pi}{8}\,\frac{h}{d},$$

where h is the depth of the sinusoidal corrugation on the film's surfaces; d is the film thickness. Unlike the Rayleigh wave case, for no angle of oblique incidence does the reflection coefficient go to zero. Forward bulk MSW are the only class of magnetostatic waves that can propagate in any direction in the plane of the ferrite film. Consequently FBMSW are employed for signal compression devices with reflecting structures of the "herringbone" type.[295] There have been proposals to control the reflecting capabilities of array elements by using reflectors fabricated by ion implantation.[309]

The reflection of backward bulk MSW (BBMSW)—which are rarely used for practical applications—from periodic systems of inhomogeneities was addressed in Ref. 310. Both forward and backward MSW are multimode waves. Their propagation through a periodic structure involves not only reflection but coupling of different modes,[304] which is usually a parasitic effect. Also, in arrays[311] and in sufficiently thin films with smooth surfaces[312] MSW can interact with exchange spin waves and magnetoacoustic waves.

9. CONCLUSION

In this review we have attempted to cover the physics of ASW propagation in periodic structures. Reflectors of ASW based on periodic arrays of inhomogeneities are the second most important type of element (after IDT's) in ASW-employing devices. Without interdigital transducers ASW-employing devices would be impossible and without reflecting strucutres the most sophisticated, unique classes of these devices—resonators and dispersive delay lines—would be unrealizable. Currently the research in this field has shifted towards investigation of more subtle, second-order effects, the development of powerful universal computational algorithms,[3 14] investigation of non-Rayleigh types of ASW and of surface wave waveguides. The scattering of ASW from arrays in anisotropic crystals has not been studied extensively. The scattering of ASW by strong inhomogeneities has been little studied experimentally and no wideband local "mirrors" (even semi-transparent ones) are available for ASW reflection. The very high frequency range ($>10^{10}$ Hz) is of great interest—there interesting phenomena are expected in ASW propagation through superlattices and thin layers, and at low temperatures.

Research into acoustic surface waves has come the full circle from original proposals and laboratory experiments to mass production of devices (the cost of all ASW devices now exceeds $100 million and the price of a filter has fallen below $1). Now technological requirements are stimulating research into new types of waves, new excitation methods, and new techniques of controlling their propagation.

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