Japanese CS program," AIAA Commun. Satellite Systems Conf., Paper 78-616, San Diego, CA, Apr. 1978.

[9] N. Fugono and R. Hayashi, "Propagation experiment in 1.7, 11.5 and 34.5 GHz with ETS-II," presented at AIAA Commun. Satellite Systems Conf., Paper 78-623, San Diego, CA, Apr. 1978. Also to be published, with data, in French *Annales des Telecommunications*.

[10] T. Ishida, N. Fugono, J. Tabata and M. Ohara, "Program of ECS of Japan AIAA," Commun. Satellite Systems Conf., Paper 78-614, San Diego, CA, Apr. 1978.

[11] P. T. Ho, M. D. Rubin, and J. G. Wherry, "Solid state amplifiers in communication satellites," AIAA Commun. Satellite Systems Conf., Paper 78-557, San Diego, CA, Apr. 1978.

[12] P. T. Ho, "A 7-watt C-band FET amplifier using serial power combining techniques," in *IEEE 1978 MTT-S Microwave Symp. Dig.*, pp. 142-144, 1978.

[13] E. W. Matthews, "Variable power dividers in satellite systems," in *IEEE 1976-MTT-S Microwave Symp. Dig.*, pp. 338-40, 1976.

[14] J. F. White, "Diode phase shifters for array antennas," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-22, pp. 658-74, June 1974.

[15] L. R. Whicker and D. M. Bolle, "Literature survey of microwave ferrite control components," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-23, pp. 908-918, Nov. 1975.

Shallow Bulk Acoustic Wave Progress and Prospects

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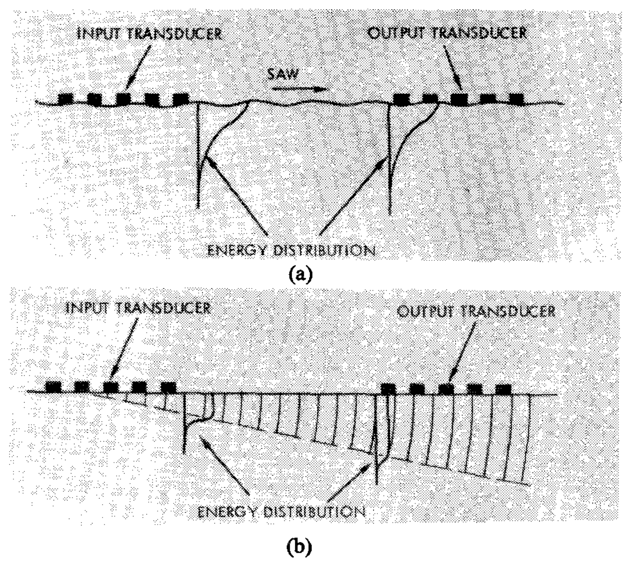
***Abstract*—Shallow bulk acoustic wave propagation in piezoelectric crystals is reviewed from the standpoint of work reported to date. It is compared to bulk and surface acoustic waves as to properties and device potential. Singly and doubly rotated cuts are considered, as are piezoelectric transduction, energy trapping, equivalent networks, as well as areas of future work such as new materials other than quartz, and nonlinear effects.**

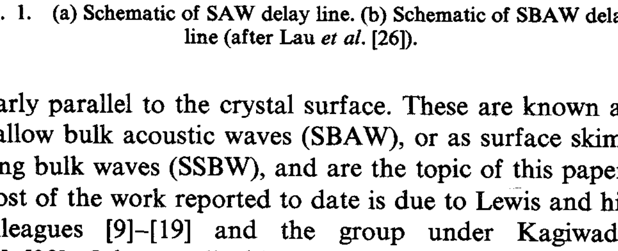
I. Introduction

THE PAST 15 years have brought about a revolution in frequency control and acoustic signal-processing capabilities. This has been due in large measure to the development of surface acoustic wave (SAW) devices [1]–[7]. These have supplemented, and in some cases taken over various functions formerly performed by bulk acoustic wave (BAW) devices [8], particularly in the area of filtering. At the same time, SAW technology expanded to create entirely new signal-processing capabilities based on the availability of the wave as a spatially distributed function at the crystal surface. Bulk-wave components, meanwhile, had also found new uses. Foremost among these are new cuts that exhibit compensation of nonlinear elastic effects, leading to resonators that are ultrastable even under severe environmental conditions. Both BAW and SAW devices profit from the favorable electromagnetic/acoustic velocity ratio which assures significant miniaturization and decreased weight with respect to the corresponding electromagnetic devices.

More recently, attention has been given to a new type of acoustic-wave device, utilizing bulk waves that travel nearly parallel to the crystal surface. These are known as shallow bulk acoustic waves (SBAW), or as surface skimming bulk waves (SSBW), and are the topic of this paper. Most of the work reported to date is due to Lewis and his colleagues [9]–[19] and the group under Kagiwada [19]–[29]. Other applicable analyses are due to Mitchell [30], Wagers [31], Jhunjhunwala *et al.* [32], and Lee [33].



(a)



(b)

Fig. 1. (a) Schematic of SAW delay line. (b) Schematic of SBAW delay line (after Lau *et al.* [26]).

Of particular importance to the operation of SBAW components is the interdigital transducer (IDT), consisting of interleaved electrode strips, between which the generating electric field is applied via a signal source, or the received field is detected. The IDT array was first applied to the production of BAW signals [34], [35], then

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to SAW devices [36], and finally to SBAW devices [9]. Fig. 1 shows, in cross section, the launching and reception of (a) SAW and, (b) SBAW. Typical energy distributions are also shown; the SAW energy is confined largely within one wavelength of the surface, with evanescent behavior in the direction of the depth. The SBAW, on the other hand, is launched from the IDT array as a shallow beam of energy with real propagation wavenumbers both parallel to the surface and in the depth direction. Without further development, the SBAW device shown would be of little use if the input and output were separated by many wavelengths, (>100), because of the large energy losses encountered; fortunately these may be obviated to a large extent as described in a later section.

II. Singly Rotated Cuts

Crystal cuts are specified [37] by their orientations with respect to the crystallographic axes. A singly rotated cut is one that undergoes one rotation about an axis; a typical example is the rotated Y cut shown in Fig. 2(a), and denoted as $(YXl)\theta$. The most popular such cut is the BAW AT cut, seen in Fig. 3 oriented within a cultured quartz bar. Its success is primarily due to the superior frequency–temperature (f–T) characteristic, which is shown in Fig. 4. Also shown in this figure is the curve for the SAW ST cut which is close in orientation to the AT. For the AT cut, $\theta = +35.25°$, while for the ST cut, $\theta = +42.75°$. Another BAW cut, having a zero temperature coefficient (TC) of frequency exists. This is the BT cut, at $\theta = -49.20°$.

When an ST cut, which normally supports SAW's propagating along X_1, has its IDT array turned by 90°, it produces SBAW's propagating along X_3' (or Z'). The ST cut is nearly perpendicular to the BT cut, so the resulting SBAW has a f–T characteristic very similar to that of the BT cut, because the BT has its BAW propagating in the thickness (X_2') direction. As seen in Fig. 4, these f–T curves are parabolic, and not quite as good as the AT curve.

A big advantage of X_3' propagating SBAW's on ST-cut quartz is that the frequency, for a given IDT, is about 1.6 times the corresponding X_1 propagating SAW frequency. This ratio depends upon the angle θ, however, and decreases to nearly unity for the BT cut. The ratio can never be less than one because the limiting SAW velocity can never exceed the velocity of the slower shear wave propagating in the X_1 direction for rotated Y cuts. This velocity is $\sqrt{c_0/\rho}$, where

$$2\cdot c_0 = \left[(c_{44}+c_{66}) - \sqrt{(c_{44}-c_{66})^2 + 4c_{14}^2} \right].$$

For SBAW's on BT-cut quartz, a compensating feature is the appearance of a cubic f–T characteristic, similar to that of the AT cut.

Another advantage of X_3' propagating SBAW's over X_1 propagating SAW's on singly rotated quartz is the absence of SAW generation. When the IDT is arranged for SAW propagation along X_1, BAW's are necessarily produced, as will be seen in a section below; but when propagation of SBAW's take place along X_3', SAW's are not generated. This produces a very clean mode spectrum for SBAW devices. For arbitrary angles of propagation between X_1 and X_3', both SAW and SBAW will in general be produced.

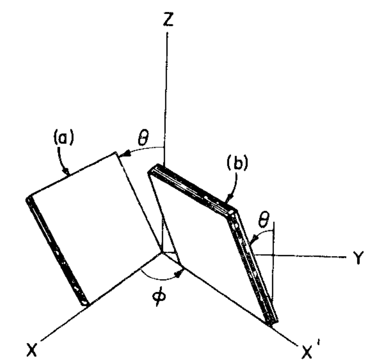

Fig. 2. (a) Singly rotated cut. (b) Doubly rotated cut.

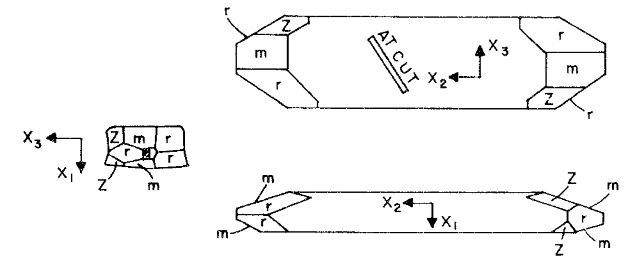

Fig. 3. Cultured bar of right-handed quartz, showing position of AT-cut.

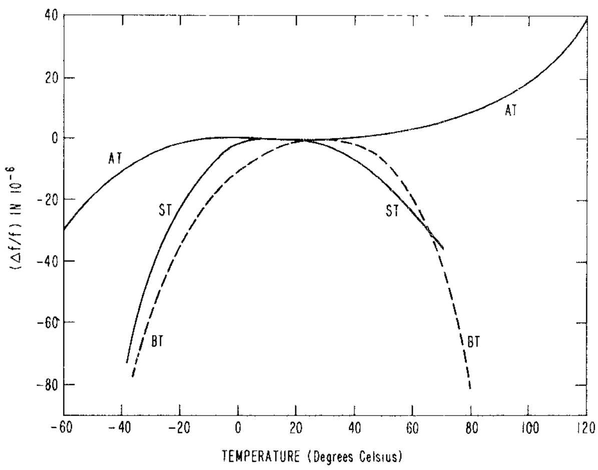

Fig. 4. f–T characteristics of AT-, BT-, and ST-cut quartz.

Lewis [12], [18] also investigated SBAW's on rotated Y cuts of lithium tantalate ($LiTaO_3$), but found that, although there was no coupling to SAW's in crystals of class $3m$, all cuts of this family had bad TC's. Because of the very large piezoelectric coupling in lithium tantalate, it is useful in wide-band filter applications despite its temperature behavior. Examples of this were shown by Yen *et al.* [24] for lithium tantalate and lithium niobate.

Based upon current work on singly rotated cuts supporting SBAW's, particularly on quartz, the key features summarized in Table I are now apparent. In Table II

TABLE I
KEY FEATURES OF SBAW

INTERDIGITAL TRANSDUCTION
HIGH FREQUENCY OPERATION
RESPONSE SHAPING BY APODIZATION
LARGE DESIGN FLEXIBILITY; SPATIAL FOURIER TRANSFORMS
PLANAR STRUCTURE
SEMICONDUCTOR FABRICATION TECHNIQUES
MICROELECTRONIC COMPONENTS/IC-COMPATABLE
MECHANICALLY RUGGED
PERFORMANCE POTENTIAL
PARABOLIC OR CUBIC TEMPERATURE BEHAVIOR
CLEAN MODE SPECTRUM
SURFACE CONTAMINATION/DEFECTS INSENSITIVITY
WAVE AVAILABLE FOR SIGNAL PROCESSING

TABLE II
DEMONSTRATED SBAW CAPABILITIES

CENTER FREQUENCY	60 MHz TO 2.3 GHz
FRACTIONAL BANDWIDTH	0.3% TO 2% (QUARTZ), 15% ($LiTaO_3$)
INSERTION LOSS	13 dB
SIDELOBE SUPPRESSION	>55 dB
SHAPE FACTOR 3 dB/40 dB	1.4
TEMPERATURE COEFFICIENT OF DELAY	ZERO FOR FIRST ORDER COEFFICIENT

SBAW capabilities that have been demonstrated in the laboratory to date are given. It appears that devices based upon the SBAW principle may very well find significant applications as follows: 1) delay lines; 2) resonators; 3) bandpass filters; 4) oscillators; and 5) synthesizers.

III. Doubly Rotated Cuts

A doubly rotated cut is shown in Fig. 2(b). It is denoted $(YXwl)\phi/\theta$. The angle ϕ gives an extra degree-of-freedom and provides additional advantages; in addition to temperature behavior, it allows other parameters to be optimized. Such cuts were investigated for BAW on quartz by Bokovoy and Baldwin [38]–[40], Bechmann *et al.* [41], and Ballato [42]. SAW propagation on doubly rotated substrates was reported by Hauden *et al.* [43]; SBAW propagation was briefly noted by Ballato and Lukaszek [44].

The BAW doubly rotated cut receiving the greatest attention at present is the *SC* cut [42]. It is shown in Fig. 5 outlined on a bar of cultured quartz grown such that the ϕ angle ($\approx 22°$) has already been incorporated. In manufacture, only the θ angle (approximately that of the *AT* cut) need be critically adjusted.

Fig. 6 depicts a doubly rotated BAW plate with bulk-wave propagation shown taking place in the thickness direction. A SBAW plate is shown adjacent. The propagation direction for the SBAW is shown between the IDT's to be along X_2'', i.e., parallel to the BAW propagation direction. This leads to a simple recipe whereby already-

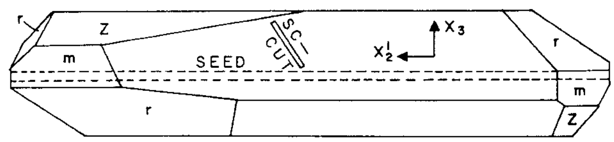

Fig. 5. Cultured bar of right-handed quartz, showing position of doubly rotated *SC* cut.

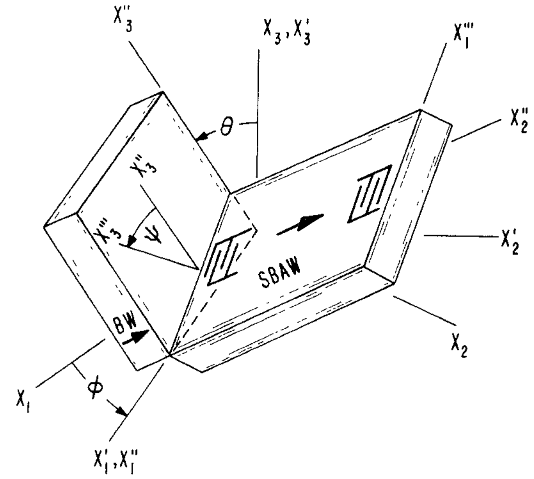

Fig. 6. Doubly rotated BAW and triply rotated SBAW plates.

known results for doubly rotated BAW plates can be used to determine the approximate behavior of the "corresponding" SBAW plate. From the figure it is seen that the plate that corresponds to the $(YXwl)\phi/\theta$ BAW plate is a plate of orientation $(YXwlw)\phi/(\theta \pm 90°)/\psi$. Notice that ϕ is the same for both plates. Also notice that θ need only be replaced by $\theta \pm 90°$ (keeping the result in the range $|\theta| \leqslant 90°$).

It will be further seen that the rotational symbol of the SBAW plate describes a triply rotated cut. The third angle, given as ψ in Fig. 6 permits the specification of a whole family of SBAW plates for each corresponding BAW plate, allowing one to optimize some parameter of operation such as temperature coefficient, coupling factor, or beam steering angle. Because the SBAW mode most adapted to satisfying the traction-free boundary conditions on the crystal surface is the horizontally polarized shear mode, ψ can be chosen so that the $X_1'''-X_2''$ surface is along the direction given by the particle motion for one of the shear waves propagating along X_2'' in an unbounded medium. This enhances the ease with which the mode can propagate, and the cleanliness of the resulting mode spectrum.

The triply rotated cut angles $\phi/\theta/\psi$ can be reduced readily to an equivalent doubly rotated set by the formulas of spherical trigonometry; doubly rotated plates are the most general type of cut.

The doubly rotated BAW cuts in quartz have been mapped for $f-T$ behavior in the entire ϕ/θ plane [41]. An altitude chart of the first-order temperature coefficient of frequency for the slower shear mode (the so-called *c*

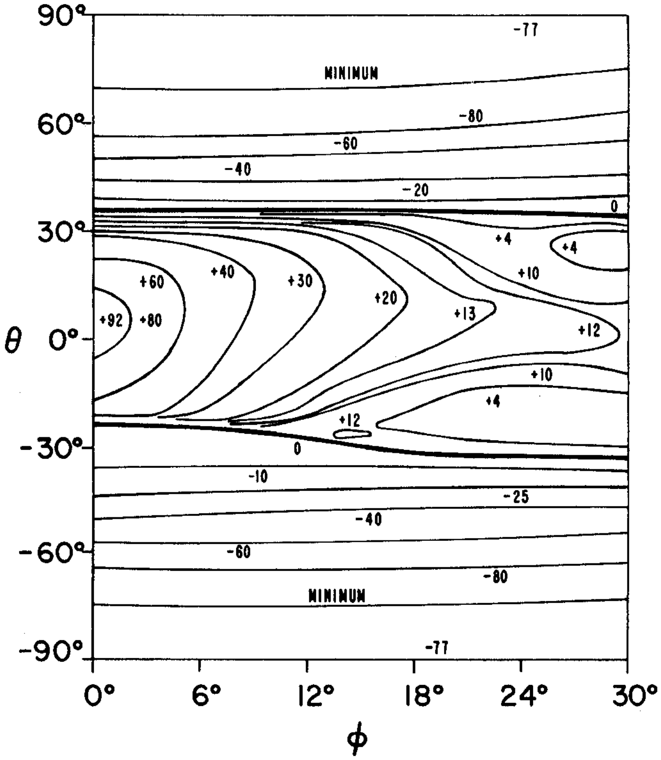

Fig. 7. Altitude chart of first-order temperature coefficient of frequency for slow shear BAW mode in quartz.

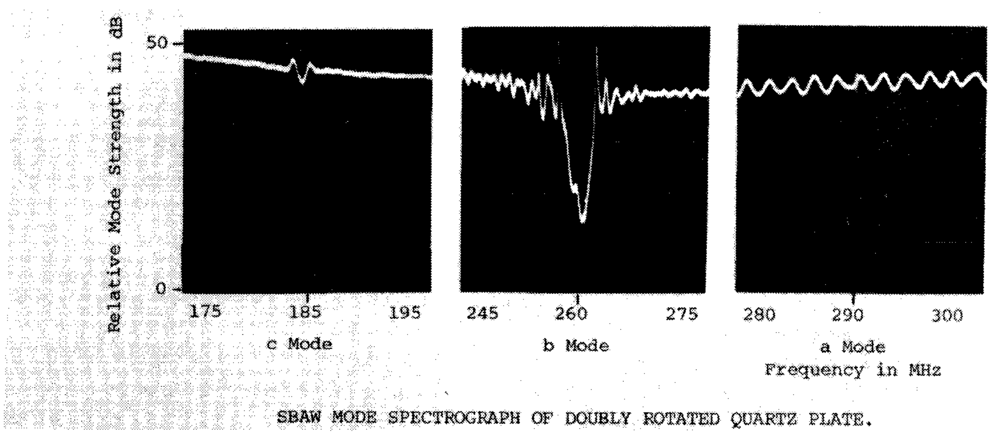

Fig. 8. Mode spectrograph of the three SBAW modes in doubly rotated quartz.

mode) is given in Fig. 7; the units are 10^{-6}/K. This quantity corresponds to the slope of the f–T curves in Fig. 4 at room temperature. By changing the ordinate scale from θ to $(\theta \pm 90°)$ one has the TC altitude chart, in first approximation, for doubly rotated SBAW plates for the slow-shear mode.

In general, all three of the wave types that exist for plane-wave propagation in an unbounded medium exist and propagate in an SBAW plate, although their properties are modified by the finite boundaries. The quasi-longitudinal (*a* mode), and the two quasi-shear waves (*b* and *c* modes) are shown by their spectrographic responses for a doubly rotated plate $(YXwl)\phi = 10°/\theta = +34°$ in Fig. 8. Propagation is in the X_3'' direction. The IDT used is comprised of split fingers and equal spaces with $\lambda/8 = 2.36\ \mu m$. Input and output transducers are 140λ long, have apertures of 54λ; the transducers are spaced 26λ apart. Here the faster shear wave (*b* mode) is more strongly driven because of its higher piezoelectric coupling, and also because its motion more nearly coincides with the direction of the surface of the plate than the slower (*c*) mode. By calculating the properties of a BAW plate having $\phi = 10°$ and $\theta = -54°$ one may get an approximate idea of the parameters of SBAW propagation in the $\theta = +34°$ plate. Some of these are shown in Table III. The top row gives the frequency constant N (one-half the acoustic-wave velocity); the second row gives the first-order TC of frequency; the piezoelectric coupling for BAW propagation is shown in row three, and the calculated frequency response of a particular IDT for SBAW is given in the last row. The frequencies and relative mode strengths are to be compared with those in Fig. 8, where it is seen that the agreement is quite good.

Certain orientations in quartz should be avoided. These include BAW plates (and their corresponding SBAW cuts) of orientations near $\phi = 0°$, $\theta \approx -24°$ and $\phi \approx 10.4°$, $\theta \approx$

TABLE III
SHALLOW BULK ACOUSTIC MODE PROPERTIES

(YXwℓ) Ø = 10° / θ = +34°, Z-PROPAGATION SBAW

	MODE C	MODE B	MODE A
N (M/S)	1873	2521	3177
T_f (10^{-6}/K)	-56.0	-20.2	-94.6
(K) %	0.78	3.77*	1.04
f(MHz)	135.3	249.4	314.3

$-26.6°$. Both of these directions are directions of degeneracy, where the two shear velocities coincide; near these points the energy flux deviations are large.

IV. TRANSDUCTION

Transduction of acoustic waves via the piezoelectric effect may be determined if the forces produced are known. The force densities are given by the stress gradients, which, in turn, are brought about by the electric fields produced by the IDT array [45]. The piezoelectric portion of the mechanical stress relation is

$$T_{ij} = -e_{kij} E_k.$$

The mechanical force densities F_j are then

$$F_j = -e_{kij} E_{k,i}.$$

IDT fingers produce electric fields E_k that are very sharply peaked at the electrode edges. An example is given in Fig. 9, where is shown the static field parallel to, and at, the crystal surface, normalized to the field that would exist between parallel plate capacitors of equal gap; the field possesses branch-point singularities at each edge. The other field components behave in a similar manner. Because of the spikes in E_k, the force densities can be represented, to an excellent approximation, as delta functions, and the excitation of acoustic waves evaluated in a straightforward manner [46].

Taking as an example a rotated Y cut of quartz of orientation $(YXl)\theta$, with an IDT array along X_1, the electric field gradients peak sharply at the electrode finger edges, and are $E_{1,1}$ (largest) and $E_{2,2}$ plus both $E_{2,1}$ and $E_{1,2}$. The rotated piezoelectric constants that are nonzero are e'_{111} $(=e_{111})$, e'_{122}, e'_{133}, e'_{123}, e'_{213}, e'_{212}, e'_{313}, and e'_{312}. Therefore, $E_{1,1}$ produces X_1 directed forces, but no forces along X_2 or X_3. $E_{2,2}$ likewise generates X_1 forces. The weaker gradients $E_{2,1}$ and $E_{1,2}$ both produce X_3 and X_2 forces. The X_1 and X_2 forces lead to SAW's.

If the IDT array is rotated so that the finger edges are parallel to the X_1 axis and propagation takes place along X_3, then E_1 vanishes, along with the gradients $E_{2,1}$ and $E_{3,1}$. The gradients $E_{2,2}$, $E_{2,3}$, $E_{3,2}$, and $E_{3,3}$ all produce forces directed along X_1 but no other component of force.

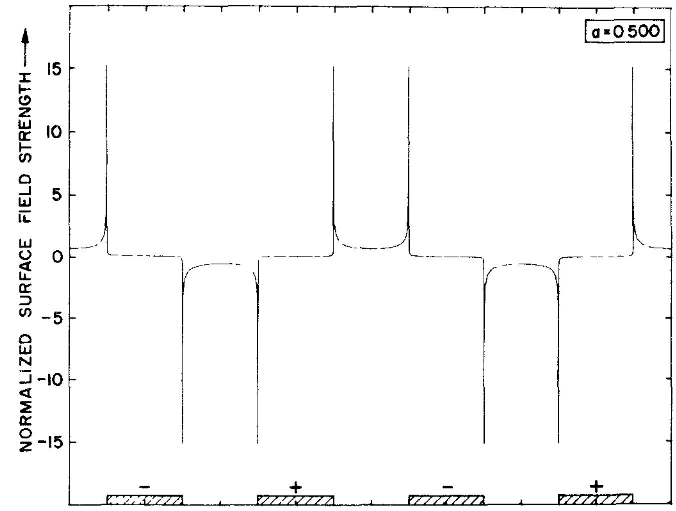

Fig. 9. Static electric-field distribution for interdigital electrodes.

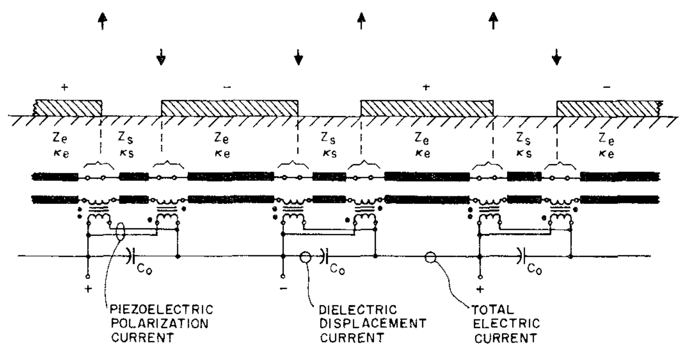

Fig. 10. Equivalent electric network for SBAW using acoustic transmission lines and piezoelectric transformers located at electrode edges.

SAW propagation cannot take place but an *SH* type of BAW propagates, and this is the SBAW that has been investigated to date.

A similar calculation shows that for rotated X cuts of crystals in class 32 (quartz, aluminum phosphate), SBAW propagation along any direction parallel to the free surface produces SAW generation as well. Again, for rotated X cuts of class $3m$, both SBAW and SAW are generated for any propagation direction parallel to the plate surface.

It appears, then, that a rather elementary consideration based on the piezoelectric relations and the delta functions produced by the IDT array yields valuable insight into the production of acoustic waves in piezocrystals. This approach can readily be placed on a quantitative basis. Another result of the delta-function model of transduction is the realization of SAW and SBAW equivalent circuits in the analog form shown in Fig. 10. The piezotransformers are placed at the locations of the electrode edges. Unattached electrodes are simply left unconnected to the supply voltage.

V. TRAPPING/DUCTING

Energy trapping was applied to BAW plates by Mortley [47]–[50], Shockley *et al.* [51], [52], and Mindlin [53].

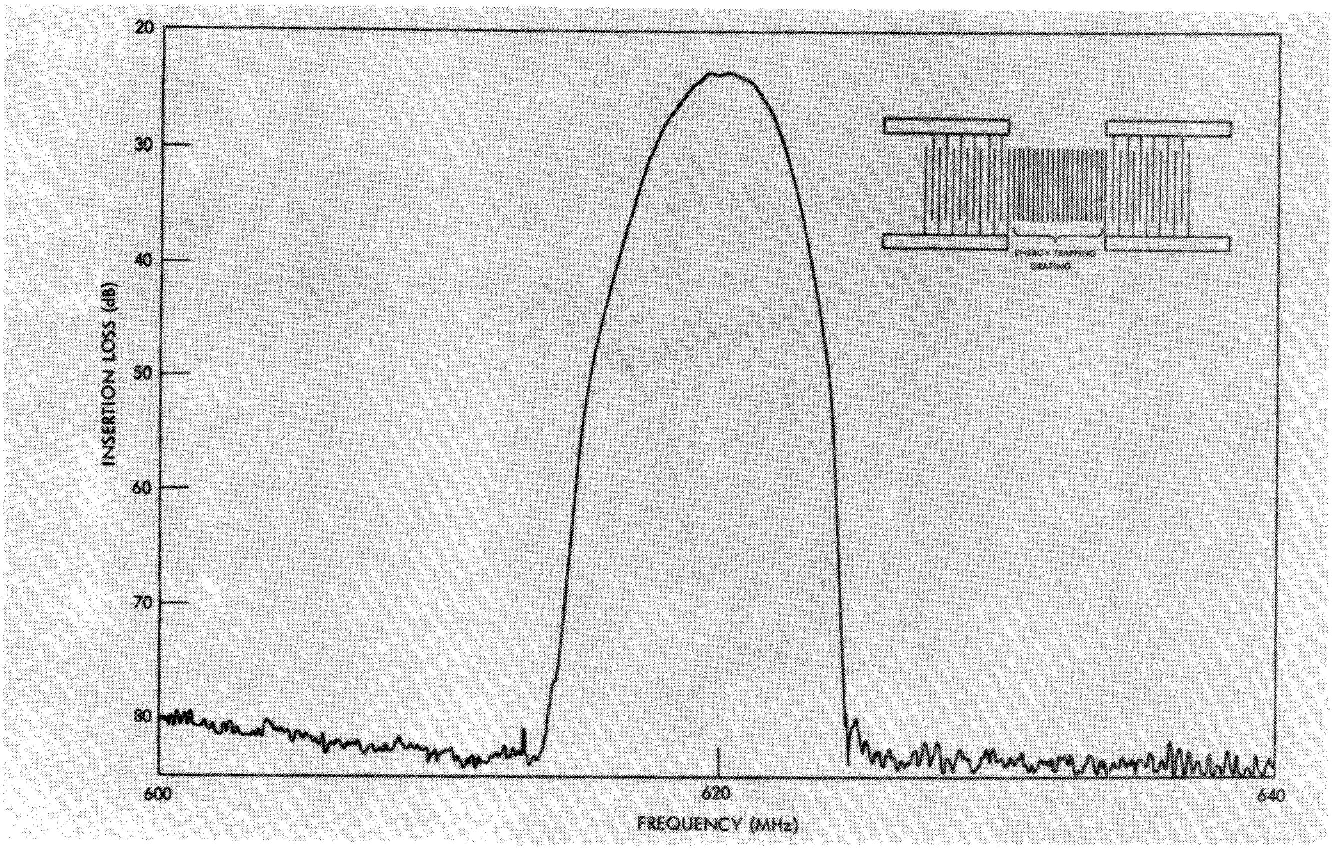

Fig. 11. Frequency response of SBAW filter with metallic grating (after Lau *et al.* [27]).

Trapping or ducting of SAW's has been treated by Oliner [54], Ash *et al.* [55], and Tiersten *et al.* [56]–[58]. It was suggested for SBAW by Lewis [14], and experimentally proven by Yen *et al.* [24], [27]. The analogy between *SH* SAW's and electromagnetic wave propagation along corrugations as ducting structures was explored by Auld *et al.* [68] and Gulyaev and Plessy [69].

The periodic perturbations resulting from the unconnected metallic electrodes placed in the SBAW path produce the ducting effect by a combination of mass loading and piezoelectric effects. The SBAW wave becomes analogous to a Love wave—a horizontally polarized shear wave that requires a discontinuity or material gradient in the depth direction for propagation.

For untrapped SBAW propagation, the transmission lines in Fig. 10 are nonuniform in their characteristic impedance and propagation wavenumber; the use of a ducting structure renders the lines uniform.

In Fig. 11 is shown an energy-trapped SBAW narrowband filter on *ST*-cut quartz [27]. It is seen how extremely clean the mode spectrum is, resulting from the absence of SAW's; this is further borne out by the broad frequency sweep of the same filter [25].

VI. Radiation Field

SBAW radiation patterns have been very successfully calculated on the basis of simple antenna theory by Lewis [14], [59], and on the basis of more extensive calculations by Jhunjhunwala *et al.* [32] and Lee [33]. Results of an exact calculation for the rotated *Y* cuts of quartz excited

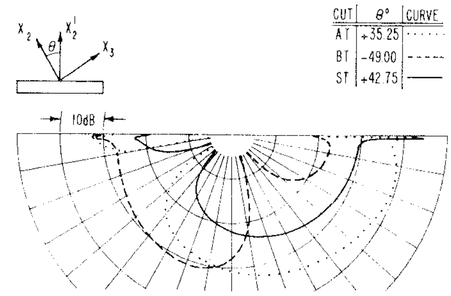

Fig. 12. Far-field radiation pattern for a line source at resonance, for rotated *Y* cuts of quartz (after Lau, *et al.* [28]).

by a single infinite line source are given by Lau *et al.*, and are shown in Fig. 12 for the *AT*, *BT*, and *ST* cuts [28]. The plots are of relative electrical potential in the far field. It is seen how dramatically the pattern varies with θ even between the adjacent *AT* and *ST* cuts. Further work will possibly make use of *Z* transforms [60]–[62], modified to account for the anisotropy of the medium, to predict accurately the radiation from IDT's.

VII. New Materials

Two areas of future device potential appear to be 1) materials with higher piezoelectric coupling than quartz, and 2) semiconducting piezoelectrics. In the first category, the strongly piezoelectric substances lithium tantalate and niobate have received some attention. Aluminum phosphate (berlinite) appears another attractive material; it has the same crystal class as quartz but is more strongly piezoelectric, as well as possessing a zero TC locus. Frequency constant *N*, coupling factor $|k|$, and first-order

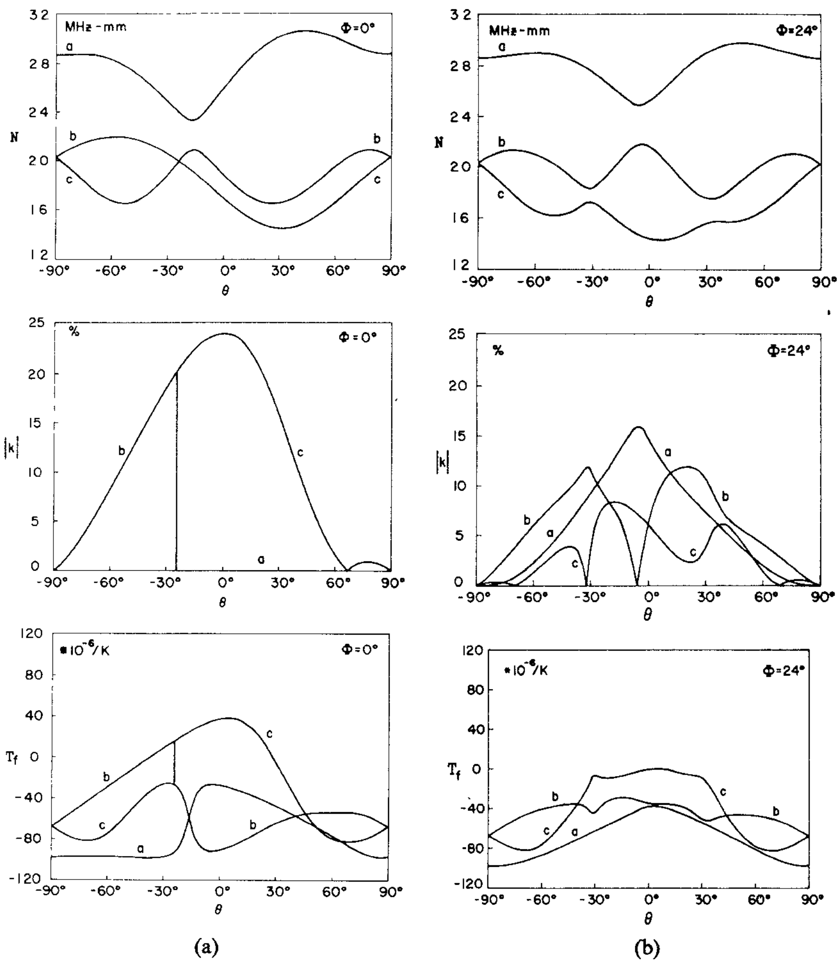

Fig. 13. (a) Frequency constant N, piezoelectric coupling $|k|$, and temperature coefficient of frequency T_f for BAW and SBAW rotated Y cuts of berlinite. (b) Frequency constant N, piezoelectric coupling $|k|$, and temperature coefficient of frequency T_f for BAW and SBAW on doubly rotated cuts of berlinite with $\phi = 24°$.

TC of frequency T_f for the three modes of an infinite BAW plate are shown in Fig. 13(a). To convert to SBAW orientations, the abscissa scale must be changed as discussed in prior sections. Fig. 13(b) shows the doubly rotated cuts having $\phi = 24°$ as an example.

As pointed out by Lewis [17], certain complications appear for SBAW propagation in high coupling materials. In addition, the electric-field pattern at the electrode edges becomes strongly modified and has to be taken into account in the model used [46].

Propagation of acoustic waves in semiconductors appears to be an attractive way to further the process of miniaturization of microelectronic signal-processing devices. Gallium arsenide is an excellent candidate material because not only is it piezoelectric, but it possesses a large bandgap, allowing high semiconductor temperature operation, as well as large mobility values, leading to high-frequency performance comparable to SAW capabilities. Using the passage of SAW's or SBAW's to modulate the active regions of semiconductor devices might be expected to lead to attractive new IC-compatible devices.

VIII. Nonlinear Effects

Nonlinear effects appear naturally in certain acoustic signal-processing devices such as convolvers [63], [64]. These operate by virtue of a nonlinear effect in the semiconductor proximate to the piezoelectric substrate that supports the acoustic wave; the wave induces an electric field in the semiconductor to produce the nonlinearity.

Dielectric materials such as quartz exhibit nonlinearities as well, primarily in the elastic stiffnesses. In this situation they are usually undesirable. Fortunately, doubly rotated quartz cuts supporting BAW's have been found that are quite insensitive to the effects of mechanical stress effects of various sorts [42], [65]. This has led to the development of resonators that have very good resistance to mechanical shocks and electrode film stress changes. Closely related to this problem is that of frequency changes in BAW resonators due to abrupt temperature changes. Once again, doubly rotated quartz cuts have been found where this nonlinear elastic effect is minimized [66].

These BAW successes naturally lead one to hope that analogous SAW and SBAW cuts exist; if they do, it is logical to look for the SBAW cuts according to the prescription given above, viz., keeping ϕ fixed, and changing θ to $\theta \pm 90°$. The additional angle ψ, shown in Fig. 6, can be adjusted for best TC or transduction efficiency.

Lewis [59] has observed nonlinear interactions between SAW and SBAW in a variety of substrates.

IX. Material Attenuation

The room temperature attenuation of acoustic waves in a crystal is a function of the viscosity coefficients of the material, and has been calculated for BAW's in quartz [42]. This intrinsic loss becomes important in the gigahertz range in quartz. A more severe restriction on the attenuation of gigahertz devices may be due to scattering losses due to etch channels [67]. These arise from chemically polishing the substrate when the source material contains impurities and dislocations; they may be largely removed by using electrically swept material.

Acknowledgment

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References

[1] Special Issue on Microwave Acoustics, *IEEE Trans. Microwave Theory Tech.*, vol. MTT-17, Nov. 1969.
[2] K. Dransfeld and E. Salzmann, "Excitation, detection, and attenuation of high-frequency elastic surface waves," in *Physical Acoustics, Principles and Methods*. vol. 7, W. P. Mason and R. N. Thurston, Eds. New York: Academic, 1970, ch. 4, pp. 219–272.
[3] R. M. White, "Surface elastic waves," *Proc. IEEE*, vol. 58, pp. 1238–1276, Aug. 1970.
[4] H. Sabine and P. H. Cole, "Acoustic surface wave devices: a survey," *Proc. IREE* (Australia), vol. 32, pp. 445–458, Dec. 1971.
[5] R. F. Wallis, "Surface-wave phenomena," in *Proc. Int. School of Phys.* "E. Fermi," Course LII, Atomic Structure and Properties of Solids, New York: Academic, 1972, pp. 370–394.
[6] Proc. MRI Int. Symp. XXIII, Opt. and Acoustical Micro-Electron., (Polytechnic Inst. of New York), Apr. 1974.
[7] M. G. Holland and L. T. Claiborne, "Practical surface acoustic wave devices," *Proc. IEEE*, vol. 62, pp. 582–611, May 1974.
[8] E. Hafner, "Crystal resonators," *IEEE Trans. Sonics Ultrason.*, vol. SU-21, pp. 220–237, Oct. 1974.
[9] M. F. Lewis, "Acoustic wave devices," U.K. Patent 1 451 326, Sept. 1976.
[10] T. I. Browning and M. F. Lewis, "New family of bulk-acoustic-wave devices employing interdigital transducers," *Electron. Lett.*, vol. 13, pp. 128–130, Mar. 1977.
[11] ——, "Bulk waves skim the surface," *Electronics and Power*, vol. 23, p. 109, Feb. 1977.
[12] ——, "A new class of quartz crystal oscillator controlled by surface-skimming bulk waves," in *Proc. 31st Annual Frequency Control Symp.*, U.S. Army Electron. Command, Ft. Monmouth, NJ, pp. 258–265, June 1977.
[13] E. G. S. Paige, "Surface acoustic wave devices—a transatlantic view," in *Proc. IEEE Ultrason. Symp.*, pp. 563–567, Oct. 1977.
[14] M. Lewis, "Surface skimming bulk waves, SSBW," in *Proc. IEEE Ultrason. Symp.*, pp. 744–752, Oct. 1977.
[15] T. I. Browning *et al.*, "Bandpass filters employing surface skimming bulk waves," in *Proc. IEEE Ultrason. Symp.*, pp. 753–756, Oct. 1977.
[16] I. Browning and M. Lewis, "A new cut of quartz giving improved stability to SAW oscillators," in *Proc. 32nd Annual Frequency Control Symp.*, U.S. Army Electron. Command, Fort Monmouth, NJ, pp. 87–94, May–June 1978.
[17] ——, "A novel technique for improving the temperature stability of SAW/SSBW devices," in *Proc. IEEE Ultrason. Symp.*, pp. 474–477, Sept. 1978.
[18] T. I. Browning, M. F. Lewis, and R. F. Milsom, "Surface acoustic waves on rotated Y-cut $LiTaO_3$," in *Proc. IEEE Ultrason. Symp.*, pp. 586–589, Sept. 1978.
[19] H. J. Hindin and K. Smith, "Riding the surface acoustic waves," *Electron.*, vol. 52, no. 1, pp. 81–82, Jan. 4, 1979.
[20] K. H. Yen, K. L. Wang, and R. S. Kagiwada, "Efficient bulk wave excitation on ST quartz," *Electron. Lett.*, vol. 13, pp. 37–38, Jan. 1977.
[21] K. H. Yen *et al.*, "Interdigital transducers—a means of efficient bulk wave excitation," in *Proc. 31st Annual Frequency Control Symp.*, U.S. Army Electron. Command, Ft. Monmouth, NJ, pp. 266–270, June 1977.
[22] K. F. Lau *et al.*, "Further investigation of shallow bulk acoustic waves generated by using interdigital transducers," in *Proc. IEEE Ultrason. Symp.*, pp. 996–1001, Oct. 1977.
[23] K. H. Yen, K. F. Lau, and R. S. Kagiwada, "Temperature stable shallow bulk acoustic wave devices," in *Proc. 32nd Annual Frequency Control Symp.*, U.S. Army Electron. Command, Ft. Monmouth, NJ, pp. 95–101, May–June 1978.
[24] ——, "Shallow bulk acoustic wave filters," in *Proc. IEEE Ultrason. Symp.*, pp. 680–683, Sept. 1978.
[25] K. F. Lau, K. H. Yen, and R. S. Kagiwada, "Shallow bulk acoustic wave devices—a new type of acoustic wave device for communication systems," presented at the Int. Telemetering Conf., Los Angeles, CA, Nov. 1978.
[26] ——, "Investigation of shallow bulk acoustic waves," Progress Rep. no. 1 to U.S. Army Res. Office, Research Triangle Park, NC, under Contract No. DAAG29-78-C-0043, Jan. 1979.
[27] K. H. Yen, K. F. Lau, and R. S. Kagiwada, "Energy trapped shallow bulk acoustic waves," *Electron. Lett.*, to be published.
[28] K. F. Lau, K. H. Yen, and R. S. Kagiwada, "Analysis of shallow bulk acoustic wave excitation by interdigital transducers," in *Proc. 33rd Annual Frequency Control Symp.*, U.S. Army Electron. R&D Command, Ft. Monmouth, NJ, May–June 1979.
[29] K. H. Yen, K. F. Lau, and R. S. Kagiwada, "Narrowband and wideband shallow bulk acoustic wave filters," presented at the 1979 IEEE Int. Symp. Circuits and Syst., Tokyo, Japan, July 1979.
[30] R. F. Mitchell, "Spurious bulk wave signals in acoustic surface wave devices," in *Proc. IEEE Ultrason. Symp.*, Nov. 1974, pp. 313–320.
[31] R. S. Wagers, "Plate modes in surface acoustic wave devices," in *Physical Acoustics: Principles and Methods*, (W. P. Mason and R. N. Thurston, Eds.), vol. 13, ch. 3, New York: Academic, 1977, pp. 49–78.
[32] A. Jhunjhunwala *et al.*, "Theoretical examination of surface skimming bulk waves," in *Proc. IEEE Ultrason. Symp.*, pp. 670–674, Sept. 1978.
[33] D. L. Lee, "A theoretical analysis of surface skimming bulk waves," in *Proc. IEEE Ultrason. Symp.*, pp. 675–679, Sept. 1978.
[34] W. S. Mortley, "Improvements in or relating to wave-energy delay cells," U.K. Patent 988 102, Apr. 1965.
[35] E. P. Papadakis, "Diffraction grating dispersive delay lines utilizing anisotropic propagation media," *Ultrason.*, vol. 8, pp. 102–104, Apr. 1970.
[36] R. M. White and F. W. Voltmer, "Direct piezoelectric coupling to surface elastic waves," *Appl. Phys. Lett.*, vol. 7, pp. 314–316, Dec. 1965.
[37] "Standards on piezoelectric crystals, 1949," in *Proc. IRE*, vol. 37, pp. 1378–1395, Dec. 1949. (IEEE Standard No. 176).
[38] S. A. Bokovoy and C. F. Baldwin, "Improvements in or relating to piezo-electric crystals," U.K. Patent 457 342, Nov. 1936.
[39] C. F. Baldwin and S. A. Bokovoy, "Piezoelectric quartz element," U.S. Patent 2 212 139, Aug. 1940.
[40] ——, "Piezoelectric crystal element," U.S. Patent 2 254 866, Sept. 1941.
[41] R. Bechmann, A. Ballato, and T. J. Lukaszek, "Higher-order temperature coefficients of the elastic stiffnesses and compliances of alpha-quartz," *Proc. IRE*, vol. 50, pp. 1812–1822, Aug. 1962.
[42] A. Ballato, "Doubly rotated thickness mode plate vibrators," in *Physical Acoustics: Principles and methods*, W. P. Mason and R. N. Thurston, Eds., vol. 13, ch. 5. New York: Academic, 1977, pp. 115–181.
[43] D. Hauden, M. Michel, and J.-J. Gagnepain, "Higher order temperature coefficients of quartz SAW oscillators," in *Proc. 32nd Annual Frequency Control Symp.*, pp. 77–86, May–June 1978.
[44] A. Ballato and T. Lukaszek, "Shallow bulk acoustic wave devices," *IEEE Microwave Theory Tech. Int. Symp. Dig.*, April–May 1979, pp. 162–164.
[45] A. Ballato, "Transduction of acoustic surface waves by interdigital arrays, and equivalent circuit representations," U.S. Army Electron. Command, Fort Monmouth, NJ Tech. Rep. ECOM-4359, Oct. 1975.
[46] R. F. Milsom, N. H. C. Reilly, and M. Redwood, "Analysis of generation and detection of surface and bulk acoustic waves by

interdigital transducers," *IEEE Trans. Sonics Ultrason.*, vol. SU-24, pp. 147–166, May 1977.
[47] W. S. Mortley, "F.M.Q.," *Wireless World*, vol. 57, pp. 399–403, Oct. 1951.
[48] ——, "Frequency-modulated quartz oscillators for broadcasting equipment," *Proc. Inst. Elect. Eng.*, vol. 104B, pp. 239–249, Dec. 1956.
[49] ——, "Priority in energy trapping," *Phys. Today*, vol. 19, pp. 11–12, Dec. 1966.
[50] W. H. Horton and R. C. Smythe, "The work of Mortley and the energy-trapping theory for thickness-shear piezoelectric vibrators," *Proc. IEEE*, vol. 55, p. 222, Feb. 1967.
[51] W. Shockley, D. R. Curran, and D. J. Koneval, "Energy trapping and related studies of multiple electrode filter crystals," in *Proc. 17th Annual Frequency Control Symp.*, pp. 88–126, May 1963.
[52] ——, "Trapped-energy modes in quartz filter crystals," *J. Acoust. Soc. Amer.*, vol. 41, pp. 981–993, Apr. 1967.
[53] R. D. Mindlin, "Bechmann's number for harmonic overtones of thickness/twist vibrations of rotated-*Y*-cut quartz plates," *J. Acoust. Soc. Amer.*, vol. 41, pp. 969–973, Apr. 1967.
[54] A. A. Oliner, "Microwave network methods for guided elastic waves," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-17, pp. 812–826, Nov. 1969.
[55] E. A. Ash, R. M. De La Rue, and R. F. Humphryes, "Microsound surface waveguides," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-17, pp. 882–892, Nov. 1969.
[56] H. F. Tiersten, "Elastic surface waves guided by thin films," *J. Appl. Phys.*, vol. 40, pp. 770–789, Feb. 1969.
[57] H. F. Tiersten and R. C. Davis, "Elastic surface waves guided by curved thin films," *J. Appl. Phys.*, vol. 44, pp. 2097–2112, May 1973.
[58] B. K. Sinha and H. F. Tiersten, "Elastic and piezoelectric surface waves guided by thin films," *J. Appl. Phys.*, pp. 4831–4854, vol. 44, Nov. 1973.
[59] M. F. Lewis, private communication, Feb. 1979.
[60] E. C. Jordan, *Electromagnetic Waves and Radiating Systems*. Englewood Cliffs, NJ: Prentice-Hall, 1950, pp. 391–450.
[61] E. I. Jury, *Theory and Application of the z-Transform Method*. New York: Wiley, 1964.
[62] P. M. DeRusso, R. J. Roy, and C. M. Close, *State Variables for Engineers*. New York: Wiley, 1965, pp. 158–186.
[63] H. Gautier and G. S. Kino, "A detailed theory of the acoustic wave semiconductor convolver," *IEEE Trans. Sonics Ultrason.*, vol. SU-24, pp. 23–33, Jan. 1977.
[64] B. T. Khuri-Yakob and G. S. Kino, "A detailed theory of the monolithic zinc oxide on silicon convolver," *IEEE Trans. Sonics Ultrason.*, vol. SU-24, pp. 34–43, Jan. 1977.
[65] E. P. EerNisse, T. Lukaszek, and A. Ballato, "Variational calculation of force-frequency constants of doubly rotated quartz resonators," *IEEE Trans. Sonics Ultrason.*, vol SU-25, pp. 132–138, May 1978.
[66] A. Ballato, "Static and dynamic behavior of quartz resonators," *IEEE Trans. Sonics Ultrason.*, vol. SU-26, July 1979, pp. 299–306.
[67] J. R. Vig, J. W. LeBus and R. L. Filler, "Chemically polished quartz," in *Proc. 31st Annual Frequency Control Symp.*, pp. 131–143, June 1977.
[68] B. A. Auld, J. J. Gagnepain, and M. Tan, "Horizontal shear surface waves on corrugated surfaces," *Electron. Lett.*, vol. 12, pp. 650–652, Nov. 1976.
[69] Y. V. Gulyaev and V. P. Plessky, *Pis'ma v Zh. Tekh. Fiz.* (USSR), vol. 3, pp. 20 ff. 1977. (Transl., *Sov. Tech. Phys. Lett.* (USA), vol. 3, pp. 87 ff, 1977.)

Practical Aspects of Surface-Acoustic-Wave Oscillators

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***Abstract*—A surface-acoustic-wave (SAW) delay line integrated with a thin film amplifier can form the basis of a small high-stability microwave oscillator. Practical aspects of delay lines and the noise properties, stabilization, frequency setting, and modulation of oscillators are presented.**

I. Introduction

THE surface-acoustic-wave (SAW) oscillator has a stability comparable to that of a bulk crystal-locked oscillator but since it can operate at a very much higher frequency, problems associated with harmonics, when deriving higher frequencies by frequency multiplication, are therefore reduced. It can also be frequency modulated. Compared to a phase-locked oscillator it has a wide-band low-noise spectrum. The SAW delay line can readily be integrated with a thin film amplifier to form a small high-stability oscillator, presently at frequencies of up to approximately 1.5 GHz. Therefore, the potential of SAW oscillators is attractive and they are now being considered for communications and navigation systems for both transmitter sources and receiver local oscillators.

In this paper it is intended to outline the basic principles and performance of SAW oscillators and the factors affecting the frequency stability, both over an operating temperature range and in the long term, the oscillator sideband noise, the accuracy of frequency setting, and the deviation and maximum rate of frequency modulation.

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