Acoustic Surface Waveguides and Comparisons with Optical Waveguides

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Invited Paper

Abstract—**An overview is presented first of the various types of waveguides for acoustic surface waves which have been studied theoretically and experimentally. Many of these waveguides resemble certain waveguiding structures proposed recently for use in integrated and fiber optics. The similarities and differences between corresponding waveguiding structures in the two different fields are then discussed from the standpoints of their properties and their mechanisms of operation.**

I. Introduction

WAVEGUIDES, meaning structures for the controlled guidance of wave energy, first reached a level of maturity and sophistication in the context of electromagnetic microwaves. Within the past decade, various waveguiding structures for *acoustic* surface waves [1] have been proposed, analyzed, and measured, but for the most part they do not resemble the familiar waveguides of electromagnetic microwaves. On the other hand, the relatively recent waveguides for integrated optics and fiber optics resemble some of the acoustic waveguides more closely than customary microwave waveguides, despite their electromagnetic character. In addition, some novel waveguiding structures for millimeter waves [2], [3] have been proposed recently, and these structures are deliberate adaptations from those for integrated optics. We thus see that *new classes* of waveguiding structures have emerged in recent years, being associated with acoustic surface waves on the one hand, and with electromagnetic millimeter-wave and optical applications on the other.

Some important similarities, and interesting differences, exist between waveguides of the acoustic and the optical types, and one function of this paper is to highlight those similarities and differences. In addition, the techniques of microwave networks can be, and have been [4]–[8], used to analyze and describe the properties of these acoustic waveguides. In this paper, the types and properties of various acoustic surface waveguides are first summarized, and then comparisons are made between some of these waveguides and the corresponding structures proposed for optical or millimeter-wave applications. Microwave network approaches are used where appropriate in the description of the guiding properties and mechanisms of operation.

Although at present almost all surface acoustic wave devices utilize wide-beam surface waves, such wide-beam waves possess certain limitations: beam spreading, inefficient use of the substrate area, and awkwardness in bending their paths. The most important of these is beam spreading, which causes crosstalk between neighboring beams. All of these problems are automatically overcome by the use of waveguides for such surface waves, where the term waveguide implies a geometrical structure which *confines the lateral extent* of the surface wave and binds the wave to itself.

Acoustic surface waveguides are currently being investigated primarily (but not only) for use in long delay lines for the storage of either digital or analog signals, principally in order to overcome the beam spreading problem. But these contemplated applications barely scratch the potential of these waveguides. The most intriguing potential application is that of a highly compact sophisticated circuit technology, often referred to as "microsound" technology [9]–[11]. A glance backwards to the electromagnetic microwave field shows that sophisticated electromagnetic microwave circuitry did not appear until waveguides were well utilized. One is encouraged to speculate, therefore, that the full potential of acoustic waves will not be realized until acoustic waveguides are thoroughly exploited.

The two fields of acoustic surface waves and integrated optics possess many similarities because of three features: the wavelengths in each are tiny, the fabrication technology is similar for each, and surface waves are common to both. It is important to be aware of such similarities because such recognition permits the interchange of ideas and technology between the two fields and helps to speed up the development of both fields. A comparison in broad terms has been presented previously [12], considering such aspects as materials, devices and applications; the present discussion is restricted only to some corresponding waveguiding structures in each field. In this discussion, it will be shown what the corresponding structures are, which were conceived independently of the other field, and which resulted from knowledge of its analog structure.

II. Types of Acoustic Surface Waveguide

Waveguides for acoustic surface waves may be classified into four types:

1) Overlay waveguides, in which a strip of one material is placed on a substrate of another material;

2) Topographic waveguides, which consist of a local deformation of the substrate surface itself (that is, a change in the local topography of the surface);

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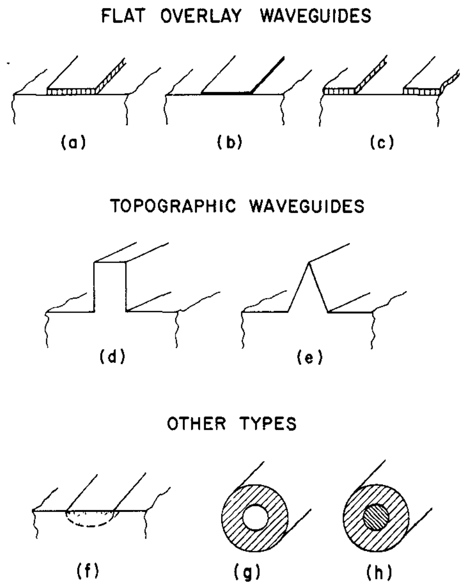

Fig. 1. Various types of waveguide for acoustic surface waves. Flat overlay waveguides: (a) strip, (b) shorting strip or $\Delta v/v$ (metal strip on a piezoelectric substrate), (c) slot. Topographic waveguides: (d) rectangular ridge, (e) wedge. Other types: (f) in-diffused or ion implanted, (g) capillary fiber, (h) cladded-core fiber.

3) Waveguides in which a local change has been produced in the properties of the substrate material;

4) Circular fiber waveguides, which do not employ a planar substrate.

Typical waveguiding structures in each of the four preceding categories are shown in Fig. 1. The properties of all of these structures, and the advantages and limitations of each one, have been treated in a recent publication [1].

The structures shown in Fig. 1(a)–(c) are the most important examples of *flat overlay waveguides*; the strip (or ribbon) guide of Fig. 1(a) is the best known of these. All have been analyzed theoretically and measured. The central region in each case is "slower" than the outside regions (corresponding to a higher refractive index in optics), so that the acoustic surface wave field is pulled in laterally toward the central region. In the *strip* waveguide of Fig. 1(a), the strip itself consists of material which is "slower" than that of the substrate. In the *slot* (or gap) waveguide of Fig. 1(c), the overlay material is "faster" than that of the substrate, so that the central slot region is "slower" and acts as the waveguiding region. The structure in Fig. 1(b) consists of a metallic strip placed on a piezoelectric substrate; the strip short circuits the electric field associated with the piezoelectric surface wave and produces a slight slowing of the wave under the strip. This waveguiding structure is herein called the *shorting-strip* waveguide; it is usually referred to as the $\Delta v/v$ guide because the velocity is changed by the shorting strip. This notation is bad, however, because *all* waveguides are $\Delta v/v$ guides in the sense that some modification has been introduced to change the velocity in some local region. Further details relating to the strip waveguide are presented later in this section.

The two most important *topographic* waveguides are the rectangular ridge and the wedge, shown respectively in Fig. 1(d) and (e). The guiding effect in these topographic waveguides results from a reduction of restraining forces acting on the material; such topographic structures have no counterpart in electromagnetic waveguides. The *rectangular ridge* waveguide possesses two dominant modes, one symmetric and the other antisymmetric. The antisymmetric, or flexural, mode is the better known of the two, and is characterized by a strong dispersive behavior; the symmetric mode has almost no dispersion and is referred to as the pseudo-Rayleigh mode because its field resembles that of a slice out of a Rayleigh surface wave. The *wedge* waveguide is of interest because it possesses no dispersion above a certain frequency (an infinite ideal wedge has no dispersion whatever). The slow nature of the antisymmetric mode on narrow-angle wedges is also of interest.

The structure in Fig. 1(f) is an example of a waveguide belonging to type 3). The substrate surface remains geometrically flat, but the properties of the material in the region shown dotted have been modified. This change may be produced in various ways such as in-diffusion, ion implantation, etc. A difficulty associated with overlay waveguides [type 1)] is the fact that a layered substrate has been found to be lossier than an unlayered one. Recent work by Schmidt [13] on certain metals in-diffused into $LiNbO_3$ has shown that the diffusion process produces a velocity increase but a negligible change in loss. Such in-diffused waveguides should therefore possess very *low loss*, and this waveguide type could become important for certain applications.

The *circular fiber* waveguides, indicated previously as type 4), are being investigated for their potential use in long delay-line applications. In different ways they are analogous to optical fibers; the structure in Fig. 1(g) is a capillary structure which guides a surface wave, resembling a compressed Rayleigh wave, on its inner surface, while that in Fig. 1(h) is a direct analog of a cladded optical fiber, in which the inner core is composed of "slower" material than the outer cladding.

Each of these waveguides in the aforementioned categories possesses its own characteristic properties and therefore has a different range of potential applications. Of these properties, two may be regarded as the most important: the acoustic field confinement and the dispersion behavior.

The *field confinement* is measured by the rate at which the acoustic fields decay laterally away from the guide. A rapid decay, implying strong confinement, isolates the waveguide from neighboring circuitry, and also permits the guide to undergo a bend with a smaller radius of curvature before measurable radiation leakage occurs. For some applications, however, a weaker confinement is preferred; for example, weaker confinement permits easier design of a directional coupler composed of two waveguides which lie parallel to each other for a specified length. For the waveguides in Fig. 1(a)–(c) and (f), the degree of confinement is directly related to the slowness of the wave; if v_R and v_z represent, respectively, the velocity of the Rayleigh wave and that of the guided wave along the waveguide (in the z direction) and k_R denotes the wave number of the Rayleigh wave, then the decay constant $|k_t| = \alpha_t$ along the substrate surface transversely away from the waveguide is given simply by

$$\frac{|k_t|}{k_R} = \left[\left(\frac{v_R}{v_z}\right)^2 - 1\right]^{1/2}. \tag{1}$$

For topographic waveguides, the field confinement is also governed by how much of the field is contained in the ridge or wedge itself, in Fig. 1(d) and (e); if essentially all the field is contained in the guide itself, then the mechanical isolation is very strong even though the guide velocity is near the Rayleigh velocity. As a general rule, the topographic waveguides offer strong field confinement or isolation, whereas the flat overlay waveguides possess weak field confinement unless the overlays produce strong loading effects.

The *dispersion behavior*, by which we mean the variation of propagation velocity with frequency, is quite different for each of the waveguides in Fig. 1. Some of the waveguides are essentially dispersionless over some frequency range. This feature is important for application to long delay lines. The wedge waveguide [Fig. 1(e)] is dispersionless above a certain minimum frequency, the symmetric mode of the ridge waveguide [Fig. 1(d)] has very small dispersion over the entire frequency range, and the slot waveguide [Fig. 1(c)] possesses a fairly flat maximum in the plot of velocity versus frequency. The virtues of the symmetric ridge guide mode mentioned previously have not been sufficiently appreciated to date; it is as close as one might come to an acoustic coaxial line mode or stripline mode, in the sense that it is very tightly confined, it propagates down to zero frequency, and it is essentially dispersionless.

Because of its close relationship to certain waveguides for integrated optics (to be discussed in the next section), let us consider more closely the best known of these, the *strip waveguide*, shown as Fig. 1(a) and repeated in Fig. 2(a). The structure consists of a strip or ribbon of "slow" material on a "fast" substrate; the term "slow" means that a bulk acoustic wave in that material would travel more slowly than such a wave in the "fast" material. The strip itself is wide and flat, with customary aspect ratios ranging from 5 to 50. The field is bound to the strip, decaying away from it in all transverse directions.

One of the analytical methods used to theoretically treat these waveguiding structures employs microwave network procedures [7]. Let us utilize one feature of that approach here because of its pedagogical value in this context. In that approach, it is necessary first to derive a transverse equivalent network for the structure under consideration. Such a network for the dominant mode of the strip waveguide is shown in Fig. 2(b). The central transmission line represents the modified Rayleigh wave supportable by the strip and substrate region, and the outer transmission lines represent the Rayleigh waves on the free substrate surfaces on each side of the strip. The geometric discontinuities between the strip and the free substrate are accounted for by the boxes shown.

The transverse equivalent network appearing in Fig. 2(b) permits us to view the propagation of the guided mode in terms of two modified Rayleigh waves in the strip region which bounce back and forth from the strip sides at angles which are greater than the critical angle, so that total reflection occurs within the strip and the wave becomes completely guided. We also conclude that the vertical decays of the field into the substrate in the strip and in the free regions correspond, respectively, to those for the modified Rayleigh and the Rayleigh waves. The transverse field behavior for the dominant mode is summarized in Fig. 2(c).

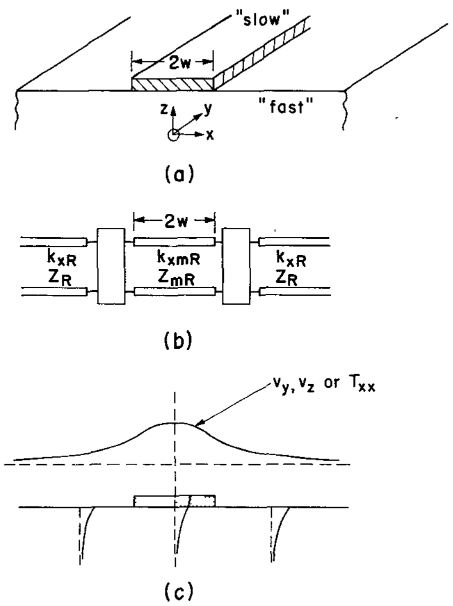

Fig. 2. The acoustic strip waveguide, consisting of an overlay of "slow" material on a "fast" substrate. (a) Geometrical structure. (b) Transverse equivalent network for dominant mode; k_{xR} and k_{xmR} are the transverse wave numbers in the x direction. (c) Transverse acoustic field behavior; v_x and v_y are particle velocity components and T_{xx} is a stress tensor component.

The transverse decay in the x direction, along the substrate surface, is that of a simple exponential, consistent with the requirement in the network of Fig. 2(b) that the Rayleigh wave transmission lines be below cutoff. This exponential decay will be a slow one for most flat overlay guides, depending, of course, on the amount by which the guided wave is slowed down [see (1)]. In general, for these waveguides the acoustic field extends out substantially so that the wave is weakly bound. Such behavior discourages sharp bends but may be useful, for example, when one wishes to obtain only mild guidance, or to construct directional couplers between adjacent lines.

The slot waveguide is in a sense the *dual* of the strip waveguide. A transverse equivalent network similar to the one shown in Fig. 2(b) for the strip waveguide can be drawn by inspection since the plated and free-space regions are simply interchanged for the slot waveguide. The basic mechanism for guiding is similar to that for the strip waveguide except that now a Rayleigh wave is multiply reflected from the step discontinuities at the edges of the slot guide; similarly, the transverse field distribution strongly resembles that shown in Fig. 2(c).

Transverse equivalent networks have also been obtained [8], [14], [15] for the modes of the topographic ridge waveguide of Fig. 1(d), but for that structure the constituent transmission lines go vertically rather than horizontally.

Detailed presentations of the microwave network approach to the acoustic waveguides described previously appear in [7] and [8]. A more complete summary of the properties of these waveguides is given in [1] and in a forthcoming book chapter [16].

III. Comparisons with Optical Waveguides

The optical waveguides which are actually counterparts of some of the acoustic waveguides shown in Fig. 1 are most easily recognized as such if we first recall certain facts relating to wide surface waves. Some basic information relating to such wide surface waves is reviewed in Section III-A.

These wide surface waves are confined vertically but not horizontally. A waveguiding structure *also* confines the wave *horizontally*. In the other sections that follow we consider strip waveguides and slot waveguides, for which analogous acoustic and optical structures exist, and the topographic ridge waveguide, an important acoustic waveguide for which no counterpart exists in optics.

The optical analog of the acoustic waveguide in Fig. 1(h) is the well-known single-mode step-index optical fiber. In fact, the acoustic structure was proposed (also analyzed and measured [17]) as an acoustic counterpart of that optical fiber. These familiar structures are not considered further here.

A. Wide Surface Waves

By wide surface waves we mean waves which have been confined in one cross-sectional dimension but not in the other; on a horizontal substrate, the wave would be confined vertically to the order of a wavelength or perhaps only a few wavelengths. An idealized surface wave on such a substrate would possess an infinite width; in practice, the wide surface wave would be about 40–100 wavelengths wide in acoustics but typically 1000 wavelengths wide in optics. In the following discussion, we consider the simplest types of idealized surface waves in both acoustics and optics.

The simplest possible surface wave in acoustics is the Rayleigh wave, which can be supported by the interface between the substrate surface and air (actually vacuum). This situation is depicted in Fig. 3(a), where the transverse field dependence is also sketched. Two exponential decays are shown, to indicate that the wave actually arises due to the coupling by the interface of the two bulk waves in the substrate, each of which possesses a different decay rate. Actually, they are superimposed so that a single more complicated decay occurs. It is also seen that no field exists in the vacuum above the interface. If air is present instead of vacuum, the Rayleigh wave actually leaks very slightly into the air region (referred to as air loading), but this leakage effect is generally neglected.

It is stressed that the wave exists even though no layer of another material is placed on the substrate surface. The

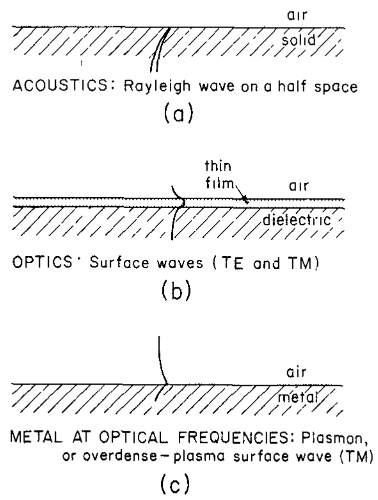

Fig. 3. The simplest types of surface waves at an interface in acoustics and in optics. The transverse field decays are also indicated.

Rayleigh wave is dispersionless, and propagates down to zero frequency. If a layer of another material is placed on the substrate surface, the wave becomes known as the modified Rayleigh wave and it becomes dispersive. Other wave types are then also possible, notably the Love wave, which is also dispersive and possesses a polarization different from that of the modified Rayleigh wave.

Surface waves in optics require a layer or thin film of material on top of the substrate, with the layer's index of refraction greater than that of the substrate. Also in contrast with the acoustics case, the wave has dispersion and a low frequency cutoff. The geometry is shown in Fig. 3(b), where the transverse field variation is also indicated. It is seen that field now exists in the air region also, but the penetration into the air is small if the refractive indices of the layer and the substrate are comparable. Actually, the TE mode has the lowest cutoff frequency, but the TE and TM waves, which have different polarizations, are quite close together in wave number.

The simplest surface waves in acoustics and in optics are therefore seen to possess features in common but also to have certain important differences. The most important distinction is that optical surface waves require the presence of an added thin film.

It is also of interest to consider the structure shown in Fig. 3(c), that of the interface between air and a *metal* at optical frequencies. At these frequencies the metal behaves like an *overdense plasma*, so that its dielectric constant is essentially negative real, but with a small imaginary part. Such an interface can guide a TM surface wave; this wave is sometimes referred to as a plasmon or as a surface polariton. As seen from Fig. 3(c), the wave decays transversely away from the interface in both media, with the greater extension occurring in the air region. The wave is strongly frequency dependent because the dielectric constant of the metal varies with frequency, and it has a low frequency cutoff.

This wave type is sometimes carelessly confused in the literature with the Zenneck wave, because the field behaviors

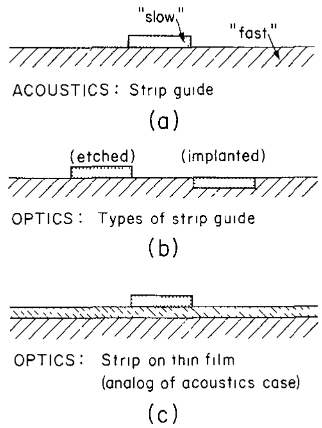

Fig. 4. Examples of strip waveguides in both acoustics and optics. Note that optical waveguide (c) is the analog of acoustic waveguide (a).

of the two waves are rather similar. The Zenneck wave, which also exists at the interface between air and metal, is valid in a very different frequency range, for which the metal's dielectric constant is essentially purely *imaginary*. In the aforementioned surface wave, however, the metal's dielectric constant is essentially *negative real*. Many of the features of the field distribution associated with these two wave types are similar, but on closer examination one notes certain differences, as, e.g., in the frequency dependence of the attenuation constants. The main point to note, however, is that, despite the similarities, the mechanisms associated with the two wave types are different.

B. Strip Waveguides

The cross section of the acoustic strip waveguide was shown in Fig. 1(a) and is repeated in Fig. 4(a). Since the substrate–air interface can support a (wide) Rayleigh surface wave by itself, the effect of the strip is to pull much of that surface wave into the strip region, and thus confine the wave laterally. The field decays transversely away from the strip both along the surface and into the substrate. It does not exist in the air region. The wave is now dispersive, and slower than the wide Rayleigh wave.

The early optical strip waveguides are shown in Fig. 4(b). They are of two types, as shown, one having a strip etched on the surface and the other consisting of a strip implanted into the surface. In both cases, the index of refraction of the strip must be greater than that of the substrate in order for the field to be pulled toward the strip. The fields here also decay away from the strip itself, but in a somewhat different fashion from the acoustic waveguide of Fig. 4(a); also, of course, some of the field penetrates into the air region above the substrate. These structures do not act to pull in a surface wave which could exist in their absence; their behavior is instead similar to that of a dielectric rod or strip in space.

The optical strip structure appearing in Fig. 4(c), on the other hand, is actually an analog of the acoustic strip waveguide of Fig. 4(a). Due to the thin film on the substrate, a wide surface wave could exist in the absence of the strip; as in the acoustics case, the strip serves to confine that wave laterally. Three differences from the acoustics case should be noted. First, some of the field in the optical structure penetrates into the air region. Second, it is not necessary, as in the cases shown in Fig. 4(a) and (b), for the strip to possess an index of refraction greater than that of the substrate; any real dielectric material will do since its index need only be greater than that of air. Third, all modes of the optical waveguide will possess a low frequency cutoff, whereas the lowest mode of the acoustic waveguide will propagate down to zero frequency.

The structure shown in Fig. 4(c) was analyzed and built recently by Furuta *et al.* [18]. In their version of this structure, the refractive index of the strip material was lower than that of the thin film. The field in the strip region therefore decays vertically upwards and the field is concentrated primarily in the thin film. As a result, the strip produces only a small perturbation in the original wide surface wave; the lateral binding is weak, but sufficiently effective, and the precise shape of the strip and its material properties are not critical. In order to achieve tighter lateral binding of the wave, Uchida [19] in a more recent paper analyzed the case for which the refractive index of the strip is greater than that of the thin film. The strip now exerts a stronger effect on the wave, and the resulting waveguide is a more direct analog of the acoustics structure.

A similar structure was built and measured by Goell [20] and by Reinhart *et al.* [21] and analyzed by Marcatili [22] and by Ramaswamy [23]. They called their structure a "rib" waveguide, and it is a special in-between case of Fig. 4(c) in which the strip is composed of the same material as the film. The theoretical analyses are more general, however. Optical strip waveguides have also been fabricated by others; see, for example, [24].

Although all of the aforementioned authors recognized independently the advantages of this structure, they apparently did not know of its similarity to the acoustic strip waveguide. They therefore did not take advantage of the body of knowledge already available for the acoustics case. Such recognition of similarity could have saved them some effort; for example, they could have used one of the methods of analysis employed previously (and successfully) for the acoustics case.

C. Slot Waveguides

The acoustic slot waveguide depicted in Fig. 1(c) and repeated in Fig. 5(a) possesses the optical analog shown in Fig. 5(b). An optical analog to Fig. 5(a) is not possible using normal dielectric materials, but it becomes feasible when metal platings are employed.

We recall from Section III-A that at optical frequencies a metal behaves like an overdense plasma and therefore possesses an essentially real and negative dielectric constant. As an example, silver at a wavelength of about 6000 Å has an equivalent dielectric constant of approximately $-16 - j0.5$. The wave in the region under the metal plate therefore travels more rapidly than in the slot region. Hence the slot region becomes "slow" and the plating regions become "fast," as in the acoustics case, and the structure now

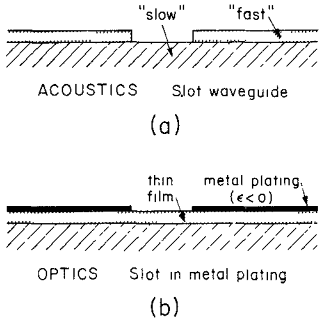

Fig. 5. The acoustic slot waveguide and its optical analog employing metal platings.

is able to support a guided wave along the slot region. The thickness of the metal plating is unimportant because the field in the metal region possesses an extremely rapid decay rate vertically upwards from the interface between the metal and the thin film.

The writer was the first to recognize [12] that the structure of Fig. 5(b) could guide optical waves. This fact was recognized independently by Hamasaki and Nosu [25], who also fabricated such a waveguide. Yamamoto *et al.* [26] analyzed and measured a similar structure soon afterwards. Oliner and Peng [27] recently pointed out that for one polarization the analysis of Yamamoto *et al.* is incomplete. For that polarization, the plasmon mode associated with the metal-plated region was omitted in their analysis; when that mode is included, the guided wave becomes slightly leaky and also has a lower cutoff frequency or thickness.

The structure of Fig. 5(b) is of particular interest because metal-plated structures of this sort are often used in devices for integrated optics, such as modulators and switches [28], which require the application of electric fields.

D. Topographic Waveguides

A topographic waveguide is formed by a deformation or modification of the substrate surface itself. Such waveguides are possible in acoustics, and various types have been investigated, such as a rectangular ridge, a wedge, and a trapezoidally shaped ridge, each located on a substrate. Each type has its own special advantages, but we shall here consider only the rectangular ridge waveguide appearing in Fig. 6.

The acoustic rectangular ridge waveguide possesses two dominant modes, each capable of propagating down to zero frequency. The symmetric mode resembles a slice out of a Rayleigh surface wave and is due to the coupling between the two bulk modes at the top of the ridge. That mode clearly has no counterpart in optics since only one electromagnetic bulk mode exists.

The antisymmetric, or flexural, mode fills the ridge region, but decays into the substrate. Due to the nature of the field distribution (like a flexural Lamb wave) in the ridge region, the ridge region is effectively "slow" relative to the substrate region, and the structure is capable of guiding a purely bound mode. This situation is depicted on the left side of Fig. 6.

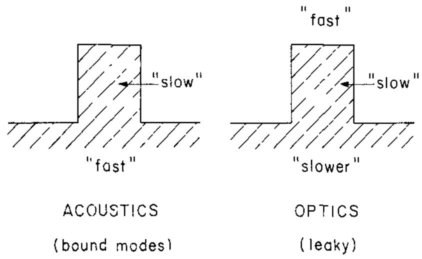

Fig. 6. The topographic ridge waveguide. It can support bound modes in acoustics but not in optics.

Can a corresponding topographic ridge structure guide an *optical* wave? Let us divide the structure into three constituent regions: the air above the ridge, the ridge and the air on its sides, and the substrate below. Call the middle region "slow"; then, if the other two regions are "fast" relative to it, bound-mode guiding can occur. Upon inspection, however, one sees that while the air region is indeed "fast," the substrate region is even "slower" than the middle region, as indicated on the right side of Fig. 6. Hence if optical energy is fed into the ridge, the wave will become a *leaky wave*, with energy leaking from the ridge into the substrate as the wave progresses down the ridge. In electromagnetics, topographic structures cannot guide purely bound modes.

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Transferred Electron Logic Devices for Gigabit-Rate Signal Processing

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***Abstract*—A new approach for designing transferred electron logic devices (TELD's) is presented and experimental results described. Electrolytic thinning of GaAs wafers has been used to maintain uniform *nd* product across the wafers and minimize variations in the device characteristics. TELD's have been fabricated and their performance studied. The devices are evaluated as threshold logic elements. The parameters studied are 1) switching characteristics, 2) shortest pulses that can be processed, and 3) device delay and dissipation. Experimentally, pulses as small as 80 ps wide have been processed through transferred electron logic gates (TELG's) with device delays of the order of 50 ps and delay–dissipation product of 5–10 pJ, which make them suitable for gigabit-rate signal processing.**

LIST OF SYMBOLS

A	Cross-sectional area of the test Schottky diodes.
c	Input capacitance of a TELD + capacitance of the interconnecting lines.
d	Active layer (channel) thickness.
e	Electronic charge.
E	Electric field.
g_m	Transconductance below threshold field.
G_v	Voltage gain.
I	Device current.
I_{th}	Device threshold current.
l_c	Distance between the cathode and gate.
l_{ca}	Distance between cathode and anode.
l_g	Gate length.
l_t	Distance between the gate and anode (transit length).
n	Doping density.
Q	Total charge.
R_L	Load resistance.
S	Device cross-sectional area ($= Wd$).
V_o	Output voltage developed across the load resistor due to the signal present at the gate.
W	Width of the active layer.
x_{1th}, x_{2th}	Depletion layer thickness at the anode and cathode edge of the gate, respectively, normalized to the channel thickness.
ΔI	Current dropback when the device thresholds.
ΔV_g	Trigger signal at the gate.
σ	Electrical conductivity.
μ	Electron mobility.
ϕ	Voltage drop across the depletion layer at the anode edge of the gate.
ϕ_b	Built-in diffusion potential.
ϕ_p	Channel pinchoff voltage.
τ_D	Propagation delay.

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