SURFACE MICROACOUSTICS

M. EPSTEIN

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Information-Processing And Control SYSTEMS LABORATORY

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Preface

The application of elastic surface waves in solids to devices in communications and radar is gaining impetus. The studies of materials and techniques reported during the past five years show a steady and large increase in this area of scientific and technological activity. In particular, during the last two years it became obvious that the methods of signal processing by means of acoustic surface-wave devices are sufficiently refined to be used in numerous practical devices. When the preparation of this report was originally suggested by Dr. A. Shostak of the Office of Naval Research, it was clear that there existed a need for review literature in this field. However, during the past year significant reviews and summaries of the state-of-the-art of surface microacoustics have been published in both professional and trade journals. The most notable is the special issue on Microwave Acoustics which appeared in the IEEE Transactions on Microwave Theory and Techniques of November 1969 (vol. MTT-17, no. 11), and which significantly enough, while it was aimed to cover all of microacoustics, dwelt on surface microacoustics in considerable proportion. Also, in the series "Physical Acoustics" edited by W. P. Mason and R. N. Thurston and published by Academic Press, two chapters appear in recent volumes which deal with elastic surface waves. ("Properties of Elastic Surface Waves" by G. W. Farnell in volume 6, March 1970, and "Excitation, Detection, and Attenuation of High-Frequency Elastic Surface Waves", by K. Dransfeld and E. Salzman, volume 7, August 1970.)* Among the reviews

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*At the time of completion of this report, a paper "Surface Elastic Waves", by R. M. White appeared in the August 1970 issue of the Proceedings of IEEE (pp. 1238-1276), which constitutes the most extensive and up-to-date review of this subject and which also contains a bibliography of nearly the same coverage as the one included in this report.

in trade publications are those by Collins and Hagen [57,58,59], and by van den Heuvel [232].

The objective of this report is to provide an introduction to the field of surface microacoustics which can serve new research workers such as graduate students as well as provide a useful source of information for the practicing engineer. This report consists mainly of two parts: 1. An introduction to and review of the field of acoustic surface waves, and 2. An annotated bibliography The review sections are sketchy and are intended only to provide a guide to the existing literature. The latter has been restricted to published journals which are available in most industrial and university libraries.

My own introduction to and activities in the field of surface microacoustics have been greatly enhanced by the cooperation of my associates Drs. A. P. van den Heuvel, S. G. Joshi and R. J. Serafin of the IIT Research Institute in Chicago, Ill.

Max Epstein

Table of Contents

		Page
I.	Introduction	1
II.	Elastic Waves	4
III.	Acoustic Surface Waves	7
IV.	Propagation in Anisotropic Solids	13
V.	Generation and Detection of Elastic Surface Waves	19
VI.	Amplification of Elastic Surface Waves	29
VII.	Guided Surface Waves	31
VIII.	Acoustic Surface-Wave Filters	34
IX.	Love Waves	36
X.	Magnetoelastic Surface Waves	37
XI.	Bibliography	40
XII.	Subject Index to Bibliography	74

I. Introduction

"Microacoustics" refers to the study and application of acoustic waves in solids at such frequencies at which the length of the wave is small. Since the velocity of propagation of acoustic waves in solids is five orders of magnitude smaller than that of electromagnetic waves, elastic waves at frequencies of several megahertz have wavelengths equal to a small fraction of an inch. This is contrasted with electromagnetic waves in which the so-called microwave region starts below a frequency of a gigahertz with a corresponding wavelength of about a foot. Thus, indeed the microacoustic term is appropriate for most devices utilizing the propagation of elastic waves in solids. Other terms have also been employed, such as microwave acoustics, microsound, and praetersonics (beyond sound), the latter usually applying to the range of frequencies above 100 MHz.

The excitation of elastic waves in solids has been realized primarily by means of piezoelectric crystals. These crystals, in form of wafers whose dimensions are related to the acoustic wavelength, are attached to the medium of propagation, usually chosen for qualities such as attenuation of the waves or its dispersive characteristics. The waves, which are longitudinal or shear waves, propagate towards the end of the specimen and can be detected by another piezoelectric transducer not unlike the one used for the excitation of the waves. Except for some special opto-elastic techniques of detection, the microacoustic device which utilizes bulk wave propagation, constitutes a delay line with a given fixed time delay. Thus, the access to the signal when it is propagated in the form of an acoustic wave is limited.

In applications which include processing and storage of signals, it is advantageous to have a ready access to the signal when it propagates in the form of an elastic wave. This can be realized by utilizing the surface wave mode of propagation, wherein the energy of the propagating distrubance is at or near the surface of the solid. The most common surface wave is the Rayleigh wave which is nondispersive. Currently, the most efficient method of excitation and detection of such waves is by means of interdigital transducers. The transduction is obtained by using a piezoelectric substrate for the propagation medium or piezoelectric thin films at the location of the transducer. The fabrication techniques of surface-wave interdigital transducers are similar to those used in modern microcircuit technology. Thus, in addition to the functional advantages of the surface wave, e.g., its accessibility or nondispersive characteristic, the field of surface microacoustics is quite compatible with planar technology of integrated circuits.

The frequency characteristic of a surface microacoustic device depends greatly on the design of the interdigital transducer; hence, a variety of filters can be synthesized by using such a device. The versatility with which the surface wave transducer can be designed and fabricated has been used to obtain devices with desirable frequency functions where broad-band and small sidelobes could be attained.

The deposition of thin layers of materials with acoustic parameters differing from those of the substrate can be employed to guide the surface elastic wave. Guided elastic waves can be applied to the design of surface microacoustic devices which perform functions similar to those of electromagnetic guided waves. Also, propagation of surface waves in layered structures contributed to dispersion of the wave. By controlling the loading of the layer and, thus, the dispersive characteristic of the surface wave, it is possible to design filters used in pulse compression of radar signals. Acoustically loaded substrates can be used to propagate another type of surface wave, the so-called Love wave.

Bulk magnetic spin waves and magnetoelastic waves have their counterpart in the surface mode, the latter being usually coupled to the Love wave.

II. Elastic Waves

The stresses in solids utilized for the propagation of microacoustic waves do not exceed the elastic limit of the material. It is, therefore, assumed that there exists a linear relationship between all the stress and strain components involved. To obtain a univalued relationship between the six independent components of stress and strain, the off-diagonal terms of the six-by-six matrix of coefficients are pair-wise equal reducing their number from 36 to 21 [149]. Additional symmetries in the material may further reduce the number of such coefficients; e.g., for a cubic crystal there are only three independent constants which relate the strains and stresses in the solid, ([149] page 163).

In an isotropic solid, in which the coefficients must be independent of an arbitrarily chosen rectangular coordinate system, the only non-zero coefficients are the six diagonal and upper left six off-diagonal ones of the matrix. In addition, the off-diagonal terms are all equal as are the first and last three diagonal coefficients, respectively. Moreover, the three remaining constants are not independent, reducing the number of independent elastic coefficients to two, known as the Lamé constants, and are denoted by λ and μ. The latter, thus, define completely the elastic behavior of an isotropic solid. Hence, the general linear relationship between stress T and strain S, Hooke's law,

$$\begin{aligned}
T_{xx} &= c_{11}S_{xx} + c_{12}S_{yy} + c_{13}S_{zz} + c_{14}S_{yz} + c_{15}S_{zx} + c_{16}S_{xy} \\
T_{yy} &= c_{21}S_{xx} + c_{22}S_{yy} + c_{23}S_{zz} + c_{24}S_{yz} + c_{25}S_{zx} + c_{26}S_{xy} \\
T_{zz} &= c_{31}S_{xx} + c_{32}S_{yy} + c_{33}S_{zz} + c_{34}S_{yz} + c_{35}S_{zx} + c_{36}S_{xy} \\
T_{yz} &= c_{41}S_{xx} + c_{42}S_{yy} + c_{43}S_{zz} + c_{44}S_{yz} + c_{45}S_{zx} + c_{46}S_{xy} \\
T_{zx} &= c_{51}S_{xx} + c_{52}S_{yy} + c_{53}S_{zz} + c_{54}S_{yz} + c_{55}S_{zx} + c_{56}S_{xy} \\
T_{xy} &= c_{61}S_{xx} + c_{62}S_{yy} + c_{63}S_{zz} + c_{64}S_{yz} + c_{65}S_{zx} + c_{66}S_{xy}
\end{aligned} \tag{1}$$

or

$$\begin{pmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \\ T_5 \\ T_6 \end{pmatrix} = \begin{pmatrix} c_{11} & c_{12} & c_{13} & c_{14} & c_{15} & c_{16} \\ c_{21} & c_{22} & c_{23} & c_{24} & c_{25} & c_{26} \\ c_{31} & c_{32} & c_{33} & c_{34} & c_{35} & c_{36} \\ c_{41} & c_{42} & c_{43} & c_{44} & c_{45} & c_{46} \\ c_{51} & c_{52} & c_{53} & c_{54} & c_{55} & c_{56} \\ c_{61} & c_{62} & c_{63} & c_{64} & c_{65} & c_{66} \end{pmatrix} \times \begin{pmatrix} S_1 \\ S_2 \\ S_3 \\ S_4 \\ S_5 \\ S_6 \end{pmatrix} \tag{1a}$$

with $i,j = 1,\ldots,6$ and T_i' and S_j' given in Eq. 1, reduces for the case of an isotropic solid ($c_{12} = c_{13} = c_{21} = c_{23} = c_{31} = c_{32} = \lambda$; $c_{44} = c_{55} = c_{66} = \mu$; $c_{11} = c_{22} = c_{33} = \lambda + 2\mu$) to

$$\begin{aligned} T_{xx} &= \lambda\Delta + 2\,\mu S_{xx}, \quad T_{yy} = \lambda\Delta + 2\,\mu S_{yy}, \quad T_{zz} = \lambda\Delta + 2\,\mu S_{zz} \\ T_{yz} &= \mu S_{yz}, \qquad T_{zx} = \mu S_{zx}, \qquad T_{xy} = \mu S_{xy}, \end{aligned} \tag{2}$$

where $\Delta = S_{xx} + S_{yy} + S_{zz}$ represents the dilatation or the relative change in volume [127]. Since the Lamé constant μ represents the ratio between the corresponding shear stresses and strains, it is, therefore, equal to the shear modulus or rigidity of the solid.

The other quantities of interest in elastic behavior of solids, namely, Young's modulus, Poisson's ratio, and the bulk modulus, can be expressed in terms of the Lamé constants λ and μ [127].

The equations of motion in an elastic medium are obtained by applying the forces due to body stresses to Newton's second law of motion. It is then found that in an unbounded isotropic solid only two types of waves with different velocities can be propagated. The first type is a shear or transverse wave which propagates with a velocity $v_t = (\mu/\rho)^{\frac{1}{2}}$, where ρ is density of the material, and the second type is a longitudinal wave which involves both compression and shear and which propagates with a velocity $v_{\ell} = [(\lambda + 2\mu)/\rho]^{\frac{1}{2}}$, ([127] p. 13).

At and near the surface of an elastic solid, the displacements of the material are caused by both waves of dilatation (longitudinal waves) and waves of distortion (shear waves). The displacements or amplitudes of the individual waves diminish with the distance from the surface, each with its own constant of exponential decay. The combined displacements parallel and normal to the surface propagate along the boundary of the solid with a single velocity of a wave called the surface or Rayleigh wave. At the surface of the elastic solid, which is free from external forces, the assumption of zero normal and shear stresses provides the required boundary conditions. Applying the latter to the solution for the Rayleigh wave results in a conditional equation, subject to the existance of a real exponential decay of the component (longitudinal and shear) waves. As a consequence of this condition a unique velocity of propagation of the Rayleigh wave is obtained. This velocity is only slightly lower than the velocity of the shear wave which is, in turn, lower than that of the longitudinal wave [223], [134].

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III. Acoustic Surface Waves

The propagation of elastic surface waves in solids was first investigated by Lord Rayleigh [172]. Rayleigh analyzed the case of an infinite homogeneous isotropic elastic solid and considered the case of a disturbance which was confined to a region immediate to the surface and within a thickness comparable with the length of the elastic wave. At the surface of the solid the particle displacement follows a retrograde elliptical motion with the major and minor axes of the ellipse perpendicular to the surface and parallel to the direction of propagation, respectively. At a depth below the surface of about one fifth of the acoustic wavelength, the direction of particle motion is reversed and describes a forward or direct elliptical path. The relationships between the velocities of the longitudinal, transverse and surface waves are obtained in terms of Poisson's ratio ν. Thus, the ratio of the transverse to longitudinal wave velocities is given by ([223] page 398)

$$\frac{v_t}{v_\ell} = \sqrt{\frac{1-2\nu}{2(1-\nu)}} \tag{3}$$

Since for most materials the magnitude of Poisson's ratio varies between 0.2 and 0.45, the ratio of the above velocities ranges between about 0.3 to 0.6. The relationship between the surface and transverse wave velocities is somewhat more complicated ([223], page 403, Eq. 260m) and varies, for $0.2 < \nu < 0.45$, between 0.91 to 0.95. An approximate expression for this ratio is [62],

$$\frac{v_s}{v_t} = \frac{0.87 + 1.12\nu}{1 + \nu} . \tag{4}$$

For the same range of the Poisson ratio, the ratio of the surface to longitudinal wave velocities varies between 0.55 to 0.25. The particle displacements u in the longitudinal and w in the transverse directions normalized with respect to the normal displacement at the surface, is shown in Fig. 1 as a function of depth into the solid. The latter is normalized with respect to the wavelength of the elastic surface wave [238]. The two curves (dashed and solid) represent the values calculated for Poisson's ratios of 0.25 to 0.34, respectively. Thus, the particle displacements decay rapidly with distance from the surface and the horizontal component of the displacement changes sign at a depth of about one fifth of a wavelength.

The stresses in the solid also vary with depth from the surface. Choosing Cartesian coordinates such that the surface is in xy plane, with the Rayleigh wave propagating in the +x direction and the solid occupies the half space for positive z-direction, Fig. 2 shows the variations of stress with depth from the surface normalized with respect to wavelength. The stresses T_{zz}, T_{xz}, and T_{xx} are respectively, the normal and shear stresses perpendicular and parallel to the direction of propagation of the surface wave. These are given as normalized with respect to the normal stress in the direction of wave propagation and at the surface T_{xx0}. Again, the dashed and solid curves correspond to the cases of Poisson's ratio equal to 0.25 and 0.34, respectively [238].

The attenuation of Rayleigh waves, which is due to absorption and scattering of acoustic energy, can be shown to be related to the attenuation of longitudinal and shear waves [169]. In most cases in which the loss is low, the absorption coefficient of the Rayleigh wave α_R is linearly related to the corresponding absorption coefficients α_c and α_s of the compressional and shear waves, respectively, $\alpha_R = A\alpha_c + B\alpha_s$. A and B depend on the

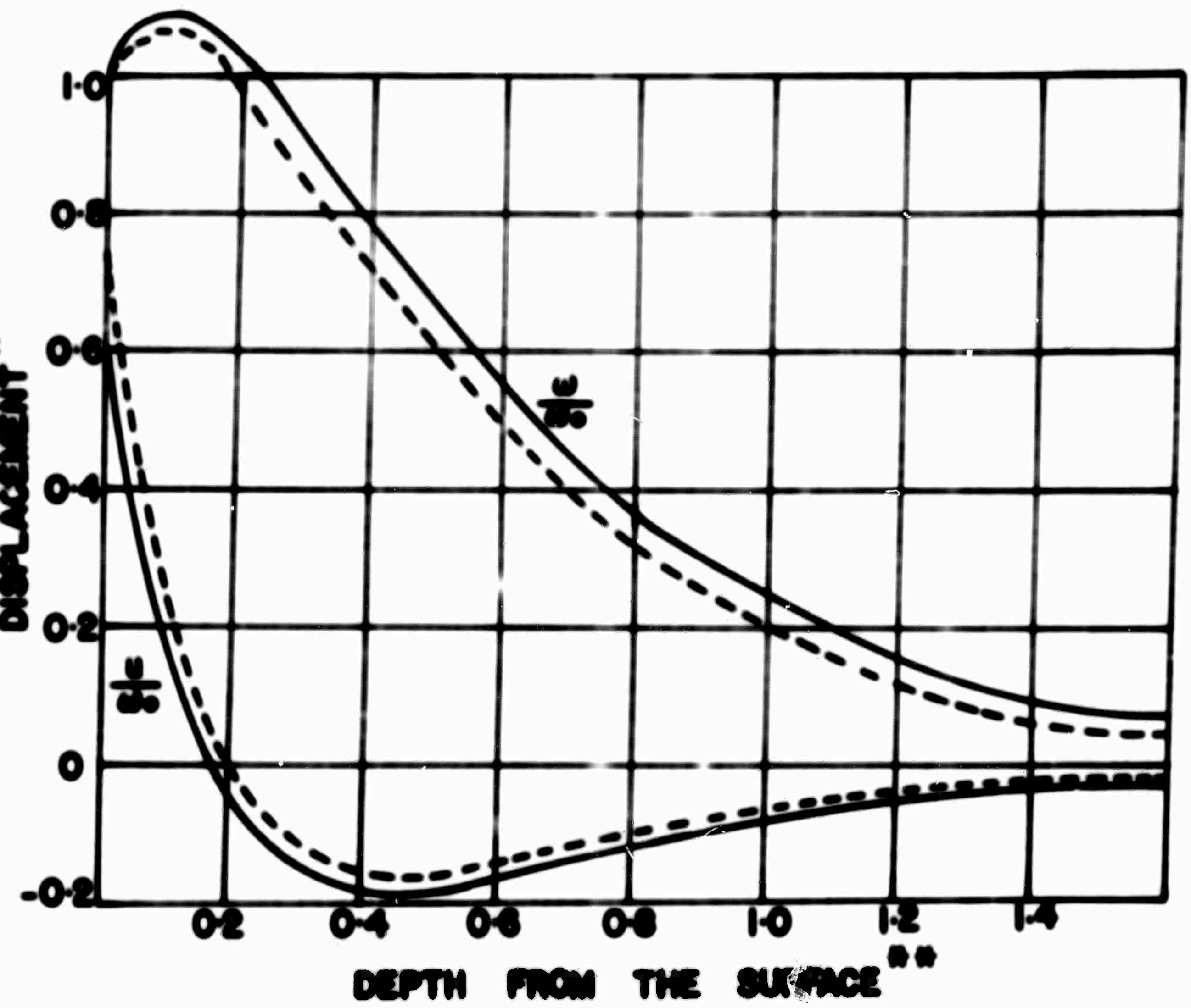

Fig. 1 - Particle displacement of the longitudinal and transverse components of surface wave.

* normalised with respect to the transverse displacement at the surface

** normalised with respect to the surface wavelength

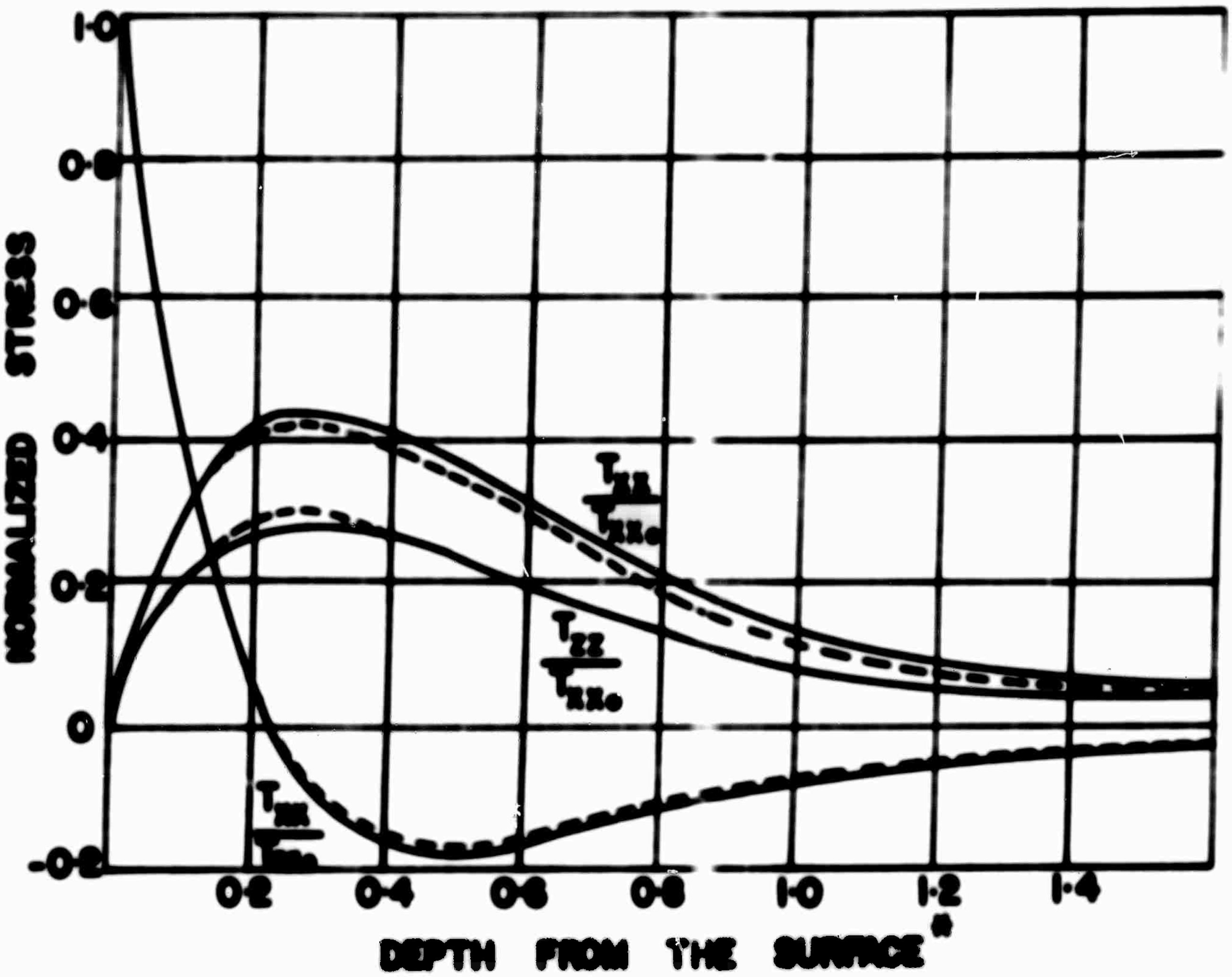

Fig. 2 - Stress amplitudes of surface wave

* normalized with respect to the surface wavelength

velocity ratios of the three elastic waves (longitudinal, transverse and surface waves) [169], which in turn depend only on Poisson's ratio [62]. Utilizing the calculated values for the velocity ratios as functions of the Poisson's ratio [62], and applying it to compute the constants A and B, we obtain

for Poisson's ratio	ν = 0.2	0.3	0.4
	A = 0.33	0.19	0.09
	B = 0.892	0.904	~1

From the values above it appears that, for the range of Poisson's ratio above 0.2, the absorption coefficient of the Rayleigh wave is nearly the same as that of the shear wave. Measurements of absorption coefficients indicate a linear dependence on frequency [169]. From data obtained at 1 and 3 MHz, for a metal (ν = 0.365), glass (ν = 0.342), and polystyrene (ν = 0.365), the attenuation in these isotropic materials varies between 0.01 to 0.1db/μ sec of delay [238]. The above values should be compared with attenuation of elastic waves in single-crystal materials as shown in Fig. 3. The latter indicates that the attenuation in crystals is considerably lower than in amorphous solids. It is of interest to note that a linear dependence of the attenuation coefficient on frequency, as found for isotropic solids at lower frequencies, implies a constant attenuation per unit wavelength. Measurements on metals, glass and fused quartz show the latter to have the highest surface-wave velocity (3.4×10^5 cm/sec) and the lowest attenuation (0.0034db/μ sec) [239].

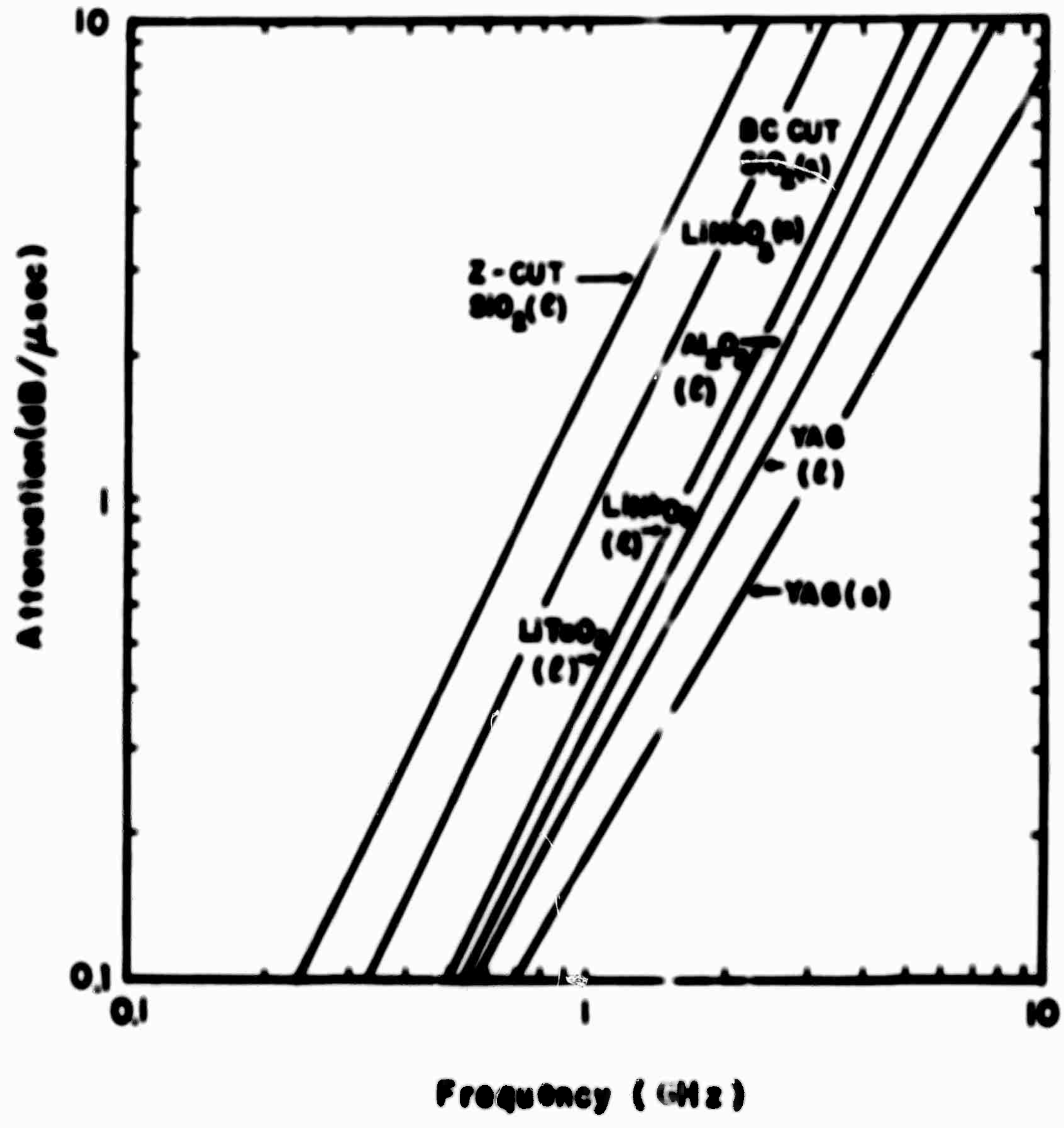

Fig. 3 - Attenuation Characteristics of Several Good Acoustic Materials

IV. Propagation in Anisotropic Solids

The high attenuation of elastic waves in isotropic solids requires that, at high frequencies, the propagation of surface waves be obtained with single-crystal materials. Also, the most common methods of excitation and detection of acoustic surface waves by means of the piezoelectric effect point to the use of anisotropic crystalline solids. (In a later discussion on guided surface waves, the above argument will be qualified.)

The derivation of solutions for the propagation of elastic waves in anisotropic solids can be very complex. Depending on the crystal system and class (there are thirty-two crystal classes [211]) the number of different elastic constants contributes to the complexity of the problem. For cases of propagation along nonsymmetry planes up to 21 independent elastic constants may be involved. The search for elastic waves propagating on the surface of an anisotropic solid indicates that Rayleigh type surface waves exist only in given directions depending on the values of the elastic constants. Moreover, surface waves have been found which are characterized by a decay with distance from the surface given by the product of a trigonometric and exponential functions. Such waves, in contrast to the ordinary Rayleigh waves which exhibit an exponential decay only, are referred to as generalized Rayleigh waves [216].

Transversely isotropic media have been investigated when the surface is normal and parallel to the direction about which there is symmetry of rotation [35]. In both cases, termed quasi-isotropic and anisotropic, respectively, the surface waves were of the generalized Rayleigh type. In the anisotropic case the solutions point to propagation of Rayleigh waves in specific directions only; however, as mentioned later by Lim and Farnell [145], the hypothesis is advanced that in most directions there is a solution for damped Rayleigh waves.

Considerable work was performed in investigating surface elastic wave propagation in cubic or isometric crystals. Next to the isotropic case, this crystal system requires the lowest number of independent elastic constants, namely three. Stoneley [213] showed that, for symmetrical cases (direction of propagation parallel to or at an angle of 45° to the x-axis), the Rayleigh type waves exist only for certain sets of values of the three elastic constants. The Rayleigh waves in cubic crystals, as well as in other anisotropic solids, remain non-dispersive; i.e., the surface-wave velocity is independent of frequency. Only in the limited cases, and well beyond present applications of microacoustics, when the wavelength is comparable with the lattice spacing of the crystal, does the surface wave exhibit dispersion [89].

The most widely used piezoelectric materials are the crystals of quartz (SiO_2), lithium niobate ($LiNbO_3$), cadmium sulphide (CdS), cadmium selenide (CdSe), and zinc oxide (ZnO). The traditional use of quartz in resonators in particular and in bulk wave devices in general, lead to an accumulation of considerable background information on this material. Numerous publications have also been made available on the propagation of surface elastic waves in single-crystal quartz. The propagation of Rayleigh waves along surfaces other than the planes of symmetry of the crystal were investigated thoroughly [73], in particular, by Coquin and Tiersten [63]. Lim and Farnell [145] claim that there always appears to be a surface-wave solution which satisfies the free-surface boundary conditions and which is unattenuated in the direction of propagation. They find that often the bulk shear wave alone will satisfy the free-surface boundary conditions, and that the resulting surface wave penetrates deeply into the bulk and, for some directions, does indeed become a bulk wave. Also, they find solutions for, what they define, a pseudo-surface wave which attenuates very slowly due to a small component of the wave radiating into the bulk. Such surface waves were found to have phase velocities greater than the velocity of the corresponding slowest volume wave [78].

The above properties of the propagation of surface elastic waves in quartz were considered without regard to the fact that single-crystal quartz is piezoelectric and that any mechanical strain in the material is accompanied by an electric field. Thus, in general, the solution of elastic waves in piezoelectric solids is not only governed by the mechanical equations of motion but by the combined mechanical, electrical and piezoelectric relations. In order to distinguish such waves from those due to a purely elastic problem, the acoustic waves in piezoelectric solids are referred to as "piezoelectric waves" [63].

The piezoelectric equations for the most general case (triclinic system with 21 independent elastic constants) relate the mechanical stress T, strain S, and electrical field and displacement E and D, as follows:

$$
\begin{aligned}
S_1 &= s^E_{11}T_1 + s^E_{12}T_2 + s^E_{13}T_3 + s^E_{14}T_4 + s^E_{15}T_5 + s^E_{16}T_6 + d_{11}E_1 + d_{21}E_2 + d_{31}E_3 \\
S_2 &= s^E_{21}T_1 + s^E_{22}T_2 + s^E_{23}T_3 + s^E_{24}T_4 + s^E_{25}T_5 + s^E_{26}T_6 + d_{12}E_1 + d_{22}E_2 + d_{32}E_3 \\
S_3 &= s^E_{31}T_1 + s^E_{32}T_2 + s^E_{33}T_3 + s^E_{34}T_4 + s^E_{35}T_5 + s^E_{36}T_6 + d_{13}E_1 + d_{23}E_2 + d_{33}E_3 \\
S_4 &= s^E_{41}T_1 + s^E_{42}T_2 + s^E_{43}T_3 + s^E_{44}T_4 + s^E_{45}T_5 + s^E_{46}T_6 + d_{14}E_1 + d_{24}E_2 + d_{34}E_3 \\
S_5 &= s^E_{51}T_1 + s^E_{52}T_2 + s^E_{53}T_3 + s^T_{54}T_4 + s^E_{55}T_5 + s^E_{56}T_6 + d_{15}E_1 + d_{25}E_2 + d_{35}E_3 \\
S_6 &= s^E_{61}T_1 + s^E_{62}T_2 + s^E_{63}T_3 + s^E_{64}T_4 + s^E_{65}T_5 + s^E_{66}T_6 + d_{16}E_1 + d_{26}E_2 + d_{36}E_3 \\
D_1 &= d_{11}T_1 + d_{12}T_2 + d_{13}T_3 + d_{14}T_4 + d_{15}T_5 + d_{16}T_6 + \epsilon^T_{11}E_1 + \epsilon^T_{12}E_2 + \epsilon^T_{13}E_3 \\
D_2 &= d_{21}T_1 + d_{22}T_2 + d_{23}T_3 + d_{24}T_4 + d_{25}T_5 + d_{26}T_6 + \epsilon^T_{12}E_1 + \epsilon^T_{22}E_2 + \epsilon^T_{23}E_3 \\
D_3 &= d_{31}T_1 + d_{32}T_2 + d_{33}T_3 + d_{34}T_3 + d_{35}T_5 + d_{36}T_6 + \epsilon^T_{13}E_1 + \epsilon^T_{23}E_2 + \epsilon^T_{33}E_3
\end{aligned}
\tag{5}
$$

where $s_{ij} = s_{ji}$,

or

$$S = s^E T + d_t E$$
$$D = dT + \epsilon^T E \qquad (5a)$$

where d_t is the transpose of the piezoelectric-strain matrix d, s^E is the alastic compliance at constant electric field, and ϵ^T is the dielectric constant at given strass. Similarly, the piezoelectric relations can be expressed as

$$T = c^E S - e_t E$$
$$D = eS + \epsilon^S E \qquad (6)$$

where c^E is the alastic stiffness at constant electric field, e is the piazoelectric-stress constant, and ϵ^S is the permittivity at constant strain.

In quartz, whare the piezoelactric coupling is small, the analysis can be separated into a puraly elastic casa and a residual electrostatic part determined by the piezoelectric coupling. Coquin and Tiersten [63] discuss in detail tha propagation of surface waves in the direction of tha x-axis of a rotated Y-cut quartz and the rotated y-axis of an X-cut quartz plate. They evaluate the "material efficiency factors" as a function of the direction of propagation of the surface wave. They find that for an X-cut plate the power-flux vector is colinear with the wave propagation in only a few special directions in the quartz plata, and only in one diraction which has an efficiency factor comparable with that of the rotated Y-cut plate. In the latter the propagation direction and power flux vector are always colinear.

Numerical data for velocities, dielectric impermeabilities, and displacement vectors of acoustic surface waves in alpha-quartz are obtained [111] based upon measured values of elastic and piezoelectric constants [19].

The attenuation of surface waves at frequencies above 100 MHz at room temperature is independent of temperature and varies as the square of the frequency [181] similar to the behavior of bulk waves and of the same order of magnitude (see Fig. 3). On the other hand, at low temperatures, the attenuation varies with temperatures as T^4 and linearly with frequency [150]. The attenuation of surface waves due to the radiation of acoustic energy in the form of longitudinal waves into the surrounding air is assumed to be significant enough [32] to suggest, for some applications, the need for encapsulation of the device.

The most efficient material to date which has been utilized for the excitation and propagation of elastic surface waves is lithium niobate ($LiNbO_3$). It is a ferroelectric crystal of class 3m and like many other ferroelectrics has a very high piezoelectric stress constant (more than an order of magnitude greater than that of quartz [116], [245]). The attenuation of elastic waves in $LiNbO_3$ is considerably lower than in quartz; for frequencies in the range of 1 to 9 GHz the losses in shear waves were found to be proportional to the square of the frequency and somewhat higher than for longitudinal waves (at 1 GHz they were less than 1 db/μ sec for shear and less than 0.3 db/μ sec for the longitudinal waves [200], [92]). For surface waves at 1 GHz, the attenuation was found to be 1.63 db/μ sec for the propagation along the z-axis on a Y-cut crystal [193], and to have a strong temperature dependence [44].

The thermal expansion of lithium niobate is of the same order of magnitude, though slightly higher, than quartz [124]. (In terms of thermal expansion, the best substrate material is nonpiezoelectric fused quartz.)

An excellent substrate material as far as attenuation at high frequencies is concerned is sapphire [175].

In addition to the trigonal crystals quartz and lithium niobate, the most widely used materials for microacoustic devices are the semiconducting hexagonal crystals cadmium sulphide, cadmium selenide, and zinc oxide. The propagation of elastic surface waves on the basal plane of such crystals were investigated by Tseng and White [229]. They find that in the case of CdS and CdSe, which exhibit relatively low piezoelectric coupling, the surface waves are similar to those obtained in transversely isotropic (non-piezoelectric) media [35]. On the other hand, for ZnO, which has considerably higher piezoelectric coupling, the surface waves are of the generalized Rayleigh type [216]. Similar results of propagation of generalized Rayleigh waves were obtained for the ferroelectric lead-titanate zirconate (PZT-4) poled in the direction normal to the surface [225].

The preceding discussion of the propagation of acoustic waves was based on analytical solutions which were obtained by the application of boundary value problems to elastic waves in solids. Not unlike the electromagnetic microwaves, the guided acoustic waves can be treated by methods of network analysis. Such techniques were recently proposed and appear to be quite effective in deriving the properties of elastic waves in solids [162].

Measured and calculated values of surface-wave velocities of many useful insulators and semiconductors is given in a short paper [240] which summarizes the results reported by a number of researchers.

V. Generation and Detection of Elastic Surface Waves

Several methods of excitation of surface waves on isotropic (non-piezoelectric) substrates have been available for a considerable time past, Fig. 4, [238]. They found widest use in applications to non-destructive testing and only in a limited form in the design of acoustic delay lines. In the latter case, the most useful methods of generation were those utilizing the comblike structure and the wedge. The former results in a more efficient but narrow-band device (provided the mechanical coupling to the substrate is high) while the latter may, in principle, be used with wide-band signals. The bandwidth of the wedge transducer depends primarily on the bandwidth of the driving compressional or shear piezoelectric crystal plate. The use of a comb transducer in conjuction with an X-cut quartz plate was employed to generate surface waves at 30 MHz, which corresponded to the period of the comb structure, and at the second and third harmonics (60 and 90 MHz) [7]. An unexpected decrease (of about 20db) of the surface-wave intensity was observed with the reduction of temperature. This decrease is attributed to the solidification of moisture at the contacts between the comb and the substrate (fused quartz) reducing the mechanical coupling between them.

The above techniques involve the use of compressional or shear wave transducers. A method of direct transduction of surface waves utilizes structures which are compatible with current microcircuit fabrication techniques and can be applied for high frequency signals [8]. It consists of a piezoelectric flat bar with its entire bottom coated with a metallic electrode and on top of the bar, along which the surface wave is to be propagated, an array of parallel metal strips deposited at intervals equal to the wavelength of the acoustic surface wave, Fig. 5a.

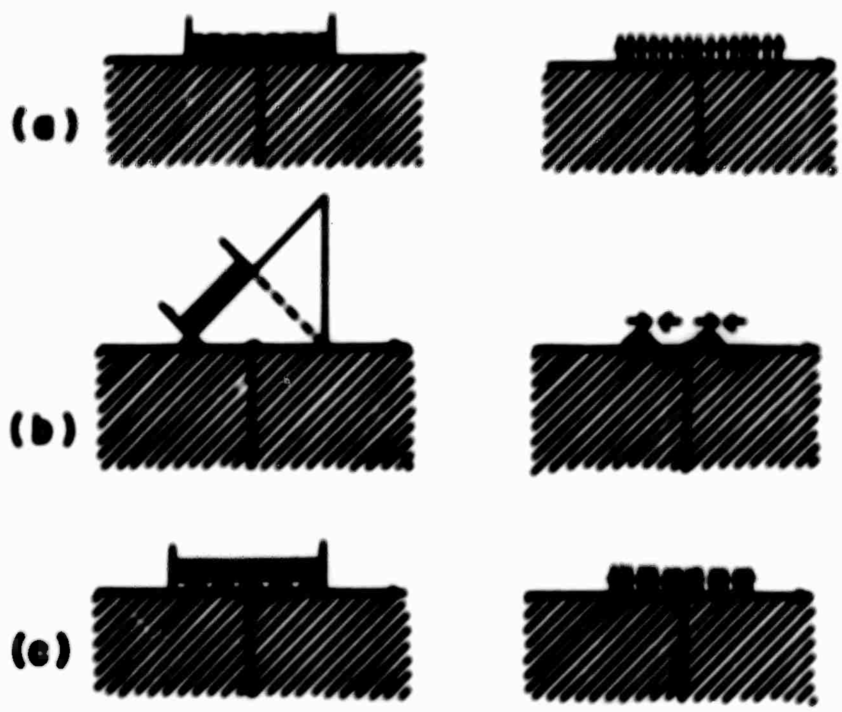

Fig. 4 - Early Methods of Excitation of Surface Acoustic Waves (Ref. 238)

(a) Quartz plate bonded to the elastic solid

(b) Quartz plate on plastic wedge

(c) Quartz plate on a comblike structure

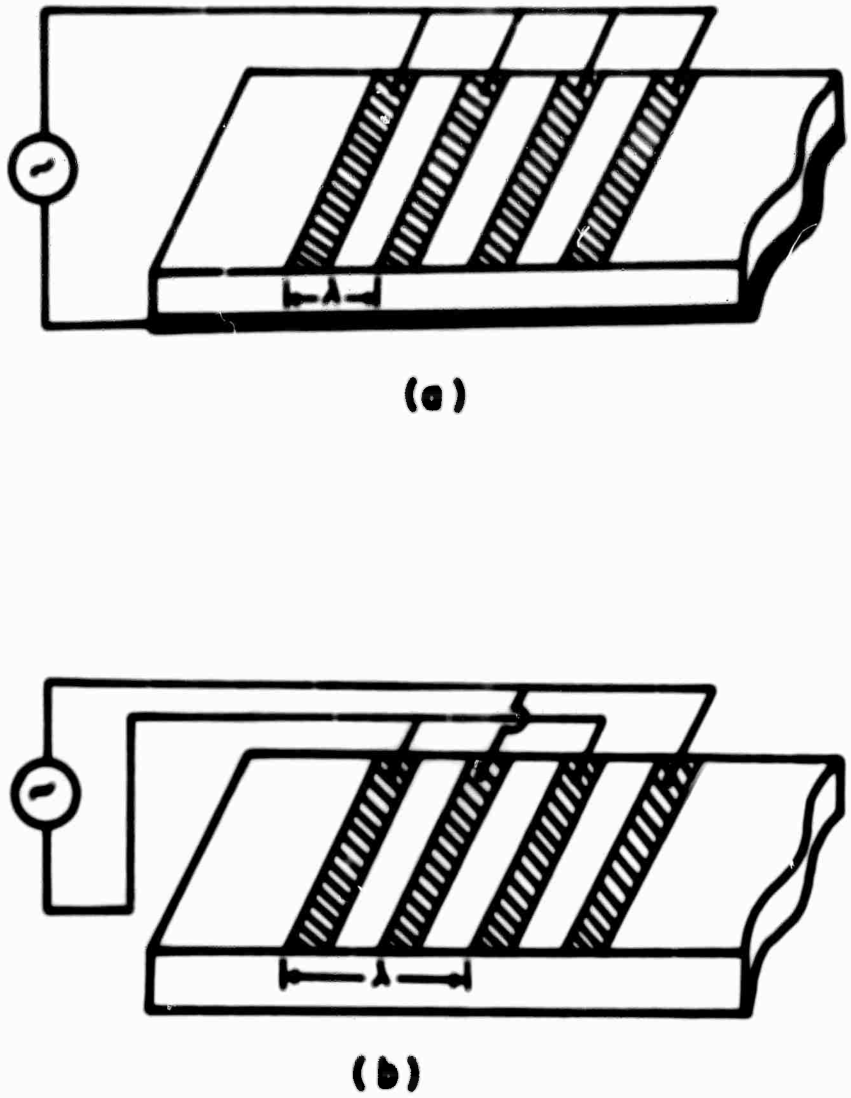

Fig. 5 - Direct Method of Excitation of Surface Acoustic Waves

(a) Single-phase array

(b) Alternate-phase array

A similar, but more efficient, method of direct excitation of elastic surface waves on piezoelectric substrates was obtained by utilizing an interdigitated structure of deposited electrodes [252], Fig. 5b. In this transducer the metal strips are separated by one half of the acoustic wavelength, with the alternate strips connected electrically in parallel. The most efficient configuration is obtained when the width of the electrodes is equal to the spacing between them [63]. For most materials the surface-wave velocity is in the range of 2 to 4 x 10^5 cm/sec., which at a frequency of 100 MHz, gives wavelengths of about 0.8 to 2 mils (1 mil = 0.001 inch). The resolution required in the fabrication of electrodes with widths and separation equal to a fraction of a mil cannot be obtained by conventional methods of vacuum deposition of metals, and requires the use of photo-resist techniques currently employed in microcircuit design. For surface-wave devices operating in the range of 1 GHz and higher, the required resolution cannot be obtained by exposing the photoresist pattern to visible, such as green, or ultra-violet light. To obtain conducting lines several thousand angstroms wide, the transducers have been fabricated by exposing the photoresist to an electron beam in scanned electron microscope [33]. Although somewhat less efficient but still quite effective is the use of an interdigital surface-wave transducer at odd integral multiples of its fundamental frequency [226], [193].

A comprehensive analytical treatment of the excitation of surface waves on quartz has been reported by Coquin and Tiersten [63]. In their method the effects of the material, the electrode configuration and the electrical termination are separated into three distinct parameters. Thus, they are able to show that the effectiveness of the alternate-phase or interdigital array, Fig. 5b, is more than an order of magnitude greater than for the single-phase array with a backing electrode, Fig. 5a. Unlike the case of interdigitated electrode structures, the optimum width of the electrodes in a single-phase array is less than one tenth of their separation which is equal to the surface acoustic wavelength at the resonant frequency of the transducer. A 100 MHz delay line on YX quartz utilizing a pair of interdigital transducers was designed and shown to have an insertion loss of 10db, -3db bandwidth of 3.5 MHz, and a spurious echo rejection of 20db [54].

In addition to the thorough analytical treatment of surface-wave excitation in quartz by Coquin and Tiersten [63], a number of papers treat the problem of transduction of surface waves by means of interdigital electrode structures [226], [120], [251]. An exact treatment of the excitation in piezoelectric crystals requires a solution which satisfies the piezoelectric relations as given in Eqs. 5 and 6. Even for materials with simple crystal symmetry such treatment can be prohibitively complex. The methods adopted by Coquin and Tiersten [63], and Joshi and White [120] are to separate the electric and elastic solutions by assuming weak piezoelectric coupling, which is well justified for the case of materials with low coupling coefficient such as quartz and cadmium sulphide. Coquin and Tiersten [63] first solve for the particle displacement by neglecting the piezoelectric coupling, and then use it to solve a forced electrostatic problem while Joshi and White [120] proceed in the reverse. The latter claim that their technique leads more readily to an equivalent circuit for the transducer and closed-form expressions for the frequency response of the transducer. Tseng [226] treats the problem by assuming an idealized electric field distribution at the surface wherein the tangential field is constant between the electrodes and zero at the electrodes and the normal field is also constant but in the opposite sense, i.e., constant at the electrodes and zero elsewhere.

Since the acoustic wave amplitudes of the various spatial harmonics of the fundamental transducer period are proportional to the corresponding Fourier components of the electric field distribution, the latter can be used to study the frequency response of the transducer [77].

The use of this method and the approximation in the shape of the electric field appears quite useful in analyzing various transducers. For example, the frequency response of a log-periodic transducer for a broad-band delay line can be obtained by taking the Fourier transform of the above mentioned approximation to the electric field distribution and is shown to agree quite well with experimental results [158].

The characteristics of an interdigital surface-wave transducer have been studied by Smith et al [206], [205], using an equivalent circuit model. They utilize a three-port electromechanical equivalent circuit for a piezoelectric crystal by Mason [152], [22], to represent one periodic section of the interdigital transducer and obtain a one-dimensional model of the entire structure. Not unlike Tseng [226], Smith develops the Mason equivalent circuit by using the "in-line" or tangential and "crossed-field" or normal electric field approximations. This circuit approach to the analysis of surface-wave transducers was shown by Smith and other researchers at the W. W. Hansen Laboratories at Stanford University to give satisfactory agreement with experimental results [205], [90].

While the analytical treatment of the surface-wave transducer requires the assumption of weak piezoelectric coupling, the most efficient and thus useful transducers are those utilizing piezoelectric materials with very high coupling such as lithium niobate ($LiNbO_3$), zinc oxide (ZnO) and barium sodium niobate ($Ba_2NaNb_5O_{15}$) [244]. A very effective and relatively simple method of determining the electromechanical coupling in such materials was developed by Campbell and Jones [40], who showed that the efficiency of coupling can be related to a change in velocity of a piezoelectric surface wave which occurs when an ideal, infinitely thin conductor is placed on the surface supporting the surface wave propagation. These two conditions of the free surface, i.e., with and without a conducting boundary can be treated quite easily and Campbell and Jones proceeded to evaluate the optimum crystal cuts and direction of propagation of surface waves in the case of lithium niobate. The conclusions of the analytical treatment by Campbell and Jones, which indicate that the optimum performance is obtained for a Y-cut crystal of $LiNbO_3$ with the surface-wave propagating in the Z-direction, have been verified experimentally by Collins, Gerard and Shaw [56] who constructed a 100 Mhz delay line with -3db bandwidth of 24 MHz and an insertion loss of 11.5db. More recent studies suggest a somewhat different cut for optimum performance [197].

Surface acoustic waves can also be generated by conversion from bulk waves. As mentioned earlier, this technique was utilized in the wedge transducer, Fig. 4 [238]. The main disadvantages of this technique are the need for a material with a velocity of propagation of the bulk wave to be less than the surface wave velocity in the substrate over which the surface elastic wave is propagated. This restriction results in a severe limitation of available materials most of which exhibit high losses due to the attenuation of the bulk waves. Also, the need for a proper mechanical coupling of the wedge to the substrate which is best accomplished through a thin film of a liquid makes this method of surface wave generation cumbersome and is prohibitively complicated in microstructures. Two methods of generation of surface elastic waves by conversion from bulk acoustic waves have been proposed which do not require the use of a separate wedge. One of these utilizes a corrugated surface capable of converting bulk longitudinal and shear waves into surface waves and vice versa [105]. The use of asymmetrical teeth in the corrugations results in a directional transducer diminishing the usual loss of 3db encountered in nearly all conventional surface-wave transducers. This method of surface-wave excitation can be applied in materials which are not piezoelectric. Another method of excitation of Rayleigh waves has been proposed which utilizes the scattering of bulk waves from metallic strips deposited on the surface of a piezoelectric crystal [25].

All of the above methods of excitation of surface elastic waves can be applied to the detection of such waves as well. The reciprocal theory in elasticity ([149] page 173), has been used to show the reciprocity for a piezoelectric transducer [63].

A method of excitation of surface elastic waves which cannot be used readily for detection, utilizes transient heating of a very thin film of aluminum [143]. The rapid heating of the surface obtained by means of a laser beam, produces temperature gradients and thermal expansion which, due to the generated stresses in the solid, produces elastic waves. This method of generation has the advantage of being applicable to nonpiezoelectric solid as well.

Still another method of excitation is by means of the magneto-strictive effect. Surface elastic waves were generated on an yttrium iron garnet plate in a static magnetic field by passing an rf current through an evaporated aluminum meander line to produce a spatially periodic rf magnetic field at the surface of the crystal [241].

A mechanically movable transducer can be obtained by fabricating an interdigital transducer on a nonpiezoelectric substrate and placing it next to a piezoelectric crystal [248]. The electric field produced by the interdigital array extends far enough into the piezoelectric material to provide sufficient piezoelectric coupling. When compared with a transducer fabricated directly on the piezoelectric substrate, the movable structure on YZ lithium niobate was found to have an additional insertion loss of 14db or less [158]. (YZ lithium niobate designates a Y-cut crystal with the elastic wave propagating in the direction of the z-axis of the crystal).

In order to generate elastic surface waves on a nonpiezoelectric structure a modification of the interdigital array called the "hybrid" transducer has been developed [233]. It consists of a small piece of single crystal piezoelectric material placed on top of the nonpiezoelectric substrate with the electrode array deposited on either one. The mechanical coupling between the two surfaces is provided by a varied selection of liquids or solids such as ethyl alcohol and phenyl benzoate, respectively.

A number of transduction techniques have been investigated which can be utilized to only detect the elastic surface wave. It consists of a narrow conductor deposited on the wave-carrying substrate with a steady magnetic field applied perpendicular to both the substrate and the conducting strip. The latter moves with the mechanical wave and causes an electromotive force in the conductor [190]. This method of surface-wave detection is applicable to any nonpiezoelectric substrate. Although the device is very simple to fabricate and can be conveniently applied in the design of multiple-tap delay lines, it major disadvantages are the need for a magnetic field and poor sensitivity which is at least two orders of magnitude smaller than a corresponding single-pair transducer on a piezoelectric substrate.

The electric fields associated with a propagating elastic wave on the surface of a piezoelectric have been used to control the electron emission from a photoemissive surface placed on a piezoelectric substrate. This method permits the visualization of the elastic surface strains as well as a detection scheme for elastic surface waves [26].

A scheme of detection of elastic surface waves which also provides for the feature of an electronically variable delay line is contained in the electron beam sensing of surface waves [80]. The method is based on the modulation of secondary emission of electrons from a piezoelectric substrate by the electric field and charge distribution arising from the strain wave. In addition, due to nonlinearities inherent in the secondary emission process, the detected signal has the form of the envelope of the propagated r-f signal.

The detection and visualization of elastic surface waves has been obtained by using the scattering of light from the surface perturbations [128], [4]. Since the surface acoustic wave is confined to a narrow region near the surface, the Raman-Nath type of scattering has been effectively utilized to observe and measure elastic surface waves [114], [130]. These techniques follow the field of extensive use of light interaction with volume elastic waves. An excellent discussion on this subject is given by R. Adler in a review article in the IEEE Spectrum of May 1967.

VI. Amplification of Elastic Surface Waves

In piezoelectric crystals the propagating elastic wave produces a longitudinal electrostatic field. If the piezoelectric solid is also conducting, the interaction of these properties can affect the velocity and attenuation of the acoustic wave. A linear theory of elastic wave propagation in piezoelectric semiconductors has been first proposed by Hutson and White [108], which considers the effects of drift, diffusion and trapping of mobile charge carriers as they interact with the longitudinal electric field produced by the acoustic wave. The attenuation of acoustic waves has also been obtained by applying an external drift field in the direction of wave propagation. For electric fields which cause the carriers to drift faster than the sound velocity, the attentuation becomes negative or the acoustic wave can be amplified [107], [249]. The material most widely used is the piezoelectric semiconductor CdS. An excellent review of acoustic wave amplification in piezoelectric semiconductors is given by McFee, one of the original contributors in the study of this phenomenon [161].

The amplification of surface elastic waves in single crystal CdS was first reported by White and Voltmer in 1966 [253], [251]. To reduce losses due to the heating of the crystal the electric field was applied in the form of pulses and the conductivity was limited to the surface layer only using doping or illumination. A method of surface-wave amplification which separates the need for semiconducting and piezoelectric characteristics of the crystal has been first proposed by Gulyaev and Pustovoit [95]. In this scheme a semiconductor thin plate is placed on a piezoelectric crystal. The electric field associated with the elastic wave through the piezoelectric effect penetrates the semiconductor and provides the mechanism of interaction of the acoustic wave with the drifting carriers in the semiconductor.

The surface-wave acoustic amplifier using separate media for the semiconductor and piezoelectric was experimentally verified with n-type germanium on a PZT ceramic [259] and with an n-type silicon on YZ lithium niobate [60]. In the latter, a net terminal gain of 7db was reported. In order to reduce the drift power in the semiconductor, a thin film of n-type silicon grown epitaxially on sapphire was shown capable of utilizing CW signals and providing net electronic gain up to a frequency of 1 GHz [132]. A discussion on the merits of a separate medium amplifier (SMA) with a short analysis are given in a paper by Lakin and Shaw [133].

VII. Guided Surface Waves

Surface acoustic waves can be guided along prescribed paths. Such waveguides are analogous to electromagnetic guides used in microwave integrated circuits. However, since the velocity of propagation of acoustic waves is so much smaller (10^5 times) than an electromagnetic wave of the same frequency, the dimensions of surface acoustic guides become comparable with present electronic microcircuits. The guiding of acoustic surface waves is most effectively attained by utilizing thin films [189], [155]. Two types of guides have been used which are known as the strip and the slot guides. The strip guide consists of a thin film of material with an acoustic surface wave velocity which is lower than that of the substrate and the film is said to load the substrate. As a result of this loading, an infinite number of surface waves is possible all of which are dispersive, with velocities which are lower than the Rayleigh velocity of the substrate. Therefore, just as the conventional Rayleigh wave is confined to the surface of a semi-infinite solid because its velocity is lower than that of the bulk waves, so does the surface wave remain confined mostly to the area of the deposited thin film. The slot guide, on the other hand, utilizes materials which stiffen the substrate; thus, a thin film of such material is deposited everywhere but where it is desired to have the surface acoustic wave confined. The velocity of the surface wave guided by a slot is consequently slightly higher than the Rayleigh velocity of the substrate. The most thorough analysis to date on elastic surface waves guided by thin films is that by Tiersten [222]. In his paper Tiersten discusses strip guides formed by gold films on fused silica and slot guides made of aluminum films on T-40 glass substrates. Tiersten's theoretical treatment includes solutions of

Love and Sezawa modes which exist in thin films structures, and also of the coupling of energy between adjacent surface waveguides. A somewhat different analytical approach as well as experimental results of strip guides consisting of gold films on fused quartz were reported by Adkins and Hughes [2].

As early as 1967, Ash and Morgan [9] proposed structures for the guiding of acoustic surface waves which consist of either deep slots in the substrate to define a confined path for the wave propagation or by forming a projection on the surface of the substrate. However, such guides appear to suffer from considerable leakage of acoustic energy into the substrate [10]. In their paper [9] Ash and Morgan suggest that a non-uniform cross-section of the protrusion or deposited film could lead to the propagation of a guided surface wave which does not leak into the substrate. In a most recent paper, not included in the bibliography, van Duzer* describes a strip guide formed by the deposition of a heavy film of graded thickness. Using geometrical optics, van Duzer also describes guiding of acoustic surface waves by a series of lenses which can be obtained by thin film deposition or by depressions formed in the surface of the substrate.

Dispersive characteristics of the acoustic surface waveguides have been measured by Knox, van den Heuvel and Owen [126] at the IIT Research Institute and found to be in good agreement with the theoretical predictions of Tiersten. However, they find that for curved guides there is an additional mode which propagates with a velocity higher than the fundamental guided mode. They

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* T. van Duzer, "Lenses and Graded Films for Focusing and Guiding Acoustic Surface Waves", Proceedings of the IEEE, vol. 58, no. 8, pp. 1230-1237, August 1970.

have concluded that this higher velocity mode was actually traveling along the inside curvature of the guiding strip and termed it the "Whispering Gallery" mode. It should be noted that when the guiding structures are curved, as it is usually intended in the design of microwave integrated circuits, the substrate material must be isotropic.

The coupling between adjacent waveguides has been utilized in the design of directional couplers [1], and of directional band-reject filters using strip guide ring resonators [126].

VIII. Acoustic Surface-Wave Filters

The effectiveness of the interdigital transducer is due primarily to the fact that, in a given frequency range, the transduction of electro-acoustic energy in each elemental transducer, consisting of one pair of electrodes, add coherently. As such, the interdigital transducer acts as a bandpass filter. As indicated earlier in the discussion on excitation and detection of acoustic surface waves, the interdigital transducer can be designed with varying periodicity in the electrode array.

The structure of the interdigital surface wave transducer was used by researchers at the Zenith Radio Corporation to design a bandpass filter to be used in a television IF amplifier. They have shown that an economically compatible filter can be fabricated by using a PZT substrate, and, by proper design of each filter and by cascading three such filters, an amplifier which fulfills most of the specifications for a color television IF bandpass can be obtained [74].

In addition to a variation in the periodicity of an interdigital transducer it is possible to control the amplitude response of an acoustic surface-wave device by varying the length of the metallic electrodes. It was indicated earlier that the amplitude vs frequency response of an interdigital transducer can be related directly to the field distribution at the transducer [79], [158]. Thus, by using appropriate variation of the electrode lengths, bandpass characteristics of a surface-wave delay line were synthesized [102]; e.g., using an interdigital transducer with electrode lengths varying as sin x/x, a nearly uniform amplitude vs frequency response was obtained [103].

In addition to variation of periodicity and length of electrodes, the interdigital surface-wave transducer can be modulated by phase coding of adjacent electrode pairs. A surface-wave filter with narrow correlation function and with uniformly small sidelobes was designed using the Barker code [254]. To facilitate the polarity inversion of adjacent electrode pairs, a modified structure of the interdigital transducer has been developed by Whitehouse [255] which utilizes an additional electrode.

If the input and output interdigital transducers of varying periodicity are fabricated on the substrate in such a way that the interelectrode spacings vary in the opposite sense, then the normally nondispersive device becomes a dispersive delay line. Dispersive delay lines can be used for pulse compression and expansion in Chirp radars. The effectiveness of a pulse compression filter, as measured by the compression ratio, depends on the time delay and the bandwidth of the device. The flexibility in the design of a dispersive surface-wave device makes its application to pulse compression filters very desirable [38], [59], [104].

IX. Love Waves

Another type of surface wave, which, analogous to the Rayleigh wave, decays exponentially with depth from the surface, is the Love wave. The Love wave mode consists of particle motion which is in the plane of the surface and perpendicular to the direction of propagation of the wave. It is generated only when the substrate is covered with a thin film of another solid material, the thickness of the film being considerably smaller than the wavelength of the Love wave. Love waves, unlike the Rayleigh wave, are always dispersive.

The excitation of Love waves is accomplished by means of an interdigital transducer. An effective technique of excitation and detection of Love waves is to fabricate the interdigital electrode structure in the interface between the substrate and the film [154]. Other techniques include the wedge type transducer and bonding of shear transverse transducers to the substrate [137], [224].

Love wave dispersive delay lines are characterized by good linearity of the group delay vs frequency and are, therefore, useful in the design of pulse compression filters with high compression ratios [137].

X. Magnetoelastic Surface Waves

Magnetoelastic surface waves are a direct extension of the bulk magnetoelastic wave phenomena [81], [163]. The magnetoelastic effect combines the properties of acoustic waves and of spin waves. The latter are created by oscillations of the angle between adjacent atomic moments in a ferromagnetic solid. The spin waves are highly dispersive and their dispersive characteristic depends on dc magnetic field. A strain of the crystal lattice can affect the magnetic moments resulting in a coupling between acoustic and spin waves. This coupling is most effective when the wavelengths and frequencies of the two waves are comparable. Devices which utilize magnetoelastic wave propagation in solids use non-uniform internal dc magnetic fields. Thus, since the acoustic waves are usually nondispersive while the spin waves are highly dispersive, the interaction of the two waves takes place over a limited region only. Hence, the magnetoelastic devices operate in effect as a combination of two distinct modes, where over most of their path of propagation they are either acoustic or spin waves only [198].

A magnetoelastic delay line is obtained by electromagnetically exciting spin waves which in turn couple to an acoustic mode. Since the wavelength of the electromagnetic field at any frequency is usually much greater than that of the spin wave its realization is not obvious. The mechanism of the spin wave excitation is quite complicated and can be indicated in qualitative terms as follows: By a proper choice of the magnetic-field bias the region near the end faces of a ferromagnetic rod is made to fall in the range of spin wave resonance; i.e., the highly dispersive characteristic of the spin wave mode as a function of the dc magnetic bias is adjusted to fall in the $k = 0$ range, where $k = \frac{2\pi}{\lambda}$ is the wave number. In other words, the dispersive characteristic is adjusted so that the k = 0 point on the frequency vs wave number plot corresponds to the frequency of the exciting electromagnetic field. A magnetostatic wave (spin wave of very long wavelength or low wave number) is thus launched and proceeds into the rod. If the internal magnetic field is made to be non-uniform, decreasing towards the center of the rod, the generated spin wave propagates into lower magnetic fields and consequently higher values of wave number. This comes about due to the fact that the highly nonlinear and saddle-shaped dispersion characteristic (frequency vs wave number) of the spin wave shifts downward with lower magnetic field bias. Eventually the wavelength is reached at which, for the given frequency of the wave, the spin wave is converted into an acoustic wave which continues to propagate as a nondispersive circularly polarized shear wave. At the other end of the rod the process is reversed and the signal is retrieved in the form of an electromagnetic wave.

The delay obtained in the spin wave region depends on its extent which can be adjusted by the gradient of the magnetic field. Hence, it is possible to design variable delay lines by utilizing the magnetoelastic-wave device. Also, although the dispersive characteristic of the spin wave is highly non-linear, it is possible, by a judicious choice of the regions of spin wave and acoustic wave propagation, to obtain a linear dispersion characteristic over a reasonably wide range of frequencies. Magnetoelastic bulk wave devices have been applied in the design of pulse compression filters.

It should be noted that the above discussion of the excitation of spin waves in structures which utilize magnetic field bias with rising skirts at the ends of the rod is not desirable because of strong defocusing effects on the spin wave [198]. It also requires special arrangements to obtain such a field configuration. On the other hand, in a ferromagnetic solid in the form of a rod in a uniform applied magnetic field, the internal magnetic field is non-uniform with falling skirts towards the ends of the rod. In such a structure the excitation of magnetoelastic waves is slightly more complicated, with the magnetostatic waves traveling in the direction of increasing field. The magnetostatic wave travels toward a turning point at which it is reflected as a high-k spin wave and travels in the direction of decreasing internal magnetic field and, as before, is coupled into an acoustic wave. The acoustic wave is then reflected from the flat ends of the rod and can, if desired, propagate to the other end of the rod. An excellent discussion on the mechanism of relection of the spin wave at the turning point is given based on an analogy to the propagation of electromagnetic waves in dielectric guides with varying dielectric properties.*

Magnetostatic surface waves have been investigated for the past several years. First predicted by Eshbach and Damon [81] and observed experimentally by Olson et al [163], they have received considerable attention in the past two years [34], [208], [219], [260]. Recently, the coupling of this wave to the Love mode surface wave was investigated theoretically indicating the feasibility of surface magnetoelastic devices [153], [164], [165], [166].

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* B. A. Auld, J. H. Collins, and D. C. Webb, "Excitation of Magnetoelastic Waves in YIG Delay Lines," Journal of Applied Physics, vol. 39, no. 3, pp. 1598-1602, 15 February 1968.

XI Bibliography

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XII. Subject Index to Bibliography

Acoustic beam scanning	12
Acousto-electronic amplification	
carrier waves	85,86,125
in CdS	107,234,253,261
thin film	151
in CdSe	101
combined medium amplifier (CMA)	133
in composite structures	85,86
fluctuations	96,97,98,160
gain	3,131,132,249
guided waves	87
in InSb	178
in magnetic field	24,125
of magnetic surface waves	183
nonlinear theory	94
reduced voltage	230
review	58,133,251
saturation	48
segmented drift-field electrodes	230
separate medium amplifier (SMA)	60,61,95,101,133
at 100 MHz	132
shear waves	261
theory	3,85,94,98,161,209,249
normal mode	28
two sets of carriers	170

Acoustic noise	
in CdC	16
in CdSe	17
Amplification	
parametric	49
Attenuation	169,237,251
in CdS	111
film on quartz	110
in hard materials	239
in InSb film on quartz	29
in $LiNbO_3$	44,92,99,193,196
in $LiTaO_3$	201
in quartz	8,44,67,111,181
by CdS film	252
temperature dependence	8,67,69
in plexiglass	169
by thermal phonons	150,160
Bibliography	199
Bonding	18
Brillouin scattering	171
Coupled elastic surface waves	
across air gap	30
with electric field	121
across fluid interface	50
Damping by air	32
Delay lines	
dispersive	137,191,217

$LiNbO_3$	56
loss compensation	133
mechanically variable	158,177,248
for pulse compression	220
review	175
tapped	64,167,190
at 2.5 GHz	138,139
wideband	137
Directional coupler	1
Dispersive surface waves	157
"additional" waves	121
by conductive grating	119
in gold	
on $LiNbO_3$	206
on quartz	39,157
Love waves	224
in piezoelectric with semiconducting film	110,186
in quartz on silicon	157
with sidelobe compensation	102
in Si and CdS on sapphire	157
Elastic constants	
in $Ba_2NaNb_5O_{15}$	244
in $LiNbO_3$ and $LiTaO_3$	245
in quartz	19,46
standards for	211
synthetic sapphire	23

Electromechanical coupling	21
in CdS film	15
Excitation and detection of elastic waves	44,251
amplitude	113,130
by electron beam	80
by Gunn oscillator	144
by magnetostriction	241
on nonpiezoelectric substrates	238
hybrid transducer	233
optimal crystal cuts	40
by scattering of bulk waves	5,25,105
by surface electrodes	63,120
by transient heating	143
Filters	38,65,76,103,210
I-F television	74
matched	52,54
using tapped delay lines	64
pulse expansion and compression	104,220
review	59
sidelobe suppression	52,102
UHF	218
Generalized Rayleigh waves	89,216,231
propagation	231
Guided surface waves	9,10,126,155,189,222,243,250
directional coupler	1
gold on fused quartz	2
network analysis	162

review	232
theory	243
Interdigital transducer	252
alignment	195
analysis	120,204
capacitance	47,83,120
coded	120
composite	118
coupling	156,221
design	205
differential electrodes	255
diffraction	51
dispersive	119,192,217,218
efficiency	120
equivalent circuit	44,66,120,129,204,221
fabrication	
by electron beam	33,138,139,202
photo-resist	203
sputter etching	202
field distribution	47,83
frequency response	226
at 100 MHz	54
hybrid	233
insertion loss	44,195,205
on $LiNbO_3$	6,56,72,197,205
log-periodic	158,205
low microwave region	6

on PZT	74
radiation resistance	11,54,56,109,120,156,204,205
review	53,57,65,251
scattering from	90
spatial harmonics	77
undirectional	55,57
Lamb waves	71
Love waves	137,154,224
magnetoelastic	153
Nonlinear effects	
in α-quartz	140,148
interaction with electric field	215
in $LiNbO_3$	141,142,194
Optical interaction	4,10,13,97,106,114,123,128, 130,142,171,173,174,182,195, 207,247,256,257
electron emission	26
photoconductivity	122
Propagation of elastic surface waves	44,251
additional in piezoelectrics	121
analysis	41,43,109,112,113,127,134, 159,172,223
computer	93
in anisotropic media	36,84,91,145,216
on boundary of liquid	42,70,117,136
in $Bi_{12}GeO_{20}$	43
in CdS	43,111,225
thin film (Sezawa mode)	151,184
(Love mode)	184

on Ge	185
on copper	176
in cubic crystals	43,89,91,213,228
on curved surfaces	135,179
on cylinders	37
degenerate modes	43
displacement	145,256
energy	84,111,145
in GaAs	43
of generalized Rayleigh waves	231
in gold on $LiNbO_3$	206,242
in hexagonal crystals	43,229
in layered media	71,82,110,147,184,186,242
in $LiNbO_3$	79,99
magnetoelastic waves	164,165,166,198
magnetostatic waves	34,75,81,163,208,260
dynamic mode	219
in orthorombic crystals	227
in PZT	74,[illegible],99,225
in quartz	8,69,73,78,79,111,235
reflection electrically controlled	14
on rough surface	180
in silicon	168
strain	190
intransversely isotropic media	35
in ZnO	43,225
Pseudo-surface waves	78,84,111,145,146

degenerate SH mode 27

Review 53,57,58,59,232,258

Transducers

bulk-surface wave 105

comb 7,236

composite 118

conversion loss 246

equivalent circuit 22,152

hybrid 233

interdigital see Interdigital transducer

liquid wedge 5

magnetostrictive 241

piezoelectric materials for 20,115

wedge 236,256

Velocity

group 10,111

phase 10,13,31,40,44,54,68,71,99,109,130,145,147,168,190,206,239,240,251,252

in CdS 111,225,229

on Ge 185

effect of metallic coating 225

influence of curvature 135

in $LiNbO_3$ 40,207

in PZT 225

in quartz 39,54,78,111,235

in silicon 168

in ZnO 225,229

on AP_2O_3 68

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An introduction to the field of surface microacoustics, includes a review of the present state-of-the-art and an annotated bibliography.

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Microacoustics						
Surface-wave devices						
Microsound						
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