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Acoustic Surface Waveguides—Analysis and Assessment

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Invited Paper

Abstract—**The properties of acoustic surface waveguides are reviewed, with particular reference to topographic structures in which guiding is achieved by drastic deformation of the substrate surface. A numerical technique, capable of computing efficiently and with high accuracy the mode spectrum of an anisotropic piezoelectric heterogeneous waveguide of arbitrary cross section, is described. Characteristics of both the ridge guide and the recently discovered wedge waveguide are discussed in some detail.**

Techniques for the fabrication of and transduction onto acoustic surface waveguides are discussed, and a preliminary assessment is made of potential linear and nonlinear waveguide applications. A number of experimental devices are described.

I. Introduction

ACOUSTIC surface waves represent solutions of the wave equation which lead to a concentration of the acoustic energy near to the free surface of a half-space. One can, however, make the stronger statement that the surface *guides* the wave, since it will continue to propagate near the surface even if this should have a small convex curvature [1]. Diffraction for acoustic surface waves is therefore confined to a single plane—that of the free surface. In most devices which have been considered so far one accepts the fact of lateral diffraction as one of the constraints in device design, though one may seek to minimize its effects by the choice of a low diffraction propagation direction [2]–[4]. There are, however, situations where one would like to obtain guiding action in the plane of the free surface so as to eliminate diffraction completely. A number of types of acoustic surface waveguides have been considered in the past, and detailed accounts will be found in recent review papers [5]–[7]. It is the main purpose of the present paper to review some recent advances in this field, both with regard to the understanding of the characteristics of such guides which has been achieved and to some experiments which bear on possible applications.

Since acoustic surface waveguides are necessarily "open," true guiding action, devoid of leakage, implies that the propagation velocity must, in the guiding region, be reduced to a value less than the Rayleigh velocity and less than the velocity of any coupled bulk waves. Waveguides may be classified in accordance with the means adopted for effecting this velocity reduction. In principle, this can be done by causing a local change in the material itself; for example, by doping in the case of a semiconductor [8], or by depoling in the case of a ferroelectric [9]. There may well be developments leading to applications for such guides. However, the two main categories that have been considered are thin-film guides, in which the velocity reduction is effected by the perturbation effected by the elastic [10]–[12] or electric properties of a deposited thin film [14], and topographic guides, in which the velocity reduction is achieved by a change in the topography of the free surface [7], [13], [15]–[17].

Perhaps the most important single characteristic of an open guide is the strength of the guiding action, as portrayed by the extent to which the acoustic fields extend within the substrate on either side of the guiding structure. It is this which determines the minimum radius of curvature through

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which the guide may be bent for a given radiation loss. The strength of the guiding is determined by a combination of two factors: the ratio of the guide phase velocity, relative to the substrate Rayleigh velocity [18], and the degree of mechanical isolation between the guiding region and the substrate. A large velocity reduction is in itself sufficient to ensure strong guiding; it is, however, quite possible in the case of some topographic structures to obtain strong guiding at velocities quite close to the Rayleigh value.

The rigorous theory of open elastic waveguides is intractable. Analysis forces the use either of drastic intuition-based assumptions or the resort to purely numerical techniques. In recent times, considerable success has been achieved by both approaches, with the latter providing justification for the former. For complex-shaped topographic guides, the numerical approach alone is open. This work will be reviewed in the next section, followed by a discussion of the modes of propagation which are predicted by the analysis and indeed observed. It will emerge that, for the first time, theory and experiments are in satisfactory contact.

Transducers currently used in acoustic surface-wave technology are several tens of wavelengths wide; in contrast, the width of single-mode waveguides is of the order of one wavelength. There are, therefore, problems in both fabrication and mode transduction at high frequencies. Recent advances, both conceptual and technological, which bear on this issue will be discussed in Sections IV and V.

The high power densities which can be reached in waveguides make their use in parametric signal-processing devices attractive. We will describe some relevant experiments which we have carried out in Section VI, which is devoted to an assessment of the various possibilities for the application of waveguides.

II. Theory

The theory of thin-film waveguides is well established [11], [12] and, at least for situations involving moderate velocity reductions, gives results in satisfying agreement with experiment. Until recently this has not been the case with regard to topographic guides. It is possible to analyze rigorously only those structures whose boundaries conform to a simple orthogonal coordinate system (half-space, plate, wire, sphere). However, as will emerge in the next section, in some cases it is possible to achieve results to a very useful accuracy by means of approximate analytical techniques based on an intuitive understanding of the waveguide modes. For more complex structures it is necessary to resort to numerical techniques. Fortunately, a powerful approach based on the use of a variational formulation is now available, and forms the main topic of Section II-C.

A. Transverse Resonance

It has proved possible to gain a rather detailed understanding of the modes of propagation of the simplest topographic guide—the rectangular ridge—by using quite simple physical arguments. If we consider the case of a tall or high aspect-ratio ridge ($H/W>2$; Fig. 1), provided that a tightly bound mode exists at all, the disturbance will presumably reach the substrate in greatly attenuated form. The behavior of the structure should therefore be similar to that of semi-infinite plate. It is known that a semi-infinite plate supports a symmetrical mode on the edge having a velocity very close to the Rayleigh value [19], [20]. This mode is guided primarily

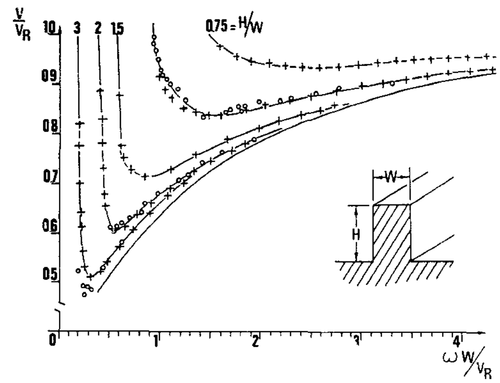

Fig. 1. The rectangular ridge waveguide (inset). Measured dispersion characteristics of the fundamental ASF mode in an isotropic Duralumin 17S guide. The parameter is H/W. Circles denote laser probe results, crosses the results of ring resonator experiments. The dispersion characteristic of the fundamental ASF Lamb wave is also shown.

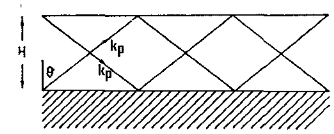

Fig. 2. Traveling-wave constructive interference of reflected fundamental ASF Lamb waves.

by the edge discontinuities which confine the disturbance to the region near the top of the ridge. It is also known that an infinite plate supports a spectrum of Lamb waves, including a fundamental having a velocity which tends to zero at low frequencies [21]. This anti-symmetrical flexural wave (ASF), since it propagates slowly, is clearly of great potential interest for guiding structures. While in a ridge guide, the presence of the substrate must have a significant effect, one can nevertheless hope to see a related mode which retains the essential property of having a velocity well below the Rayleigh value.

Experiments have indeed confirmed this hope [22]. In Fig. 1 the lowest ASF mode for an infinite plate is compared with experimental results for ridge guides for a range of H/W values. The experimental results indicated a velocity which rises rapidly at what is apparently a low-frequency cutoff. At higher frequencies, the characteristic is seen to tend asymptotically to the infinite plate ASF curve.

The low-frequency cutoff condition corresponds to cantilever resonance of the ridge waveguide. We have established experimentally that at cutoff, the rectangular ridge guide is approximately one quarter of a plate wavelength high. In cantilever resonance, the guide loses energy to freely propagating bulk modes. A tall cantilever can, nevertheless, resonate with a high Q.

The dispersion characteristic for most rectangular guides is well represented by the ASF plate characteristic when $H>\lambda_p$. Even for $H/W=1.5$, the velocity discrepancy at frequencies above this point is less than 5 percent. The asymptotic behavior at high frequencies suggests that at lower frequencies it may be possible to represent the propagation in terms of two ASF plate modes reflected progressively from the ends of the waveguide (Fig. 2). The mode must then satisfy the phase condition that

$$2k_pH\cos\theta-\phi_1-\phi_2=2m\pi$$

where $\phi_{1,2}$ are the phase changes suffered by the ASF plate

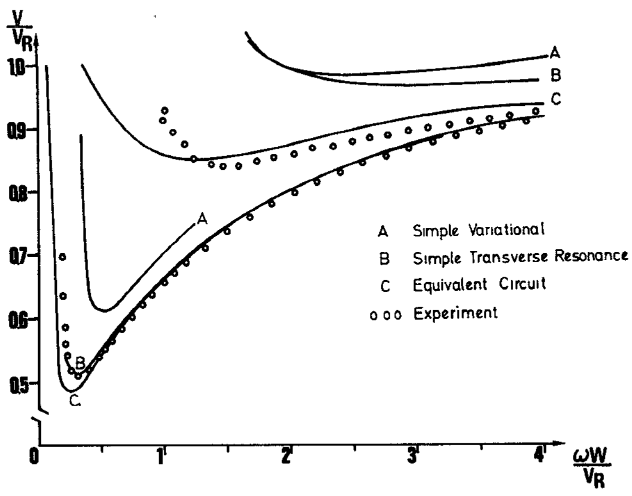

Fig. 3. Fundamental ASF rectangular ridge mode. Comparison between approximate theories and experiment.

waves at the free end of the ridge and at the substrate. If we assume that the discontinuities are of the open- and short-circuit types, so that the phase changes are 0 or π, the effect of the $\phi_{1,2}$ is simply to translate the mode numbers from $2m$ to $(2m-1)$. In this case, the result for the axial propagation constant $k_g = k_p \sin\theta$ is given by an expression of the same form as for electromagnetic waves in a rectangular waveguide

$$k_g^2 = k_p^2 - \left(\frac{n\pi}{2H}\right)^2$$

where n is an odd integer. Using the known form for the dispersion characteristic of k_p, one can then plot the dispersion characteristic for the ridge ASF mode. Results for the lowest ASF ridge mode are compared with experiment in Fig. 3. For tall ridge guides ($H/W \geq 3$) the agreement is excellent. Energy propagating in the substrate, discounted in this theory, becomes more significant for lower aspect ratios ($H/W \simeq 1$) and the discrepancy increases [23].

Oliner *et al.* have developed a general equivalent-circuit formulation based on transverse resonance techniques [24]. This has recently been applied to the problem of the ridge guide by Li *et al.* [25]. The ridge itself is as before represented by reflected fundamental ASF Lamb waves, and the top of the ridge is still visualized as an "open circuit." The role of the substrate, however, is now represented by an assumed coupling to *SH* bulk waves. This coupling leads to the dispersion characteristic

$$(k_p^2 - k_g^2)^{1/2} = \left(\frac{k_p}{k_s}\right)^2 (k_p^2 - k_s^2)^{1/2} \cot\left[(k_p^2 - k_g^2)^{1/2} H\right]$$

where k_p, k_s, and k_g are, respectively, plate, bulkshear, and guide wavenumbers. The characteristic computed from this equation has again been compared in Fig. 3 to experimental results. It is seen that the agreement with experiment is now remarkably good and gives tolerable accuracy for H/W as low as unity.

Equivalent-circuit methods are in principle general enough to take discontinuities at the free and the substrate end of the ridge into account. It might also prove possible to represent guides having forms other than rectangular. However, in pursuing either of these aims, the remarkable simplicity of the transverse resonance formulations will be lost.

B. Variational Methods

Variational methods have been widely used in calculating waveguide characteristics. One could hope for simple solutions in cases such as the ridge guide, where one might be able to advance simple trial functions on an intuitive basis. Using a Rayleigh–Ritz technique, we have computed the dispersion characteristic for a trial function which is linear in each of the coordinates and achieved tolerably accurate results for large H/W [26]. However, the extension of such analytical variational techniques to more complicated trial functions rapidly leads to discouraging quantities of algebra.

Tu and Farnell have used an approach in which the trial functions are developed as Legendre polynomials. These are chosen to give continuity of displacement in all parts of the structure, including the half-space. A variational solution is then used in order to minimize the stress discontinuities. Results have been published for both ridge [27] and thick overlay guides [28]. Their formulation has particular value in extending perturbation theories of thin-film guides to take the finite thickness of the layer into account.

C. Finite-Element Formulation

A complete formulation of the topographic waveguide problem should allow one to compute efficiently, and with high accuracy, the mode spectrum of an anisotropic piezoelectric heterogeneous waveguide of arbitrary cross section. In a finite-element approach, one divides the guide cross section into a number of (usually triangular) elements, in each of which the field variables are defined by simple polynomial trial functions. With a first-order approach these are linear.

Finite-element methods have been applied to a wide variety of electromagnetic and structural mechanics problems. First-order finite-element techniques were first applied to the topographic waveguide problem by Burridge and Sabina [29]. It is known that the efficiency of computation is a sharply rising function of the order of the trial functions used in the triangles [30], [31]. The displacement function is more efficiently modeled by quadratic, cubic, or even quartic line segments. The number of triangular elements required to describe a given waveguide depends on both its geometrical complexity and on the anticipated gradients of the field quantities. The topographic waveguide analysis program has been designed to permit any element order between one and four to be specified at the outset.

As a first step in writing the program, one must find an appropriate variational principle. This is a laborious task [26], best undertaken by trial and subsequent test against two criteria: that the Euler equations applied to the presumed Lagrangian density must lead to the appropriate wave equations; that the natural boundary conditions are those met by an elastic waveguide—namely absence of stress at the free surface. A functional L, containing the 45 different elastic, piezoelectric, and dielectric constants, has been constructed to meet these conditions [33].

The elastic displacements and electric potential associated with a propagating mode can be written as

$$U_i = U_i(x_1, x_2)\exp(-jk_g x_3), \qquad i = 1, 2, 3, 4.$$

If an elastic waveguide is aligned with a symmetry direction in orthotropic material, it can be shown that displacement variables $U_{1,2}$ are purely real and that U_3 is purely imaginary.

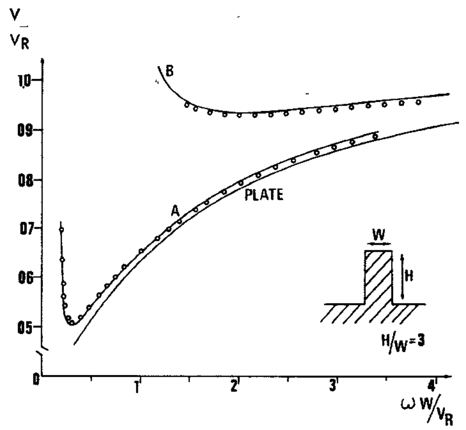

Fig. 4. Comparison between second-order finite-element calculations and experiment for the two lowest order ASF modes in an $H/W=3$ Duralumin 17S rectangular ridge waveguide.

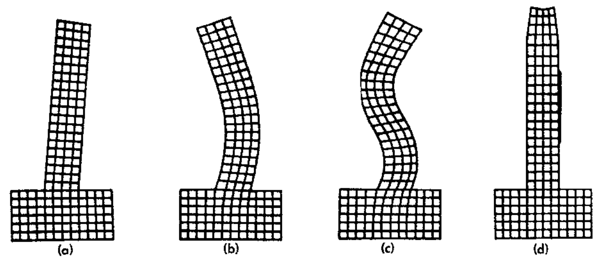

Fig. 5. Displacement patterns of four tightly bound modes that exist in a high aspect ratio ($H/W=5$) rectangular single-material ridge waveguide.

Applications of the finite-element method to the variational principle lead to a matrix eigenvalue equation in stiffness $[S]$, mass $[T]$, and the field variables $[U]$

$$[S][U] = \omega^2[T][U].$$

ω, in this equation, is the mode eigenfrequency. Derivation of the analytic form of the $[S]$ and $[T]$ matrices for one triangle is a laborious algebraic operation, which fortunately needs to be done only once. The complete eigenvalue equation can be assembled numerically.

The size of the matrices increases with the number of triangular elements needed to describe the structure. For general anisotropy, the dimensions of the $[S]$ and $[T]$ matrices are twice those encountered in orthotropic calculations. It is interesting to note that the matrix dimensions are *not* altered by the inclusion of piezoelectricity. The eigenvalue problem is solved using standard routines. The time required for a solution on a given computer is roughly proportional to the square of the size of the matrix. In analysis of a "typical" waveguide, one encounters matrices of approximately 100×100.

A comprehensive set of boundary and symmetry conditions has been implemented into the program by introducing appropriate constraints on the field variables. In order to minimize the cost of computation, it is essential to take full advantage of any structural symmetry possessed by the guide. The zero-displacement boundary condition at infinity, required by the use of semi-infinite substrates, is approximated to by placing an artificial zero-displacement boundary at some considerable depth in the substrate. One can gain assurance that a computed mode is indeed a good approximation to that which would obtain for a semi-infinite substrate by observing the effect on the displacement pattern of moving the rigid boundary further away from the waveguide.

The assessment of achieved accuracy in a computation of this nature is notoriously difficult. Fortunately, we have accurate experimental information on dispersion in a variety of topographic guides. We can also model the problem of Rayleigh-wave propagation and compare our results with those derived from established analytical techniques.

Extensive computations of the mode spectrum of ridge waveguides have been performed. Fig. 4 shows the dispersion characteristics of an $H/W=3$ rectangular ridge waveguide, for the fundamental and first higher order ASF mode, compared with experimental data. The correspondence shown was obtained using second-order elements, in a computing time of 45 s per data point, on an IBM 360/65.

The inclusion of piezoelectric effects leads to further opportunities for testing the program. One can compute the velocity of Rayleigh waves, with and without a metallized layer on the surface of a crystal. It is of great importance in transducer design to achieve an accuracy which allows a reasonably precise estimate of $\Delta V/V$. In the following table we compare finite-element predictions of velocity for CdS and PZT 4A, with exact results computed using established programs [34]:

	CdS		PZT 4A	
	Exact Analytical	Finite Element	Exact Analytical	Finite Element
Free surface (m/s)	1729.0	1732.0	2256.0	2257.4
Metallized surface (m/s)	1724.9	1727.3	2191.0	2192.3
$\Delta v/v$ percent	0.24	0.27	2.83	2.88

The finite-element method is adequate for estimating $\Delta V/V$, even for relatively weak piezoelectric materials. The computer time needed for such a calculation is again approximately 45 s on a 360/65. To test heterogeneous cases we have computed the dispersion characteristic of a fused silica half-space covered by a uniform gold layer. The correspondence with analytical results is within 0.2 percent over the complete characteristic.

Finite-element techniques based on a variational formulation provide a powerful approach to the general problem of elastic waveguide analysis. The method has enabled us to characterize a variety of topographic guiding structures. The mode spectra of such guides are discussed in the following section.

III. The Modes of a Topographic Waveguide

Accurate experimental dispersion characteristics have proved of the greatest possible value in comparing alternative methods of waveguide analysis. All of our experiments have been conducted at low frequencies on model waveguides machined to a high tolerance using ring-resonator and laser-probing techniques [35]. We have concentrated on single-material ridge guides having parallel or sloping sides.

Experimentally derived dispersion characteristics of the fundamental ASF mode in a series of rectangular ridge waveguides were shown in Fig. 1. The rectangular ridge guides support a spectrum of ASF modes and at least one symmetric mode. In Fig. 5 we show computed displacement patterns of four of the modes of a tall ($H/W=5$) waveguide. Particle motion in the three anti-symmetric modes is predominantly

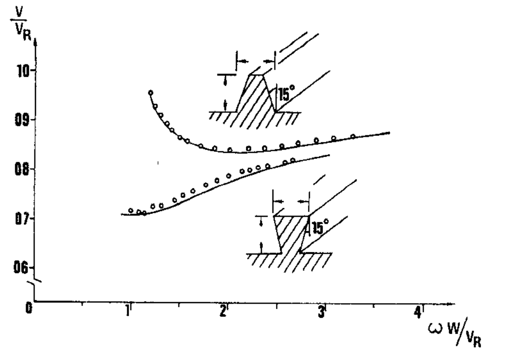

Fig. 6. Comparison between finite-element calculations and experiment, for Duralumin 17S guides with sloping sides.

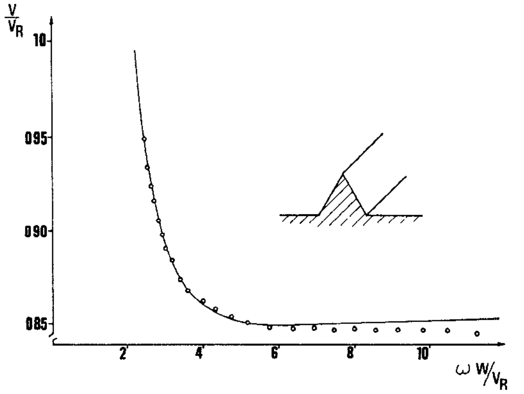

Fig. 7. Correspondence between computation and experiment for fundamental ASF mode propagation in a knife-edge waveguide. The scale is highly expanded.

in the plane of the substrate, normal to the direction of propagation. In the fourth mode shown, particles move primarily in the sagittal plane, as in a Rayleigh wave.

Very tall ridge waveguides are heavily overmoded over most of the usable operating band. It can be seen in Fig. 4 that moderately tall ($H/W=3$) guides offer a large single-mode operating bandwidth and an even larger bandwidth for which the phase velocities are widely separated. As expected, we find that the fundamental suffers the least attenuation in negotiating a bend. This suggests that a relatively tight bend might act as an effective mode filter.

The close correspondence between theory and experiment for the rectangular ridge has already been mentioned. One of the principal objectives in developing a finite-element computational approach was to study the effect on the mode spectrum of varying the guide cross section. Waveguide geometry has, as one might expect, a marked effect on dispersion. We compare in Fig. 6 numerical and experimental dispersion characteristics of fundamental ASF modes in guides having sloping sides. We see that for guides which get narrower with distance from the substrate the dispersion characteristic is flattened [23]. If we continue to increase the slope angle to form a knife-edge, we find that the waveguide becomes virtually nondispersive at high frequencies [36]. The correspondence between theory and experiment is shown in Fig. 7.

This behavior can be understood by noting that at high frequencies an infinitely tall knife-edge has no characteristic dimension. If any wave is guided by the apex of a wedge, it must necessarily be nondispersive. It is perhaps of interest to note that while this argument is quite elementary, the

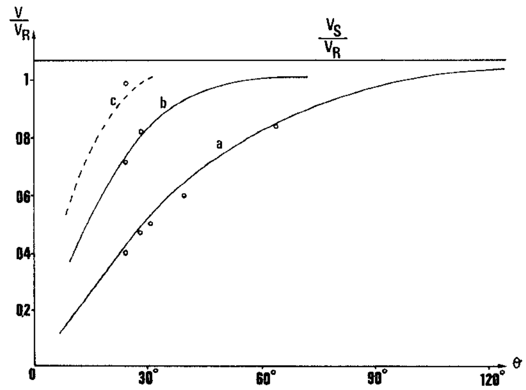

Fig. 8. The effect of varying apex angle on the propagation velocity of the three lowest order nondispersive wedge waves. Curves were computed using fourth-order finite elements for Duralumin 175. Circles represent experimental results.

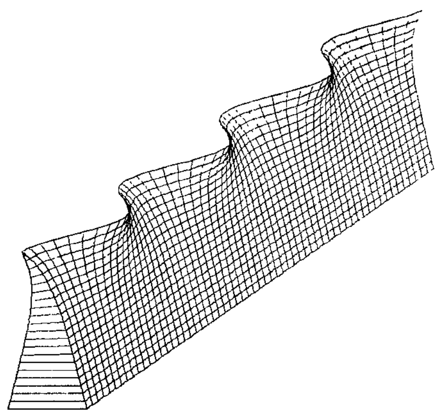

Fig. 9. Computer-generated perspective view of propagation in the lowest order mode on a narrow apex wedge. Wave motion is predominantly antisymmetric flexural.

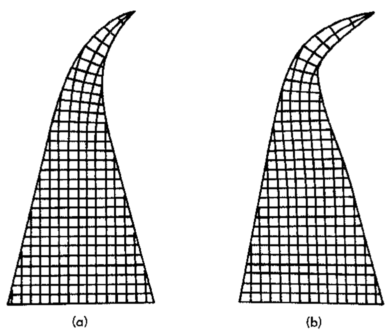

Fig. 10. Displacement characteristics of the two lowest order ASF wedge waves. Energy is tightly bound to the apex. The lateral displacement phase change, characteristic of the second mode, is therefore difficult to see.

existence of the anti-symmetric flexural wedge wave was in fact discovered on the computer.

The relation between velocity and wedge apex angle is shown in Fig. 8. We have observed, experimentally, three nondispersive ASF modes in narrow apex angle wedges. Fig. 9 shows a computer-generated perspective view of propagation in the lowest order mode. The mode is tightly bound to the wedge apex, and the particle motion is predominantly normal, both to the direction of propagation and to the plane bisecting the apex. The displacement for the fundamental falls from the tip approximately as exp $(-2x/\lambda)$. In Fig. 10

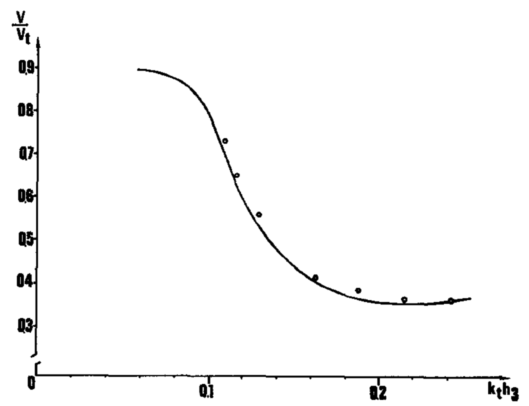

Fig. 11. Comparison between Tu and Farnell's and our own predictions (circles) of dispersion in a rectangular gold overlay waveguide.

we show displacement patterns for the two lowest order modes.

The computer-generated characteristics suggest an extremely simple empirical relationship for the mode velocity

$$v \doteq v_R \sin(m\theta), \qquad m = 1, 2, 3, \cdots, \quad m\theta < 90°$$

where v_R is the half-space Rayleigh velocity and m is an integer denoting mode order. For sufficiently small θ, it should be possible to obtain nondispersive guided propagation at velocities approaching the velocity of sound in air.

It should be noted that sharp wedges are prone to overmoding. The above expression suggests that m modes may propagate in wedges for which $\theta < \pi/2m$. Wedges with $\theta > 45°$ are effectively single moded. We have found for $\theta = 90°$ that the propagation velocity is just less than the Rayleigh velocity. Wedge and ridge guide modes are related. A rectangular ridge, for example, provides two 90° wedges at its upper free boundary. A pair of 90° wedge waves, propagating in phase up the edges, must at high frequencies form a symmetric mode of the system.

Rectangular overlay waveguides have been considered by a number of workers. While model experiments have been performed, accurate experimental dispersion characteristics have not (to our knowledge) been published. Tu and Farnell have recently published computed characteristics of rectangular gold overlays on a quartz half-space [28]. While our approach is better suited to studying thicker overlays, we show in Fig. 11 the close correspondence obtained between their results and our own.

IV. Fabrication

The application of waveguides is circumscribed by our ability to solve fabrication problems. Very little effort has so far been devoted to surface waveguide technology. In the following, we will make brief remarks on what has been achieved and on the prospects for the realization of waveguides in more demanding circumstances.

A. Thin-Film Guides

On a strongly piezoelectric substrate, it is possible to achieve significant guiding action by the deposition of a metallic film, which is only just thick enough to short out the piezoelectric field. Such $\delta v/v$ guiding, first described by Engan [14] and recently analyzed by Hughes [39], has the advantage that the technological problems are no more severe than in the photolithographic definition of the transducer structures; such guides have recently been successfully used in a weak guiding application at a frequency of 50 MHz [40]. For situations requiring a stronger guiding action or the use of a nonpiezoelectric substrate, one is involved with the deposition and subsequent photolithographic delineation of thicker films.

Most of the experiments which have been reported are concerned with mass-loading thin-film guides [41] using gold as the layer material—a choice dictated largely by convenience. Nevertheless, at frequencies below 100 MHz, it is possible to obtain strong low-loss guiding. For example, at 60 MHz, Au/SiO_2 ring resonators with a velocity reduction of ~10 percent had measured Q values of ~10^3 [42]. An example of an $Au/LiNbO_3$ guide operating at just under 100 MHz is given in Section VI.

At higher frequencies, strong guiding applications will require the use of a nonmetallic layer. Dielectric overlays are widely used in the semiconductor industry, and the known technology should be directly applicable to guide fabrication. A detailed analysis bearing on the compatability of various substrate-layer materials combinations has recently been published—though in the context of dispersive delay lines [43]. There is one combination which is particularly attractive technologically—the SiO_2/Si system. Measurements at 600 MHz on a thermally grown oxide layer have recently been reported. At higher frequencies it will probably be essential to resort to single crystal layers. Advances in heteroepitaxy and in RF sputtering techniques give some promise that suitable combinations could be realized.

B. Topographic Guides

At frequencies below 20 MHz, topographic guides can be fabricated using conventional workshop or optical shop techniques. One can, for some applications, use metals; in this context, it is interesting to note that a steel edge can be honed to a tip radius of 100 Å. By using the very low-velocity modes of topographic guides and steering information about the substrate, one can achieve a reduction in both frequency and size while retaining signal processing capacity.

The advent of high-performance overlay transducers allows the use of nonpiezoelectric substrates [44]. It is therefore natural to look at silicon technology for suitable constructional techniques. One can obtain some extension of conventional machining methods by the use of airbrasive techniques followed by chemical or electrochemical polishing [45]. Wedge guides suitable for frequencies up to several tens of megahertz have recently been fabricated. For higher frequency operation it will, however, be essential to adopt fabrication techniques where the critical dimensions can be controlled by photolithography. A number of etching techniques can be used with isotropic etches; undercutting limits the aspect ratios which one can achieve. However, using selective etches, which show markedly differing etching rates depending on crystalline planes or doping concentration, provides a great deal more control. A considerable amount of work which, though motivated by purely electronic requirements, is nevertheless very relevant has been reported [46]–[48]. Fig. 12(a) and (b) shows some results which we have recently obtained using a water amine etch [49]. The walls of the guide expose the (111) plane. The significant point is that very sharp edges can be defined using techniques of this kind. Topographic guides with very large H/W ratios have recently been fabricated [50]. Further work is, however, required on the problem of bends in the waveguide—which necessarily involve changes in the orientation of the waveguide walls—and on

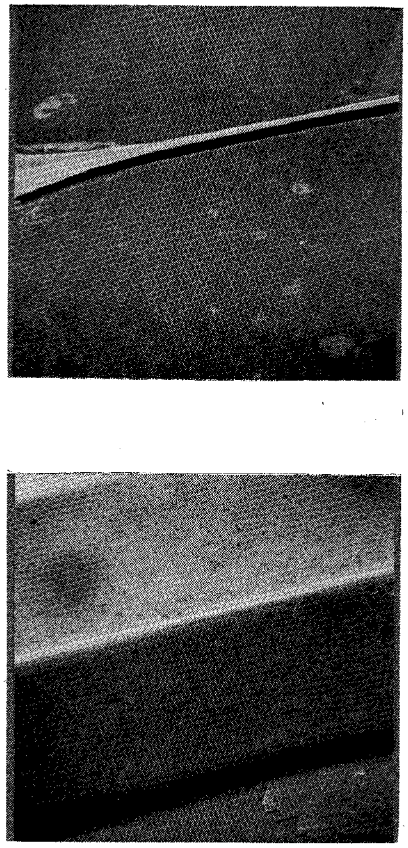

Fig. 12. Fabrication of a 40-μm$\times$40-μm rectangular silicon ridge waveguide by selective etching.

the problem of transduction. A number of possible approaches to the latter are discussed in the next section.

V. Transduction

A. General Considerations

Typical interdigital transducers for commonly used materials have a width of the order of several tens of wavelengths, the main design criterion being the achievement of a radiation resistance which is not too far from 50 Ω. The radiation resistance is proportional to w^{-1}, so that narrow transducers inevitably have a high radiation resistance.

The maximum width of single-mode waveguides depends on the strength of guiding required; thus for a 0.6-percent velocity reduction $\Delta v/v$ guide, the width for single-mode operation can be as large as 10 λ. However, for moderately strong guiding, the width will be of the order of one wavelength. The guide-width issue represents the primary problem in devising transducers to waveguides.

In principle, one can envisage three distinct approaches to the problem, Fig. 13. One can seek to effect transduction directly onto the guide structure [12], [52]—and accept the VHF penalties of a high input resistance. One can devise a focusing system which will radiate into the end of the guide from a substantially larger transducer [26], [54], [55]. Finally, one can also seek to couple laterally into the guide, again from an extended transducer source [53]. All of these approaches have been used in differing circumstances.

We will very briefly note some of the results which have been achieved for both topographic and thin-film guides. However, it should be recognized that efficient, wide-band transduction remains as perhaps the major outstanding problem in projecting the viability of waveguide applications.

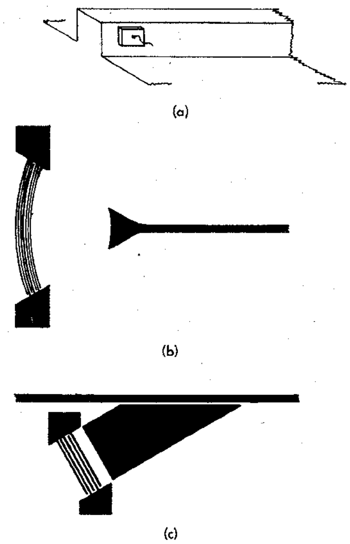

Fig. 13. Transduction techniques. (a) Direct. (b) Focusing. (c) Lateral coupling.

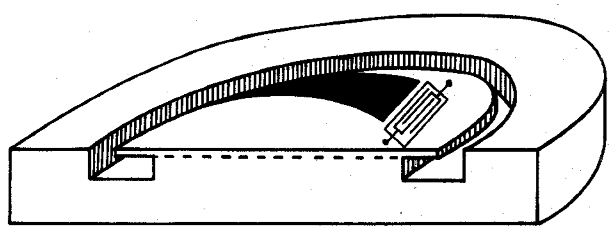

Fig. 14. Proposed topographic guide formed on the edge of an epitaxially grown silicon disk. A thin-film guide is used to couple from the overlay transducer.

B. Thin-Film Guides

Most experiments with thin-film guides have been carried out using a gold film and without any attempt at achieving efficient transduction. However, some quantitative results are available for both endfire and lateral transductions systems. Adkins and Hughes have used horns 100 λ long to couple from a 25-λ-wide transducer to a 1-λ-wide guide [54]. At 25 MHz, the loss attributed to the horns was estimated at 5 dB. We have recently carried out similar experiments on a gold-on-$LiNbO_3$ waveguide convolver at a frequency of 96 MHz [55]. The loss per funnel attributable to the horns is estimated at 2 dB. In our design funnel length was based on the crude assumption that waves emerging from the guide could be regarded as cylindrical and on the requirement that phase errors across a plane transducer at the output should not exceed λ/2. By apodizing and curving the transducer itself, the funnel length could be greatly reduced.

A lateral approach, involving evanescent field coupling, has recently been reported by Yen and Li [53]. Their configuration, which is sketched in Fig. 13(c), led to comparatively efficient coupling over a 25-percent band centered on 5.5 MHz. In Fig. 14 we show an alternative lateral arrangement, which provides the opportunity of launching an edge mode in a disk, using conventional wide interdigital transducers and a hybrid-guide horn coupler.

C. Topographic Guides

Both endfire and lateral systems are harder to implement in the case of topographic guides; there is, accordingly, every incentive, particularly in the case of piezoelectric materials,

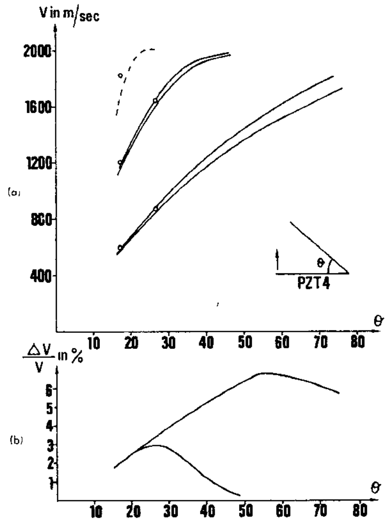

Fig. 15. Characteristics of the PZT 4A wedge wave. (a) Velocity as a function of apex angle. (b) The change in velocity resulting from a thin shorting layer on the free surfaces. The material is poled normal to one of the free surfaces. Circles denote experimental results.

to effect transduction directly. In the case of Rayleigh-wave transducers, it has been established that the velocity reduction resulting from imposing short-circuit boundary conditions on the surface provides a quantitative measure of the strength of coupling achievable with an interdigital structure. It is plausible that the corresponding values of $\Delta v/v$ in the case of a topographic guide will again give some indication of the strength of coupling attainable to various propagating modes. We have carried out a series of preliminary experiments using a PZT 4 wedge guide. The computed velocity for several modes are compared with experimental results in Fig. 15(a). Computed results for $\Delta v/v$ are shown in Fig. 15(b). These results suggest that efficient direct broad-band transduction may well be feasible.

The electric field distribution associated with a mode on a wedge guide is of critical importance in the design of transducer structures. One is particularly concerned with the change in the distributions which arise when the surfaces are metallized. Fig. 16 shows computed results for a 26° wedge, for the fundamental, and first higher modes [33]. For the second mode, the potential changes sign close to the tip irrespective of whether the surface is metallized. The symmetrical nature of the potential pattern arises from the combined effects of an asymmetrical mode, and a poling direction which is normal to one of the faces—and hence also asymmetrical.

The symmetrical nature of the potential distribution suggests that it should be possible to effect efficient transduction by the use of an interdigital transducer, folded over the edge as shown in Fig. 17. Preliminary experiments have led to encouraging results [52].

VI. Applications

It is only in very recent times that surface-wave devices have been incorporated in operational systems. Applications other than simple delay lines have been limited to radar pulse-compression filters and a particular class of frequency filter. Against this background the assessment of device applications for waveguides might seem premature; however, the level of

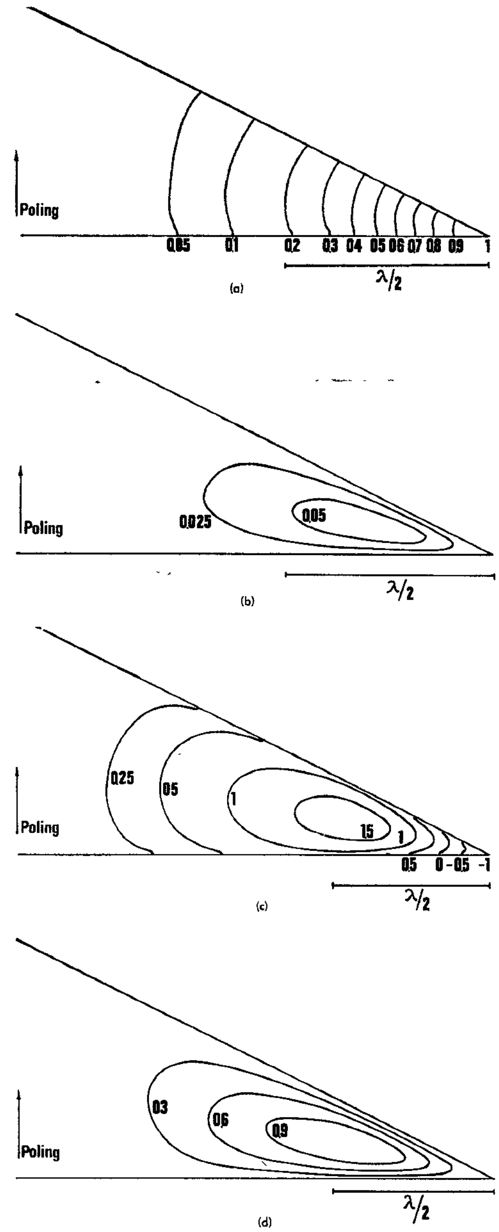

Fig. 16. Cross section of the equipotentials associated with propagation of lower order modes ($m=1$, 2) in a 26° PZT 4A wedge. The material is poled normal to one of the free surfaces. (a) $m=1$, free. (b) $m=1$, shorted. (c) $m=2$ free. (d) $m=2$ shorted.

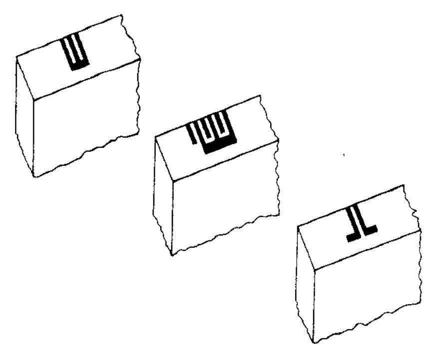

Fig. 17. Photolithographically compatible taps for the wedge wave. Information can, as with a Rayleigh wave, be tapped at any point along the propagation path.

understanding of waveguide characteristics which has now been achieved does allow some tentative conclusions.

One can broadly classify potential applications according to whether they relate to linear applications or rely on some nonlinear property of the waveguide. The former will be discussed in parts A–D; the latter in parts E–G of this section.

A. Mass Digital Stores

Acoustic delay lines were used for storage in the earliest computers, and their revival using modern technology has been suggested by a number of authors [57]–[59]. The main attraction lies in the attainability of bit rates which could be in excess of 100 Mbit/s, together with the ability to achieve moderately high bit densities. Using large H/W topographic guides etched in silicon, one might be able to achieve bit densities approaching $10^5/\text{cm}^2$. However, it is difficult to foresee how such devices might fit into either the central or the pheripheral units of a digital computing system. In particular, one must be aware of the alternative based on MOS technology. Although current MOS speeds are typically below 10 Mbit/s, it is possible to combine many channels in parallel using high-speed bipolar combinational circuits. The costs which apply to such a system are tending toward 10^{-4} dollars/bit and may well sink by a further order of magnitude. It is our belief that acoustic delay-line memories, with or without waveguides, working with input and output digital streams, are most unlikely to appear competitive in anything but the most specialized systems.

B. Delay-Line Storage of Analog Signals

MOS storage techniques can be used to store analog information at the expense of quantization noise and a complicated analog-to-digital (A–D) converter. The cost of an A–D converter rises rapidly with information rate. For these reasons, the pessimistic conclusion on the competitive strength of acoustic delay lines in digital systems does not apply to wide-band relatively low time–bandwidth analog systems.

The use of analog acoustic delay lines is particularly attractive for applications (e.g., display) where information is needed strictly in sequence. In a number of TV systems there is a need to store a complete frame involving delays of up to 20 ms. This implies at once that, using available substrates, some means must be found for folding the delay path. The most direct approach to this problem is to define a delay path on the outside of a cylinder, a technique used by Ross *et al.* [15], and subsequently on a CdS crystal by Gloersen [5]. More recently, Adams *et al.* [40], by using wide plates of $Bi_{12}GeO_{20}$, obtained delays of several milliseconds at a frequency of 50 MHz. In order to avoid diffraction effects and also coupling between adjacent helical tracks, they have used a $\Delta v/v$ guiding technique.

An alternative possibility, envisaged in the original Seidel and White patent [10], is to realize a long delay line by spiralling a surface waveguide. Using an Au/SiO_2 guide, this approach has recently led to the realization of a 30-MHz delay line with a 250-μs delay. This type of delay line could also be fabricated using the technology indicated in Fig. 14. There is every reason to suppose that as fabrication technology develops, the performance of such structures will become attractive. The chances of adoption of any such system will depend on a number of critical specifications, including the allowable dispersion, the allowable spurious level, particularly as determined by coupling between adjacent turns of a spiral or helix, and the required dynamic range.

C. Filters

Metal-strip delay lines are widely used as dispersive filters for pulse compression at HF frequencies; in fact, one of the earliest pulse-compression systems used a clockspring as a Lamb waveguide [60]. Ridge guides represent a natural extension of such techniques to higher frequencies, where the strip can no longer be self-supporting. The prospects for application would appear to be most favorable for situations involving long-chirp pulse lengths.

The nondispersive nature of wedge guide modes, and the fact—which we have demonstrated—that they can be tapped using structures very similar to those used in transduction, suggests that one may be able to realize a class of extremely simple and compact matched filters at frequencies below those at which one would otherwise contemplate resorting to acoustic surface waves.

The relatively wide beams of surface waves normally used offer the possibility of processing information *laterally* as well as in time. So far very little use has been made of this potentiality; apodization of transducers to control the amplitude of excitation associated with a section of a transducer forms almost the only example—and even here the lateral "information" is incidental and certainly undesirable. It has been suggested that using lenses one could devise a Fourier transformer [61], [62]. It is now possible to design high-quality lenses [63]. The remaining problem is to present the information to the lens and then to abstract the transform from the other side. Waveguide techniques offer possible solutions to this problem. The time–bandwidth products which, in principle, could be achieved in such a device make this possibility one which we regard as well worth pursuing.

D. Microsound

One of the early motivations for acoustic surface-wave work was the possibility of developing a highly compact surface-wave circuit technology [7], [17], [62]. While some of the components which one would need in such an endeavor have been fabricated—notably the directional coupler—the close analogy with microwave microstrip circuits which was envisaged has not been demonstrated in practice. In particular, there are no results on stubs; indeed, comparison with dielectric guides to which at least thin-film acoustic guides bear some resemblance, does not encourage the view that such structures would have acceptable losses. There is also no evidence that thin-film guides can be open circuited without incurring severe radiation losses. The situation with topographic guides may be more favorable.

For the moment, these limitations, as well as the lack of any evidence of a demand, have led to slow progress in this direction. The situation may change; we have only just begun to understand the modes of waveguide propagation. A Fourier transformer has, in our view, the best chance of early implementation.

E. Nonlinear Applications—General Comments

Nonlinear interaction processes have an efficiency which, in principle, is proportional to the power densities of the participating waves. This fact at once provides a motivation for the use of waveguides in such interactions, since their width

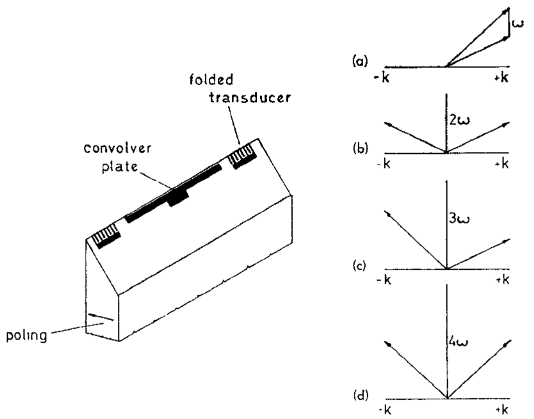

Fig. 18. Configuration of an experimental degenerate wedge wave convolver. Traveling-wave interactions between the two lowest order wedge waves.

is typically one to two orders of magnitude less than that of freely diffracting beams. It is, however, important to appreciate that whether this increase in the efficiency of the *mechanism* is seen at the *terminals* depends on whether the coupling structures used for deriving the nonlinear output can make full use of the highly compressed beam.

Nonlinear interactions require that both energy and phase-matching conditions are satisfied. In a freely diffracting beam one is always concerned with a continuum of k-vectors, while in single-mode guides there is a unique k-value. This circumstance can also contribute to an improved performance.

F. Parametric Interactions of Guided Waves

The signal processing possibilities arising from nonlinear interaction of acoustic waves have recently created a great deal of interest. Even in the best materials, the inherent nonlinear interaction is relatively weak, leading to problems of inadequate dynamic range and excessively large spurious signals. To improve the situation one can either seek to increase the inherent nonlinearity by the use of semiconductors [64]–[66], or to make better use of the available-materials' nonlinearity by exploiting the high power densities attainable in guides. The low velocity associated with guides, particularly with narrow-angle wedge guides, provides a further enhancement of the interaction efficiency, since (as recently shown by Luukkala [67]) this increases rapidly as the velocity decreases.

The dispersive nature of waveguides will lead to some distortion in convolution and correlation experiments. However, wedge guides are nondispersive. In using other guides it is important to appreciate that $d^2\omega/dk^2$ is the first aberration term in the characteristic. If the system is designed to operate around a point of inflexion of the $\omega-k$ characteristic, this form of distortion is minimized.

The low velocity and lack of dispersion of ASF wedge modes makes their use for nonlinear signal-processing particularly attractive [52], [56]. The system with which we are concerned is shown in Fig. 18. Interdigital transducers at either end of the 26-PZT 4 wedge are capable of launching fundamental ($m=1$) ASF waves, as well as the second-order mode ($m=2$) having the same wavelength. A total of eight three-wave interactions can therefore be envisaged. However, since in our experiments we wished to extract the output with a simple uniform electrode, we have confined our attention to the four cases which lead to a zero k output signal. The Tien diagrams for these are shown in Fig. 18. Fig. 18(a) shows a codirectional correlation for the case when the frequency and velocity of the $m=1$ wave are just half the corresponding quantities for the $m=2$ mode. The correlation output is extracted at the difference frequency. Fig. 18(b)–(d) shows the contradirectional convolution of two $m=1$ and two $m=2$ waves, respectively. Here the convolution signal is extracted at the same frequency. Fig. 18(c) show the contradirectional interaction of one $m=1$ and one $m=2$ mode. The output here, taken at the sum frequency, is a time-distorted convolution of the two input signals.

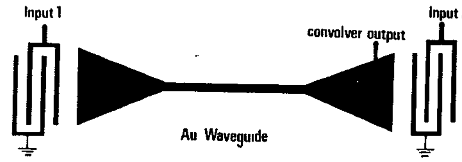

Fig. 19. Configuration of an experimental thin-film waveguide convolver.

All four of these interactions have been observed. The interaction involving similar modes is, as expected, stronger than that observed between modes of different order.

We have also carried out experiments with a gold-on-$LiNbO_3$ convolver, shown in Fig. 19 [55]. Transducers with 20 finger pairs having a center frequency of 96 MHz were coupled to a waveguide 30 μm wide and 2000 Å thick (giving a velocity reduction of 10 percent). The design of the horns was described in part B. The total insertion loss between the two transducers was 19 dB over a bandwidth of 2.3 MHz. The bidirectional and matching loss of the transducers accounted for approximately 11 dB; the guide-materials' losses could not be separately measured, but extrapolating from previous experience are estimated at 4 dB. The remaining losses are attributed to phase errors in the horns. The device was tested as a convolver with an output frequency at 192 MHz.

A striking feature of the results is the relative lack of spurious signals as compared with our experience with Rayleigh-wave convolvers. The largest spurious output was the convolution of the signals arising from transducer reflections. If we assumed that these could be reduced by a large factor, using multistrip coupler unidirectional transducers [68], the dynamic range (as determined by the maximum reduction in the signal power in one arm for unity ratio of the signal to the remaining spurious power level) was 60 dB. This favorable result is attributed to the very weak coupling between the guide and bulk waves.

There is, in this experiment also, a contribution to increased convolution efficiency arising from the reduced width of the convolution electrode. In the present arrangement, only a modest improvement has been gained on this account since convolved power was not optimumly matched to the output port. Alternative matching structures are being examined.

G. Acoustooptic Interactions

Acoustic surface waves have been used to interact with optical-guided waves to deflect the optical waves in the plane of the film [69], to effect a mode conversion of the optical wave [70], and to deflect the optical wave out of the plane of the film so as to realize a potential display device [69]–[71]. In all of these interactions, relatively high efficiencies were obtained, but with acoustic powers which are higher than would be desirable. In the latter experiments, greatly improved performance could be obtained by the use of much narrower acoustic beams. The use of acoustic waveguides could provide a greatly enhanced power density over a longer interaction region. The case for waveguides in the application appears strong. The likelihood of their incorporation in practical display systems depends of course on the viability of the optical devices envisaged.

It is also worth noting the possible use of waveguides for interaction with unguided optical waves, as in an ordinary acoustooptic deflector. Here the large velocity reduction of the wedge guide suggests a substantial increase in the acousto-optical figure of merit for the material used.

Acknowledgment

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Acoustic Surface-Wave Recirculating Memory

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Invited Paper

Abstract—An acoustic surface-wave memory is described, operating at a bit rate of 220 MHz and storage capacity of 1280 bit per recirculation loop. The transducers are coded using orthogonal pairs of Golay complementary sequences to obtain pulse-in pulse-out behavior. The shape of the delayed pulse is analyzed and compared with the pulse shape that is obtained using a simple single finger pair transducer. The recirculation electronics uses standard MECL-III logic for both the amplifier and the write, read, inhibit, and reclocking functions. The cost of the recirculating memory and the feasibility of constructing larger capacity stores are also discussed.

I. Introduction

Ultrasonic delay lines have been used in recent years in two modes of operation. The first one is the analog mode, in which an RF signal is either pulse, frequency, or phase modulated and delayed or temporarily stored for later signal processing such as correlation. The other is the digital mode, in which a series of pulses, representing digital data, are stored in temporary memories such as are used in graphics storage, desk calculators, etc. In the latter application, video pulses are inserted into a delay line, and when they emerge at the output are amplified and inserted back into the delay line, thus forming a recirculating loop. In this paper, we will be concerned with the digital application, using acoustic surface waves.

The basic recirculating memory has the configuration as shown in Fig. 1. Binary data are fed into the loop through the "write" gate. The new data are then amplified in the delay line driver (this step may not be necessary, depending on the voltage levels in the circuitry and delay line insertion loss) and fed into the delay line. At the output of the delay line, the pulses are amplified back up to logic level and retimed with respect to a continuously applied clock signal to correct for small delay time variations. The data can also be read out at the output of the amplifier without disturbing recirculation. An inhibit signal interrupts the recirculation when new data are to be inserted into the loop.

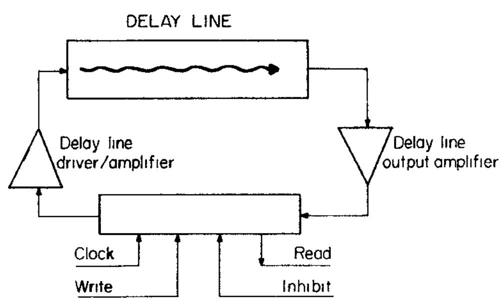

Fig. 1. Basic recirculating memory.

There are obviously many considerations that go into the design of a recirculating memory, and each design will always be a compromise between many factors, such as short latency time (the time that elapses before a given bit emerges at the output), large storage capacity, convenient frequency of operation, and, above all, the intended application and the cost of the memory [1], [2]. In the past, delay lines for digital storage were designed for maximum storage capacity in order to minimize the cost of access circuitry. Capacities of up to 20 000 bit have been reported at a frequency of a few megahertz, but with long latency time and large size [3], [4]. More recent considerations have indicated an optimum design that

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