THE TRANSITION REGION BETWEEN BOUND-WAVE AND LEAKY-WAVE RANGES FOR A PARTIALLY DIELECTRIC-LOADED OPEN GUIDING STRUCTURE

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Abstract

Most modes on partially dielectric-loaded open guiding structures are purely bound in some frequency range and leaky in another. The transition region between them is complicated and interesting, including a section where the dispersion curve doubles back, because it connects a complex nonspectral (leaky-wave) solution with a real spectral (bound-wave or surface-wave) solution. The physical nature of this type of transition region is discussed in the context of a recently proposed novel leaky-wave antenna structure, and some anomalous features are described.

I. INTRODUCTION

Most modes on open structures that are partially dielectric-loaded are completely bound in some frequency range and leaky in some other frequency range. The transition region between the bound and leaky ranges turns out to be rather complicated and interesting, with two solutions in each range, only one of which is physical, and with a small portion in which the dispersion curve doubles back. The reason for the complicated behavior is that the transition region connects a purely real (bound) spectral, or proper, solution with a complex (leaky) nonspectral, or improper, solution. This paper presents the detailed behavior for this type of transition region for a specific leaky-wave structure that has been proposed as a novel type of millimeter-wave antenna [1], but the qualitative behavior is typical of that for a large class of open structures.

It has been known for many years that for modes on dielectric layers the transition between surface-wave solutions (which are real and spectral) and leaky-wave solutions (which are complex and nonspectral) includes a region in which the wavenumber values double back and the solution itself is nonphysical. Numerical values had been obtained for some simple cases, but the transition region was not carefully examined and understood. A second structure that was examined many years ago [2] is an idealized open periodic structure comprised of a sinusoidally modulated reactance surface with a half space above it. Complicated transition behavior was indeed found, but no interpretations were attempted.

Some very recent investigations, in addition to the one discussed here, also show qualitatively similar behavior at these transition regions. One example involves a pair of dielectric layers on a ground plane, where the layers are in a "high-gain" relationship. It has been shown that the high gain that results due to dipole (or microstrip patch) excitation can be explained in terms of a leaky wave excited on the layers that has a low attenuation rate [3]. When the frequency is raised, this leaky wave turns into a surface wave, and the transition between them exhibits behavior of this type [4]. Other examples are furnished by printed-circuit waveguides, where leakage in the dominant mode occurs above a critical frequency; transitions of this type have been noted for microstrip line on a suitable anisotropic substrate [5,6], and for slot lines and coplanar waveguides of finite or infinite width [7].

The most complete and accurate examination so far of this type of transition region has been made for the millimeter-wave antenna structure discussed here, which is shown in cross section in Fig. 1. As will be explained in the next section, the dominant mode is leaky for lower frequencies, corresponding to the antenna range of operation, whereas for higher frequencies the mode is purely bound. The transition between these ranges of operation occurs when $\beta/k_0 = 1$, where k_0 is the free-space wavenumber and β is the mode's phase constant in the longitudinal (z) direction. This simple condition, which in fact occurs in many physical problems, also makes it easier to identify the

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critical points in the dispersion plot within the transition region.

The structure and its operation as a leaky-wave antenna are described briefly below, where it is also made clear why the transition occurs at $\beta/k_o = 1$. The dispersion curve over a wide frequency range is then presented, on which two solutions appear in the bound-wave range; it is then explained which one should be rejected. The transition region between the bound and leaky ranges is then shown on an enlarged scale, where the complicated nature of the curve becomes apparent. The various spectral and nonspectral portions of the dispersion curve are then identified and discussed. Numerical results for the dispersion curve and for the transverse wavenumber complex plane will be presented during the talk.

What is interesting and puzzling is that, even for the correct solution to be chosen, the result is real but nonspectral (and therefore nonphysical) in a small frequency range. Physical arguments will be presented during the talk to clarify why the specific portions of the transition region must behave as they do, in an attempt to explain this initially anomalous result.

II. PRINCIPLE OF OPERATION OF THE ANTENNA STRUCTURE

As indicated above, the millimeter-wave antenna structure discussed here is shown in cross section in Fig. 1. Actually, the full antenna [1] is an array of these leaky-wave line sources that can scan in two dimensions; what is shown in Fig. 1 is a unit cell of the array when the phasing is such that the radiation in the cross plane is at broadside, and the unit cell walls become electric walls, or metal planes.

The structure in Fig. 1 may be viewed as a dielectric-filled rectangular waveguide with an asymmetric slit in its top wall, and with an air-filled parallel-plate stub guide above. In its operation as a leaky-wave antenna, the rectangular waveguide is fed in the TE_{10} mode, with the electric field vertical. The slit in the top wall is then excited by the vertical electric field, and the air-filled stub guide, viewed in the y direction, is in turn excited in its TM_1 (first higher) mode and, because of the asymmetry, in its TEM (dominant) mode as well. The spacing $\underline{a}$ is chosen so that the lower dielectric-filled region is above cutoff, but the air-filled stub region is below cutoff for the TM_1 mode. The TEM mode is always above cutoff, however, and the power excited in that mode propagates away from the air-dielectric boundary at an angle in the parallel-plate region.

Since power is leaking away in the parallel-plate region in the form of a TEM mode at an angle, the mode propagating axially (in the z direction) becomes a leaky mode. As the frequency is raised, however, more and more of the field is pulled into the dielectric region, causing the value of β/k_o to increase. At a sufficiently high frequency, β/k_o exceeds unity, the leakage ceases, and the mode becomes purely bound. The critical frequency is the one for which $\beta/k_o = 1$ because the mode that propagates at an angle in the parallel-plate guide is a TEM mode.

Thus, the transition region between the leaky-wave solution and the bound-wave solution occurs when the dispersion curve crosses the $\beta/k_o = 1$ line. The dispersion curve over a very wide frequency range is shown in Fig. 2, where β/k_o is plotted vs. frequency for a typical antenna set of dimensions. When numerical values are sought for β/k_o, two solutions are found in the bound-mode range where the longitudinal propagation wavenumber, $k_z = \beta - j\alpha$, is purely real. (Actually, two solutions are also obtained when k_z is complex, but the a values for the second set are negative, representing a growing wave, so that this second solution is rejected immediately as nonphysical because the structure is passive.) To determine which solution in the real range is the correct one, one must examine the behavior of the transverse wavenumber; one keeps the solution for which the field decays transversely at infinity (the spectral solution) and rejects as unphysical the one for which the field increases transversely to infinity (nonspectral). The solution to keep is the lower of the two in Fig. 2.

III. THE TRANSITION REGION

The transition region occurs over a small frequency range, and it therefore cannot be seen in Fig. 2. It is necessary to employ a greatly enlarged scale, on which the dispersion plot is sketched qualitatively in Fig. 3. The transition region itself is divided into two distinct frequency ranges, one from point A to point B and the second from point B to point C. Below point A in frequency we have the leaky-wave range, in which the solution is complex and nonspectral, characteristic of all forward leaky waves. Above point C in frequency, on the solid curve, the solution is purely real and spectral, characteristic of all surface waves or bound waves.

We next examine the first of the two ranges within the transition region, namely, the one from A to B. Within this range the solutions are found to be complex and nonspectral. Transverse wavenumber β_y is positive, indicating a component of outgoing power leakage in the vertical direction (in Fig. 1), but it is much smaller than β, so that the leakage direction is primarily near endfire, and in fact approaches endfire as the curve approaches point B. Leakage constant α is small, indicating little leakage per unit length, and it gets smaller as point B is approached; α_y is negative, representing an increase transversely, still characteristic of nonspectral leaky waves. The region from A to B thus represents a winding down of the leaky-wave solution.

For frequencies slightly greater than that for point B two solutions are possible, both of which are real and nonspectral; that is, they represent surface waves with fields that increase to infinity transversely, and are therefore nonphysical. The solution represented in Fig. 3 by the dashed curve continues forever to be nonspectral; the one with a solid line changes into a spectral solution after point C, and it is therefore the one we choose to keep.

In the second range, from point B to point C, α_y approaches zero as one goes nearer to point C. At point C itself, $\beta/k_o = 1$ but $\alpha = \alpha_y = \beta_y = 0$, so that C is a transition point at which the power density has thinned out to zero. For frequencies greater than that for point C, α_y becomes positive, representing a transversely decaying wave, and therefore a real spectral solution; furthermore, as the frequency increases further, the wave becomes more tightly bound. The range from B to C thus permits the character of the mode to change from nonspectral to spectral.

The discussion above has been qualitative in nature. During the talk, accurate numerical curves will be presented for the behavior of the transition region for the antenna structure shown in Fig. 1, both for β/k_o as a function of frequency and for the variation of the transverse wavenumber values in the complex plane.

ACKNOWLEDGMENT

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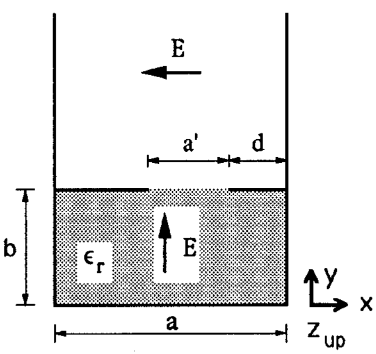

Fig. 1 Cross section of the partially dielectric-loaded millimeter-wave antenna.

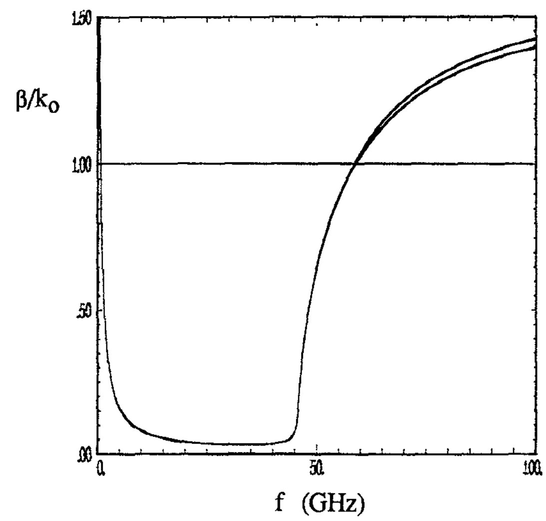

Fig. 2 Dispersion plot (β/k_o vs. f) over a very wide frequency range for the structure shown in Fig. 1 when a = 2.20 mm, a' = 1.00 mm, b = 1.59 mm, d = 0.10 mm and ε_r = 2.56. The guided wave in the z direction is purely bound when $\beta/k_o > 1$ (slow wave); the upper of the two solutions shown is nonphysical for reasons discussed in the text.

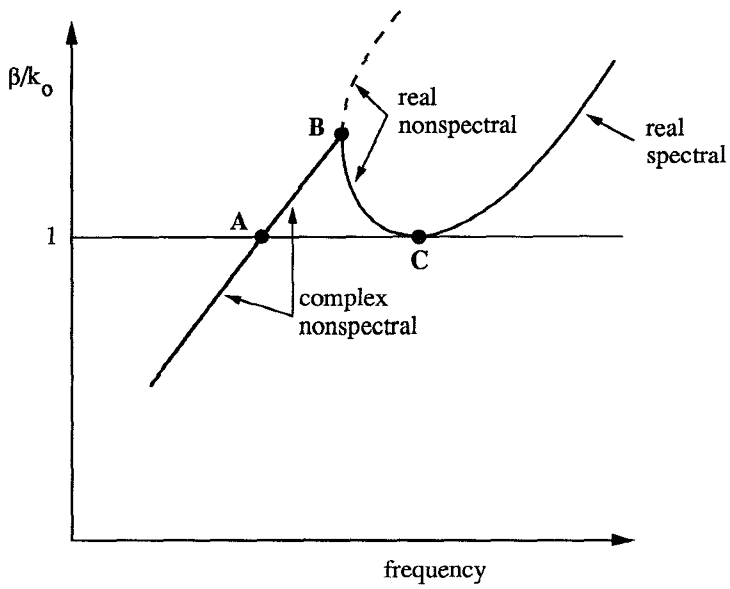

Fig. 3 The transition region around $\beta/k_o = 1$ plotted on a greatly enlarged scale. This region connects the complex nonspectral (leaky-wave) solution at lower frequencies with the real spectral (bound-wave) solution at higher frequencies. The various regions are identified and the key points A, B and C are discussed in the text. The dashed curve is the solution that is rejected.