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# Review of Electromagnetic Surface Waves: 1960 Through 1987

by  
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# Naval Weapons Center

## FOREWORD

The work described in this report was performed by the Naval Weapons Center under Naval Air Systems Command Airtask #A931931A/00/A/8BR02200-000. This report provides a survey of the open literature on electromagnetic surface waves for the years 1960 through 1987 and emphasizes mathematical analysis of simple geometrical structures. This work was carried out during fiscal year 1987.

D. J. White has reviewed this report for technical accuracy.

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<p>This report contains a literature survey on electromagnetic surface waves for the years 1960 through 1987. It emphasizes the mathematical analysis of surface waves supported by structures with relatively simple geometries (i.e., planar, cylindrical, and spherical) that operate within the S- and Ka-band frequency regimes.</p>			
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## INTRODUCTION

This report attempts to provide a general analysis of the open literature on electromagnetic surface waves from 1960 to 1987. The year 1960 was chosen as the cutoff date for two reasons. First, in 1960 Harvey wrote a review paper that summarized much of the previous surface-wave work on guiding structures (Reference 1). This paper does a good job of reviewing the work done mainly in the 1950s and has an excellent bibliography of pre-1960 material. Its only drawback is that it appeared too early in the year to include information and references from a special supplemental issue of the IRE Transactions on Antennas and Propagation, December 1959, in which a section on surface waves is included. Many of the luminaries of the time published in this 1959 supplement (see, for example, References 2 through 6). It is fascinating reading and should not be overlooked. Second, the classic text by Barlow and Brown was published in 1962 (Reference 7). Since Barlow was one of the leaders in both theory and application of surface waves, this book contains a great deal of the pre-1960 general information scattered throughout the literature. Thus, unless background on a very specific subtopic on surface waves is desired, there is no need to comb the early literature for basic knowledge that, by its very nature, will be somewhat outdated.

In this report, emphasis has been placed on surface waves supported by discontinuities in both permittivity and permeability. Mainly "simple" geometries have been considered (i.e., planar, cylindrical, and spherical). The frequency regime of interest is from 3 to 30 gigahertz, although some optical surface-wave works have been included for either their mathematical techniques or their applicability at lower frequencies. Since the very concept of the surface wave is intimately connected to mathematics and the specific interpretation of mathematics, the methods used to derive results are certainly of interest. However, any quantitative analysis and/or criticism as well as all equations have been avoided.

For both completeness and the reader's convenience, this report contains a bibliography in addition to the list of references.

## SURFACE WAVES IN GENERAL

Barlow and Brown define a surface wave as "...one that propagates along an interface between two different media without radiation, such radiation being construed to mean energy converted from the surface-wave field to some other form (Reference 7)." Since this definition covers a lot of territory, one of the major problems with the surface-wave literature is the proliferation of different names for what is essentially the same physical phenomenon (References 2 and 8). These waves--Zenneck, Norton, Sommerfeld-Goubau, inhomogeneous, radial, axial, azimuthal, lateral, creeping, etc.--are all (at least in some sense) a type of or associated with a type of surface wave. Throughout this report we will try to clarify all such terms and use them correctly in association with the appropriate physical geometry or guiding process.

A second problem is the rather arbitrary way in which surface waves have been segregated from other types of guided waves (References 9 through 11). They can be treated theoretically by the same techniques governing more conventional guided waves. Given a particular geometry, any complete solution of Maxwell's equations will include the surface-wave solution as well as more conventional solutions. The surface wave will exist only under certain conditions, which must be well understood if one is to make use of it. But we must keep in mind that the surface wave is not some fundamentally different object. It is simply a solution of Maxwell's equations at a material interface that satisfies the appropriate boundary conditions and decays with normal increase of distance from the surface on both sides of the interface. It has been stated that "any mode that is evanescent in one of its coordinates is a form of surface wave" (Reference 10). Thus, the evanescent modes that exist in closed boundary conducting waveguides are not unrelated to the evanescent waves generated on open guiding structures where the modal expansion of the guided modes must be supplemented by the radiation field. There are transverse electric (TE) and transverse magnetic (TM) surface waves as well as higher order hybrid forms (EH or HE) just as for the usual types of guided modes. We simply need to remember that electromagnetic fields are physical quantities; our efforts to create subdivisions and to consider various wave types are sometimes convenient, sometimes confusing, but always based on artificially overlaid criteria of which the physical phenomenon is entirely unaware.

## SURFACE WAVES AND PLANAR GEOMETRIES

The simplest (mathematically) geometry that can support a surface wave is the planar interface between two homogeneous isotropic media

composed of different material properties (References 7, 9, 12, and 13). When an incident plane wave strikes this type of interface, the surface wave generated is an inhomogeneous plane wave, since the fields decay exponentially over the wave front with increase of distance from the surface. It is often referred to as the Zenneck wave. The conditions for generation of this wave rely on (1) incidence beyond the Brewster angle that gives rise to total internal reflection (References 7 and 14 through 16) and (2) finite loss in one of the media. An excellent analysis of the conditions on the material parameters for existence of such a surface wave is given by Lengyel (Reference 13). When the permittivities of the two media are different and the permeabilities are equal, only TM surface waves can propagate because the TE field components vanish identically. By duality, when the permeabilities are different and the permittivities are the same, only TE surface waves exist.

Many more complicated variations of the above geometry can be used to exploit the desirable characteristics of surface waves. The analysis of two dissimilar media has been applied in particular to a planar air-water interface (References 17 through 19). An additional complication occurs when the incident medium becomes absorbing (Reference 20). It has also been found that periodic semi-infinite sequences of layers with alternately high and low dielectric constants can guide loosely bound surface waves causing most of the power to flow in free space and decreasing the amount of loss along the guiding structure (References 21 and 22).

If we consider the situation of a plane wave incident upon a planar interface with complex surface impedance (References 7, 12, and 23), we find that the existence of a TM surface wave requires a surface impedance with an inductive reactive term, while a TE surface wave requires a capacitive reactive part. Of these two cases, TM propagation is the more common, since most naturally occurring surfaces have an inductive reactance. This is what causes the field decay normal to the surface, and the larger the reactance, the more closely the wave is bound to the surface. To excite a surface wave that is closely bound to the surface with small attenuation in the direction of propagation, the surface impedance must have a large inductive reactance and a small resistance. This implies that a conducting plane can support a TM wave that is only loosely bound to the surface. To obtain a good surface for guiding, we can coat the conductor with a thin layer of high dielectric constant material (References 7, 12, and 24). This thin layer leads to a large increase in the concentration of the field near the surface along with a relatively small attenuation constant in comparison to a conventional rectangular waveguide.

The fact that open structures can outperform closed conducting waveguides leads to the application and analysis of a thick dielectric sheet or slab (sometimes referred to as a dielectric slab waveguide)

(References 9, 12, and 25 through 31). The dielectric slab is capable of supporting both TE and TM surface modes. Solutions inside the slab can be classified as "even" or "odd," depending on the boundary conditions used (i.e., either an electric or magnetic wall at the symmetry plane). For the TM case, the lowest order even TM mode has no cutoff frequency (in analogy with a conventional TEM transmission line mode). All higher order even modes have cutoff frequencies as do all the odd modes. Surface waves along a dielectric slab are often called "trapped" modes because the incidence angles associated with them are beyond the critical angle, causing total internal reflection and trapping them inside the slab. For the TE case, the lowest order even mode has no associated cutoff, while all the higher order and odd modes do. It is worth noting that if the dielectric slab is backed by a perfectly conducting ground plane, only the odd modes occur. Thus, a surface mode without a cutoff frequency cannot exist. However, if a thin horizontal wire located parallel to a dielectric-coated conducting plane is considered, we find that interaction between the wire and the surface modes of the dielectric occurs, changing the character of the possible propagating modes along the wire (Reference 32).

The dielectric slab is characterized by a finite discrete set of surface modes. These surface modes are only one part of the complete eigenvalue spectrum that comprises the entire field. The complete "proper" solution set consists of (1) a finite discrete number of surface wave modes, (2) a continuous spectrum of propagating modes, and (3) a continuous spectrum of evanescent modes. Other modes that are present and have complex eigenvalues but do not obey the radiation condition at infinity are called "leaky" modes. Physically, they correspond to the radiation field away from the surface (References 12, 27, and 33 through 35). Leaky modes are not considered to be part of the "proper" solution set.

Surface waves can also propagate along anisotropic planar stratified media (Reference 36 through 38). Specific types of anisotropy will generate a variety of wave forms in the stratified regions, but a few general relations can be determined. It has been found that the group velocity of surface waves in anisotropic media is equal to the ratio of the real part of the complex Poynting vector integrated over the stratification coordinate to the same integral of the stored energy density (Reference 39). Also, for surface waves propagating above a dyadic impedance plane, the power flow and energy density relations can be used to calculate the energy transport velocity. In multilayered structures containing anisotropy, we find that reflected waves with the same polarization as that of the incident wave vanish because of the polarization-conversion phenomenon that occurs under certain conditions (Reference 40).

Surface waves also exist along the interface between two media, one of which is inhomogeneous. When there is a continuous variation in



permittivity across a layer of material, the WKB approximation may be used to solve Maxwell's equations (Reference 41). In comparison with exact solutions for linear and exponential permittivity variation, the WKB approach works well provided the permittivity is a slowly varying function of the coordinates.

So far we have considered only planar surfaces and incident plane waves in our quest for various forms of surface waves. However, flat surfaces are capable of supporting surface waves excited by a dipole or line source. These incident waves are radial cylindrical waves, and they generate a surface wave that decays radially with distance from the surface (References 12 and 42). Such a wave is often referred to as the radial form of the Zenneck wave. It is an inhomogeneous radial wave and is represented in terms of outward- (or inward-) traveling Hankel functions. This type of wave is difficult to excite with a realistic source because it has a fairly slow decay away from the surface (References 43 through 45). The radial Zenneck wave is not the most important form of cylindrical surface wave in terms of practical applications. The axial cylindrical surface wave is much easier to launch using a realistic source; it will be discussed in detail in the next section.

A point that has been neglected in the literature is that the radial Zenneck wave is a symmetric wave, i.e., it is the lowest order cylindrical surface wave obtainable. Very little has been written about higher order waves having azimuthal dependence (Reference 46), but these are certainly valid solutions to Maxwell's equations. It is interesting to note that the value of the surface reactance required for the existence of these modes is independent of mode number. Furthermore, unlike the unsymmetrical axial cylindrical surface wave modes--which are hybrid modes--the unsymmetrical radial modes are pure modes.

Previously we have concentrated mainly on planar interfaces characterized by different dielectric properties. However, one of the major guiding structures involves surface waves on infinite or finite ferrite slabs (References 9 and 47 through 50). All of these references restrict their discussions to parallel-polarized surface waves and show that the lowest order mode continues to propagate even when the frequency or slab thickness tends to zero. When the slab is backed by a perfectly conducting ground plane and the ferrite material is homogeneous and isotropic (Reference 47), we find even and odd modes in accordance with the symmetry of the magnetic field intensity. This is very similar to the dielectric slab analysis discussed above. When the ferrite is assumed to have a tensor permeability (Reference 9), the problem is much more difficult, and circular polarization effects as well as Faraday rotation must be taken into account.

The scattering of surface waves from various types of planar discontinuities has a very large percentage of the literature associated with it. The types of discontinuities are (1) geometric, (2) material, and (3) geometric and material. The previous analyses for interfaces between two or more different media, slabs, coatings, etc. are based on exact solutions to Maxwell's equations. When discontinuities are considered, the mathematical difficulty increases accordingly, and often approximations must be used for determining the field components of the reflected and transmitted waves. One of the simplest geometries is a step in a planar dielectric waveguide where the two regions have the same (or different) dielectric properties. This problem has been analyzed for small steps using the radiated power-loss method (Reference 51), mode-matching (References 52 through 54), perturbation analysis (Reference 55), and a variational approach (Reference 56). For arbitrarily large steps, the Wiener-Hopf technique (References 57 and 58), the Ritz-Galerkin method (Reference 59), an integral formulation (Reference 60), and Laguerre transformation of the wave number (Reference 42) have been used.

There are techniques that are applicable to many different kinds of planar discontinuities. The abruptly ended dielectric slab or two slabs separated by an air gap have been analyzed using singular integral equations (Reference 61). Integral equations can be employed also to find the field scattered by a surface wave from a notch in a ground plane covered by a dielectric slab (Reference 62). Scattering from a heterogeneous discontinuity region of arbitrary cross section is approached via electric field integral equations as well (Reference 63). The moment method is the most common technique for obtaining numerical results from the above integral equation formulations. Occasionally, more exotic methods are employed. For the problem of surface wave diffraction by a truncated dielectric slab recessed in a perfectly conducting surface, a combination of Wiener-Hopf, the generalized scattering matrix technique, and the geometric theory of diffraction was used (Reference 64).

Other types of discontinuities that have not received as much attention include a surface waveguide passing through an interface between two different media (References 65 and 66), a small deformation of a surface waveguide wall, both TE and TM surface wave scattering (References 67 and 68), surface wave scattering by discontinuities on a unidirectionally conducting semi-infinite screen (References 69 through 71), and surface wave scattering by a perfectly conducting strip (References 72 and 73).

## SURFACE WAVES AND CYLINDRICAL GEOMETRIES

The first cylindrical geometry that was found to be capable of supporting a surface wave was an infinitely long cylindrical wire of finite conductivity (References 12, 74, and 75). It should be noted that this surface wave is very loosely bound to the wire just as the Zenneck wave is loosely bound to a finite conducting plane. This mode is a TM wave that is axially symmetric, i.e., no angular dependence. It has a low attenuation in the direction of propagation, but the field extends an appreciable distance radially outside the wire. In order to bind the wave closer to the surface, a thin coating of dielectric material can be added around the wire (References 7, 9, 12, and 75). This structure is the famous Goubau line, and the axially symmetric surface wave generated on it is frequently called the Sommerfeld-Goubau wave. Higher order modes exhibiting angular dependence can exist also on a conducting wire, but they attenuate so quickly with distance from the surface that they can be ignored (Reference 76). In terms of transmission line applications, the Goubau line is much preferred over the finitely conducting wire for its superior guiding properties, especially at lower frequencies.

Attempts to use various dielectric layers on coaxial cables as surface wave transmission lines have received much attention in the literature. It has been found that thin dielectric linings on either or both conductors of coaxial cables can result in reduced attenuation (References 77 and 78). The dominant mode in this type of cable has no lower cutoff frequency and is called a "hybrid TEM-dual surface wave" or sometimes a screened surface wave (References 79 through 81). More complicated variations of the coaxial geometry have been analyzed, including dielectric-coated coaxial cables with an air gap in the shield (References 82 and 83) and effects of lossy dielectrics on the external fields of such a structure (Reference 84).

The dielectric rod waveguide is a guiding structure in which a number of surface wave modes can exist (References 12 and 85). It consists of an infinite circular cylinder of some dielectric constant surrounded by a different medium (usually vacuum). Pure TE and TM modes are possible only if the field components have angular independence. This is also true when the dielectric is anisotropic (Reference 86). Otherwise, modes with angular dependence are classed as hybrid EH or HE modes, depending on whether the  $E_z$  or  $H_z$  field component dominates, respectively (Reference 87). In this structure, the  $HE_{11}$  mode has no cutoff frequency and is the dominant mode. While a number of authors have considered that surface wave modes exist in a dielectric rod, only a few have shown which modes are actually launched under a particular excitation (Reference 88). The case of plane wave incidence on the end of a semi-infinite dielectric cylinder has been considered (References 89 and 90). Also, the launching of an axial

cylindrical surface wave by finite apertures on various surfaces has been considered (References 91 and 92).

An interesting offshoot of the dielectric rod waveguide is the so-called "dipole" mode in guided-wave propagation. This mode occurs as a surface wave on a slightly lossy dielectric rod in free space. It is characterized as a slow wave having azimuthal dependence. In the lowest order, it looks like the field of a radiating dipole in the transverse plane; hence, the name. For the dipole mode to exist, we must have supporting surfaces that have anisotropic impedances. A dipole mode can propagate on a coaxial dielectric cable provided the interface impedances are suitable. It is found also in multiconductor slow wave transmission lines of circular cross section along with the Sommerfeld-Goubau wave and a variety of TEM configurations (Reference 93). What is so fascinating about this mode (and its variations) is that a hollow cylindrical waveguide having a suitable anisotropic wall impedance can support a dipole-type surface wave on its inner side (Reference 94). Equivalently, if two opposite walls are anisotropic in a rectangular hollow waveguide, a dipole-type surface mode can propagate along a guide whose cross-sectional dimensions are too small to support the existence of the usual waveguide modes (Reference 95). This mode is not subject to cutoff.

So far we have considered only homogeneous layers of cylindrical media for the support of surface waves. But it has been suggested that suitable radial dielectric variation in a coaxial cable or dielectric cylinder may lead to reduced surface wave attenuation. The problem of surface waves on radially inhomogeneous cylinders has been approached using a variety of techniques. Millington assumed that both permittivity and permeability were functions of the radial coordinate and used the Riccati equation to analyze the propagation of axially symmetric waves in a coaxial waveguide (Reference 96). He showed that when there is a dielectric layer on or near the outer conductor, there can be a small decrease in attenuation along the guide below the value for the quasi-TEM mode, which occurs with only air in the guide. However, this effect depends on the values of the inner and outer conductor radii and quickly disappears when losses in the dielectric are increased. Utilizing Maxwell's equations directly leads to fourth-order differential equations with variable coefficients; however, for certain radial permittivity variations, numerical results similar to those above are found (Reference 97). When the inhomogeneity is small, perturbation analysis and the radial transmission line formalism can be applied to radial variations in permittivity and permeability (References 98 and 99). As far as we have discovered, no form of inhomogeneity--other than radial--has been analyzed in a cylindrical coordinate system.

Ferrite rods and ferrite-loaded circular cylindrical structures are analogous to the dielectric rod and cylindrical dielectric waveguide. The ferrite is usually polarized longitudinally (Reference 9 and references therein). The problem is more difficult than that of the dielectric, because of the fact that when not on the guide axis, points on the wave fronts of the modes follow a helical path. Thus, in the case of a ferrite, the normal modes are in right- and left-helicity polarized form and travel with different velocities.

Previously, we have mentioned axial surface waves--symmetrical and unsymmetrical--which are supported under proper boundary conditions by a cylindrical surface. Another type of surface wave possible on a cylindrical surface is the azimuthal surface wave (References 7 and 100). This type of wave occurs on corrugated metal or dielectric-clad circular cylinders, both of which provide the conditions for its existence. The surface must be highly reactive and store the energy of a trapped wave. Then leakage occurs as the wave progresses around the surface, i.e., the wave is now attenuated circumferentially, not radially as in the axial case. For large cylinders, the leakage is small and the transmission properties are approximately the same as those of a trapped wave on a flat surface, i.e., a perturbation of the pure Zenneck wave. Also, theoretically, resonant azimuthal surface waves can be found on a cylindrical reactance surface (Reference 101), assuming current flow in the axial direction only. In practice, resonance is difficult to obtain because it depends on a correct choice of surface reactance in relation to the azimuthal mode number and the ratio of the cylinder radius to the wavelength. It should be emphasized that a high dielectric constant is necessary for the surface wave resonance phenomenon to appear.

While the amount of information concerning discontinuities along planar geometries is quite large, information on surface wave scattering by cylindrical discontinuities is rather scarce, no doubt the result of the formidable mathematics involved for rigorous solutions. A few cases have been found. One is the field of an incident TM axial cylindrical surface wave scattered by an abrupt discontinuity in surface reactance (Reference 102). The Wiener-Hopf technique is used to obtain analytical solutions for the transmitted surface wave, the reflected surface wave, and the radiated field. The second case is an extension of the first and assumes a general hybrid surface wave mode incident at a reactance discontinuity (Reference 103). This uses an approximate Wiener-Hopf treatment leading to coupled integral equations. Scattering of screened surface waves on a coaxial waveguide again uses a Wiener-Hopf solution method (Reference 104). Finally, scattering of an axial cylindrical surface wave by a perfectly conducting planar annulus has been analyzed using an integral equation for the current induced on the annulus (Reference 105).

## SURFACE WAVES AND SPHERICAL GEOMETRIES

The literature on the propagation of surface waves on spherical geometries is smaller than that for either planar or cylindrical geometries. Probably this is because the spherical coordinate system does not lend itself to reduction of three-dimensional problems to two dimensions by assuming infinite uniformity along one direction. Primarily, three types of boundaries have been considered: (1) a perfect conductor; (2) a dielectric-coated sphere; and (3) a sphere with an inductive boundary. The problem of a sphere with an inductive boundary excited by a radial electric dipole source was shown to generate a dominant surface wave mode corresponding to the dominant trapped mode for a planar inductive boundary in the appropriate limit (Reference 106). It was shown also that higher order modes exist that have very large attenuation.

A perfectly conducting sphere illuminated by a plane wave has been analyzed in a number of different ways based on its size and the field contribution emphasized. Creeping-wave theory was created to consider the surface fields on the sphere, and various aspects of this theory in comparison with exact Mie theory have been discussed (Reference 107). High-frequency diffraction from spherical perfect conductors usually separates the field components into several surface wave types. These are (1) the edge-diffracted wave, (2) creeping modes on convex surfaces, (3) whispering-gallery modes inside concave surfaces, and (4) waves radiated by the creeping waves (Reference 108). Each of these components is dominant in different regions surrounding the sphere. By using a Poynting vector approach (Reference 109), it has been found that the creeping wave is the dominant contribution to the surface fields.

A dielectric-coated conducting sphere, in analogy with the planar and cylindrical geometries, is capable of guiding a surface wave so that it has relatively small attenuation (Reference 110). Thus, under certain conditions, the creeping-wave component will propagate with little or no attenuation even for objects that are large with respect to a wavelength. It is necessary to understand the physical makeup of such waves, since this is a rather complicated subject. By comparing the dielectric and perfectly conducting spheres, one sees that the surface waves characterizing the two geometries are very different. On perfectly conducting spheres, the diffracted field contribution consists of a surface wave of D-type (Reference 111), which is strongly damped and can often be neglected. On dielectric spheres, the diffracted field is composed of both D- and E-type surface waves. E-type surface waves are associated with total internal reflection at certain critical angles and are usually weakly damped. They are unique to dielectric spheres and can be further divided into electric and magnetic surface waves. The number of these waves increases as the

sphere radius increases. If the coating is assumed to have some loss, we see that as this loss increases (thereby lengthening the propagation path of the creeping waves), the diffracted field component becomes more strongly attenuated (Reference 112).

Resonances in the scattering cross sections of dielectric-coated conducting spheres have been attributed to families of circumferential surface or creeping waves that are generated during the scattering process (Reference 113). At each eigenfrequency of the sphere, one of these surface waves matches phases after repeated circumnavigations around the sphere leading to scattering resonances (Reference 114). The finite width of these resonances arises from the attenuation of the surface waves. However, an alternative explanation also has been advanced. It has been suggested that the scattering resonances are caused by the interference between surface waves that are refracted in and out of the dielectric layer different numbers of times (Reference 115). The localization principle has been used as one justification for the truth of this theory, but it has been shown to be an unwarranted use of this principle (Reference 115).

#### SURFACE WAVES AND OTHER SEPARABLE GEOMETRIES

Mention should be made of other guiding structures that can be analyzed using separation of variables. Mainly, these consist of wedges, cones, and elliptical cross-section objects. The diffraction of surface waves by a right-angled wedge has been discussed by several authors (References 116 and 117). One face of this wedge is perfectly conducting, the other reactive (Reference 118). It was found that the wedge angle affects the loosely bound surface wave very little unless the angle is close to or greater than 180 degrees (References 118 and 119). General analysis of a dielectric wedge excited by a line current has been accomplished using a plane-wave spectrum solution (Reference 120), and this has been compared with the local mode solution of a tapered dielectric slab waveguide (Reference 51). It was found that the plane-wave solution is good at high frequencies and near cutoff regions where strong radiation occurs. It shows how lateral waves contribute, not only to the surface field but also to the radiation field from the wedge (Reference 121).

When the boundary of a conical shape becomes inductive, surface-wave modes arise based on the complex eigenvalues of the characteristic equation (Reference 122). For dielectric cones, it has been observed that diffracted fields show deep minima near the object (References 29 and 30). This is interpreted as interference between a plane wave and a surface guided wave; it is supported by the fact that the depth of the minima decreases rapidly with distance away from the object.

Finally, some work has been done on elliptical dielectric waveguides. For an infinite elliptical cylinder embedded in a surrounding different medium, it was found that all possible modes must be hybrid (Reference 123) because of the boundary conditions. For a conducting elliptical cylinder with either a dielectric coating or loaded with a dielectric elliptical rod, a similar result was found (Reference 124). Also, surface wave transmission with very low attenuation is possible for a dielectric elliptical rod waveguide with a metallic shield. This structure is good for guiding screened surface waves (Reference 125).

### SURFACE WAVES AND ARBITRARY CURVATURE

Under the appropriate conditions, surfaces with arbitrary curvature can support surface waves. The curved dielectric slab, the curved dielectric rod or fiber, and other convex open structures have electromagnetic fields characterized by contributions from surface waves (Reference 126 and references therein).

The majority of curvature effects on surface waves are determined by using perturbation analysis of the analogous straight geometry. Usually, however, there are both quantitative and qualitative differences. For instance, one of the important differences between straight and curved dielectric slabs is that the finite curvature of the curved geometry causes attenuation of the surface wave in the direction of propagation. The attenuation is a direct consequence of the continuous radiation occurring beyond the caustic. In the flat dielectric slab, the field distribution and the phase velocity of the surface wave remain basically unchanged.

For open waveguides, the natural modes of a straight guide consist of a finite number of surface wave modes and a continuum of radiation modes, both propagating and evanescent. But curved open structures can be very different in terms of the character of their natural modes (Reference 127). For a curved convex reactive surface, it is necessary to resort to 'creeping wave modes' (Reference 126), which represent an infinite set of poles that converge slowly, or radiation 'quasi-modes' that are continuous but correct asymptotically.

Finally, we should mention the problem of surface wave scattering from curvature discontinuities (References 126 through 128). The quasi-mode representation mentioned above is applicable to this type of problem. It has been used for mode-matching analysis of a discontinuity in curvature on a reactive surface and has the possibility of application to other similar problems.



## DIELECTRICS WITH UNUSUAL PROPERTIES

A few examples of surface waves generated in unusual ways will be considered. A topic that has been of interest recently is that of surface waves on the boundary of a dielectric with nonlinear properties. It has been found that a TM-surface electromagnetic wave will propagate on the interface of a dielectric whose permittivity depends on the square of the electric field strength (Reference 129). For other types of nonlinearities, both TE and TM surface waves can exist on the interface.

If a dielectric slab or fiber (two configurations that we have already mentioned) is surrounded by a medium that has gain associated with it, the bound modes of the dielectric structure are amplified rather than attenuated. This amplification arises from the evanescent-wave interaction with the surrounding medium (Reference 130).

Analysis of an axially magnetized planar YIG substrate indicates the existence of a new type of surface wave called a dielectrically induced surface mode (Reference 131). It was found that the dispersion relation consists of two branches; they represent two different surface waves that are unidirectional and contrapropagating. One wave is a modified magnetostatic wave, while the other is the dielectrically induced wave.

It is possible to generate nonlinear surface waves in planar waveguide structures (Reference 132). Such structures consist of interspersed layers of dielectrics and semiconductors, which are finite in the direction of propagation.

## CONCLUSIONS

The reader should be aware of the fact that in the last ten years electromagnetic surface excitations at optical frequencies have more or less dominated the literature (Reference 133). Surface plasmons (References 35 and 134 through 137), surface polaritons (References 138 through 142), surface phonons (Reference 135), etc. make up a vast optical literature, which is theoretically very different from the surface waves we have considered. We have merely included some references because the mathematical analysis of these problems or their experimental setups can sometimes be applied to lower frequency surface waves.

We have attempted to give a fairly complete survey of electromagnetic surface waves supported by various types of interfaces on structures with relatively simple geometries. It has been assumed that these structures operate somewhere between the S- and Ka-band frequency regimes. We have emphasized planar, cylindrical, and spherical geometries, although shapes with arbitrary curvature have been discussed also. Many variants of the above geometries have been mentioned as well as the mathematical techniques used to analyze such objects.

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