ACCURATE COMPUTATION OF MODE CHARACTERISTICS FOR OPEN-LAYERED CIRCULAR CYLINDRICAL MICROSTRIP AND SLOT LINES

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KEY TERMS

Microstrip, slot line, circular cylinder, layered substrate, dispersion

ABSTRACT

The results of a highly effective numerical analysis of fundamental and higher-order modes on open circular cylindrical microstrip and slot lines filled with layered dielectric are presented. The results could be used to optimize the bandwidth and mode-purity characteristics of the lines.

1. INTRODUCTION

Nonplanar microstrip and slot lines are interesting due to their potential antenna and transmission line applications. Analyses of circular and elliptic homogeneously filled striplines have been presented in [1, 2], based on the solution of Laplace or Poisson equations. These solutions imply the TEM-wave assumption, and do not cover higher-order modes of the line. A similar approach has been taken in [3] to the analogous strip lines filled with layered dielectric, within the quasi-TEM-wave approximation. The analysis given is valid, naturally, for operating frequencies much below the cutoff frequency of any higher-order modes. Besides, all these papers treated strip lines with relatively narrow strips. As for the dynamic solution, the approach based on the Green's function for the circular dielectric layer wrapped around the co-axial metal cylinder has been applied to single and coupled microstrip lines in [4, 5], but the strips were assumed to be extremely narrow.

The alternative approach is based on a rigorous analytical treatment using the Riemann-Hilbert problem technique, which imposes no restrictions on the angular widths of the strips and the radius/wavelength relation. TEM waves on the lines considered were treated using this method in [6]. A full-wave dynamic analysis method for open microstrip and slot lines on a circular dielectric core has been proposed in [7], and some of the numerical results have been reported in [8, 9]. Here we extend the same approach to the lines with layered dielectrics and give some physical results on dispersion and the layer-thickness-dependence of mode wave numbers. It is shown that by introducing additional layers of dielectric, it is possible to improve the bandwidth and mode-purity characteristics of the lines.

2. GENERAL REMARKS ON THE FORMULATION OF THE PROBLEM

The cross-sectional geometry of the transmission lines under investigation is presented in Figure 1. A perfect microstrip or slot line conductor of zero-thickness and arbitrary angular width is placed on the surface of the two-layered dielectric rod, with or without the protective outer coaxial layer.

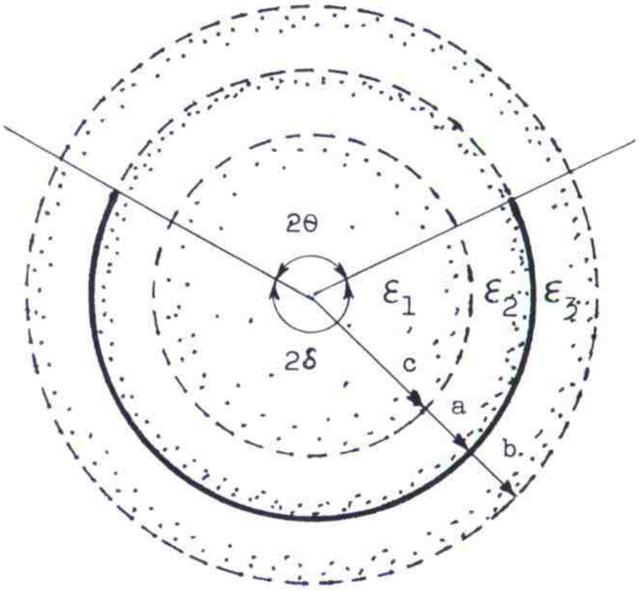

Figure 1 Cross-sectional geometry of the open waveguide under consideration. It is a microstrip line if $\theta > \delta$, and a slot line if $\delta > \theta$

Formulation of the spectral mode problem is analogous to the one treated in [7–9] for the partially screened homogeneous core with the imposition of boundary conditions on the additional dielectric boundaries. The mode field is sought as an exponential function of the longitudinal coordinate z and the time $\sim\exp(ihz-i\omega t)$. Cross-sectional field functions are assumed to satisfy the 2D Helmholtz equation inside and outside the guide, with the coefficients $g_j^2 = k^2\varepsilon_j - h^2$ ($j = 1, 2, 3$) and $g^2 = k^2 - h^2$, respectively. There are two dual-type sets of boundary conditions on the "main" boundary of $r = a$, valid on the strip and on the slot, plus conventional continuity conditions on the boundaries of $r = b$ and $r = c$. Owing to the sharp edges of the strip, a cross-sectional local energy limitation is added. Finally, the fields outside the guide are assumed to be expandable into an angular Fourier series with dependence on the radial coordinate in the form of a Hankel function $H_n^{(1)}(gr)$, where $n = 0, 1, \ldots$. The spectral parameter h is considered to be complex valued, thus enabling one to treat not only surface but leaky and other "improper" modes as well. Real and imaginary parts of h correspond to the phase and the leakage constants of propagation, respectively.

3. DERIVATION OF THE BASIC EQUATIONS

The initial problem is discretized by expanding the fields in angular series inside each of the layers over the complete set of functions $\exp(in\varphi)$, $n = 0, \pm1, \pm2, \ldots$. Using boundary conditions to exclude some of the functions, we obtain the dual-series equations for expansion coefficients of the field inside any two layers in contact with the main boundary. These equations are of the same type as for a homogeneous, partially screened dielectric rod [7]. Further treatment exploits essentially the technique of the so-called "Riemann-Hilbert problem," which is equivalent to the inversion of the static part of the dual-series equations operator. This procedure takes the edge condition explicitly into account and results in an infinite system of linear algebraic equations, which is shown to be of Fredholm second type. Thus the characteristic values of the parameter h of the infinite matrix (coinciding with the spectral values of the initial problem) may be approximated by similar values of the truncated matrix. The higher the order of truncation, the higher the accuracy of the approximation. A simple numerical rule has been verified: To obtain an accuracy within 0.1% it is necessary to take $N_{\rm red}$ = entire part of [max($g_{1,2}b$, $g_{2,3}a$, g_3c, gc)] + 5. At this point, the approach considered is much more effective and reliable than any Galerkin or finite-element method modification, because convergence is guaranteed automatically.

4. OVERVIEW OF MODE BEHAVIOR

Relative to the cross-sectional plane of symmetry, all the modes of the lines under consideration are separated into two orthogonal families characterized by the even/odd dependence of the components. In [7–9] they were denoted as E_z^+/H_z^- and H_z^+/E_z^-. There are modes within each of these families that may be considered to be of the circular nonscreened rod (or of the circular conducting-wall waveguide) type perturbed by the strip (or the slot, respectively). For these modes, it seems reasonable to keep the classification adopted for relatively unperturbed guides, complete with the term "quasi" indicating the perturbation, and thus the symmetry family.

Besides, there exists one extra mode in each of these families which is of singular nature, as one of them exists for any narrow strip but does not exist if the strip is absent, while the other has the same behavior as the slot is narrowed. The former is denoted as a "strip mode" or quasi-TM$_{00}$ mode, while the latter is a "slot mode" or quasi-TE$_{00}$ mode. If the strip (or slot) is narrow, the corresponding mode dominates, having a much greater phase constant than all the other modes of the open guide. However, there is an important difference between the strip mode and the slot mode, as regards their dispersive behavior. If the frequency of operation is decreased, the strip mode shows no cutoff, while the slot mode has an extremely low but finite cutoff frequency [$\sim a^{-1}\theta(\ln^{-1}\theta)$]. Thus, the former is one (but not the only one) of the principal or fundamental modes of this open guide, while the latter is not. Thorough investigation leads to the conclusion that, in all, there are three principal modes in the guide considered, for any angular width of the strip or the slot.

Figures 2 and 3 show the dispersion of modes on the circular cylindrical lines with homogeneous filling. For all the higher-order modes (including the slot mode), strong leakage is observed below the cutoff frequency. Besides, one can see the effect of parametric "coupling" between the slot and/or the principal modes and the higher-order ones.

5. NUMERICAL RESULTS FOR LAYERED TRANSMISSION LINES

In order to clarify the effects of the inner filling or outer cladding, the dispersion curves of the modes on three kinds of slot lines have been calculated. Besides the conventional homogeneous one, the line with an outer protective layer having a higher value of ε, and the line on the outer surface of a dielectric tube have been considered, as shown in Figure 4. In Figure 5, the corresponding values of phase constants versus *ka* are shown by solid and dash-dotted curves. The data for the slot and the next higher-order quasi-TE$_{11}^+$ mode are presented. In addition, the dispersion curve of the Goubau-line dominant mode (quasi-TM^G) is given. For the latter mode, the perturbation by the narrow slot is negligibly small, being of the zeroth order of exp($-1/\theta$). Although the slot mode dominates within the whole range considered, at higher frequencies both the Goubau-line mode and the next higher-order mode become competitive. Besides the general rise of the phase constant, the effect of the outer layer is seen in smoothing the dispersion, which may be useful for wide-band signal transmission. As for the slot line on a dielectric tube, one can conclude that making a hole inside the core has no

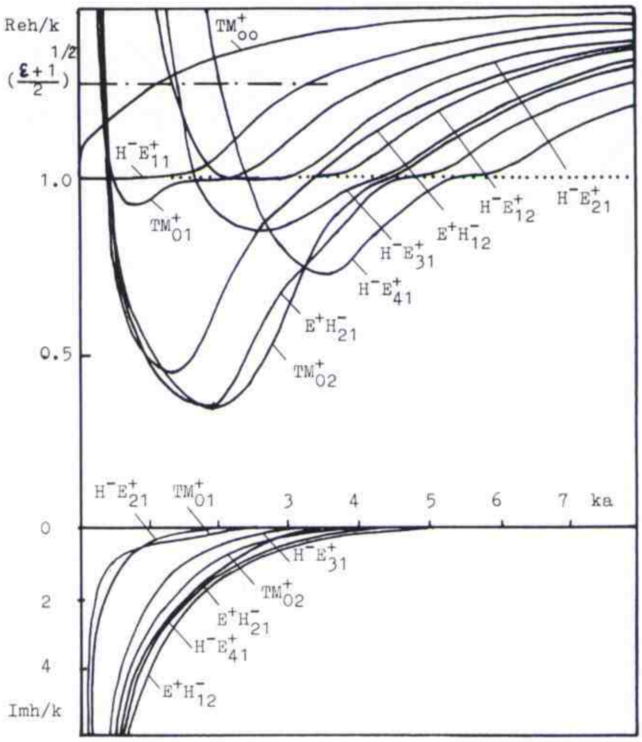

Figure 2 Dispersion curves for E_z^-/H_z^+ modes on a homogeneous microstrip line with $\delta = 20°$, $\varepsilon = 2.25$

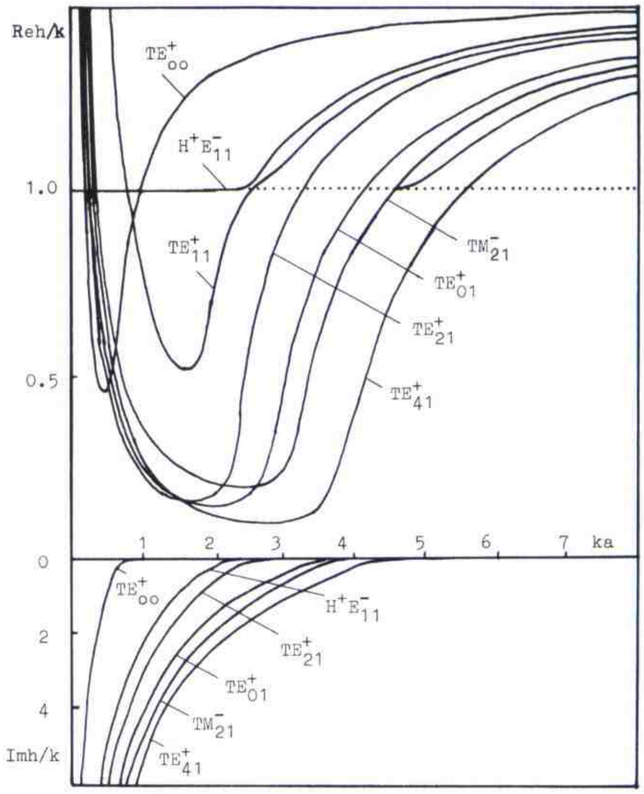

Figure 3 Dispersion curves for E_z^+/H_z^- modes on a homogeneous slot line with $\theta = 70°$, $\varepsilon = 2.25$

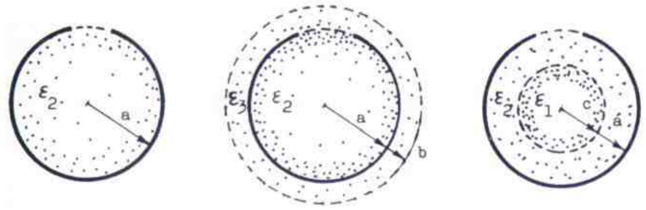

Figure 4 Circular cylindrical lines of (a) conventional type, (b) with an outer protective layer, and (c) with a layered inner filling

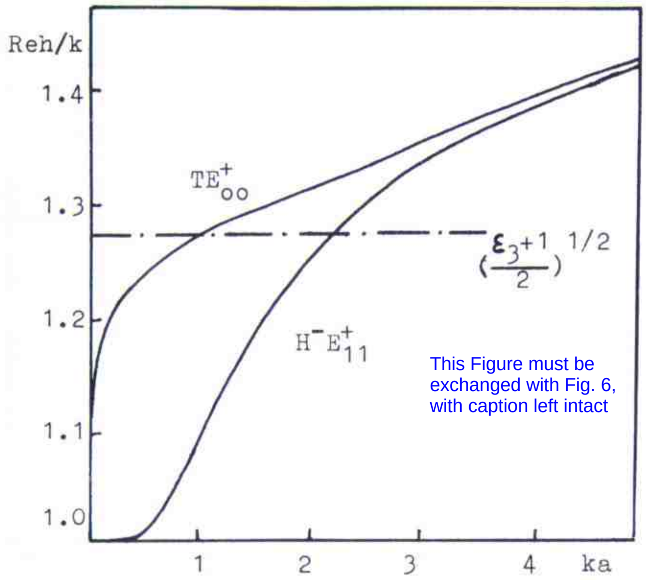

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Figure 5 On the comparison of E_z^-/H_z^+ mode dispersion for a protected (solid curve, $a/b = 0.9$, $\varepsilon_3 = 4$), inhomogeneously filled (dash-dotted curve, $c/a = 0.9$, $\varepsilon_1 = 1$), and conventional slot lines with $\theta = 1°$, $\varepsilon_2 = 2.25$

practical effect on the slot mode, but raises the cutoff frequency of the quasi-TE$_{11}^+$ mode, thus providing a much wider range of quasi-single-mode operation.

Figure 6 presents the dispersion curves of two principal modes (the strip mode and the quasi-H$^-$E$_{11}^+$ mode) on the microstrip line with the strip attached to the inner surface of the same dielectric tube. This line resembles, to some extent, the well-known Goubau line, but it may be expected to be somewhat less lossy because of the air gap near the conductor.

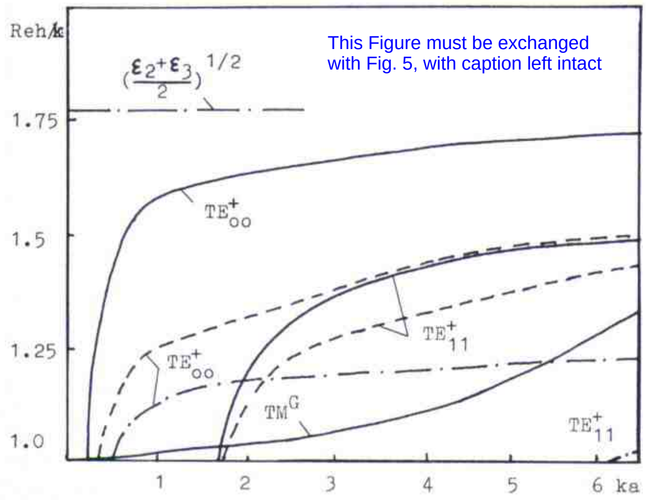

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Figure 6 Dispersion of two fundamental E_z^+/H_z^- modes on a microstrip line inside a dielectric tube with $\delta = 1°$, $a/b = 0.5$, $\varepsilon_2 = 2.25$

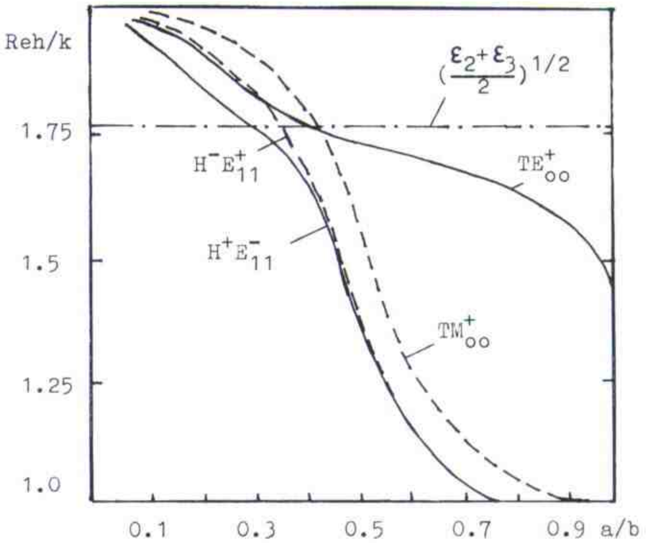

Figure 7 Wave numbers versus relative thickness of the outer protective layer for fundamental modes plus slot mode on a slot line with $\theta = 1°$, $ka = 1$, $\varepsilon_2 = 2.25$, $\varepsilon_3 = 4$

Figure 7 shows the dependence of wave numbers on the relative thickness a/b for the slot line. All three principal modes and the slot mode are shown, and it can be seen that the thinner the cladding the smaller the phase constants. Note that the thickness dependence of the slot mode wave number is smaller than that of the principal modes because of the field concentration in the vicinity of the slot. If the cladding is electrically denser than the core, as in Figure 7, and thick enough, then all the modes become highly competitive, because they propagate mostly in the cladding but not in the core.

6. CONCLUSIONS

The very reliable and effective analysis as proposed in [7–9] and based on dual-series equations by means of the Riemenn-Hilbert problem technique, has been applied to open-layered circular cylindrical microstrip and slot lines. It has been shown that by using additional inner or outer dielectric layers, one can modify the line's characteristics, such as dispersion, quasi-single-mode propagation bandwidth, etc.

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REDUCTION OF THE RCS OF THE LEADING EDGE OF A CONDUCTING WING-SHAPED STRUCTURE BY MEANS OF LOSSLESS DIELECTRIC MATERIAL

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KEY TERMS

Radar cross section, backscatter, composite structures

ABSTRACT

The radar cross section of the leading edge of a conducting wing-shaped structure is reduced by replacing part of the structure with a lossless dielectric material. The structure retains its original external shape, thereby ensuring that the aerodynamic properties are not altered by the structural changes needed to reduce the radar cross section.

I. INTRODUCTION

The radar cross section (RCS) of the leading edge of a perfectly conducting, wing-shaped structure, shown in Figure 1(a), can be reduced by making use of a combination of absorbing material, resistive cards, and lossy multilayer coatings [1]. These materials, especially coatings, are in general rather expensive and can increase the weight of the structure to unacceptable levels. A significant reduction in the leading-edge RCS can alternatively be obtained by replacing part of the conducting structure by a lossless (or low-loss) dielectric with a relatively low dielectric constant, as shown in Figure 1(b). The dielectric is virtually transparent to electromagnetic radiation so that the RCS of the leading edge is determined mainly by the shape of the conducting part of the structure. Most of the mechanical properties of the new structure, in particular the aerodynamic properties, are virtually unchanged from the original structure. The RCS of the leading edge can be reduced to more or less the same level as that of the trailing edge of the structure.

II. ANALYSIS TECHNIQUES

In order to verify the hypothesis, the radar width of a two-dimensional wing-shaped structure was computed by means of the uniform geometrical theory of diffraction (UTD) [2] and the moment method (MM) technique [3]. The rounded part of the wing-shaped structure is described by an ellipse, which is smoothly attached to a wedge with straight edges. The scattering centers taken into account in the GTD calculations [4] are shown in Figure 1(c). The scattering mechanisms associated with these scattering centers are diffraction from the wedge tip Q, diffraction from the smooth junction at $P(S)$, diffraction from the conductor/dielectric junction at $U(V)$, a ray transmitted at the air/dielectric interface, reflected internally on $\overline{UT}$ and transmitted back again, reflection from the rounded part of the structure, and a ray transmitted through the air/dielectric interface, diffracted at T and transmitted back again, respectively.

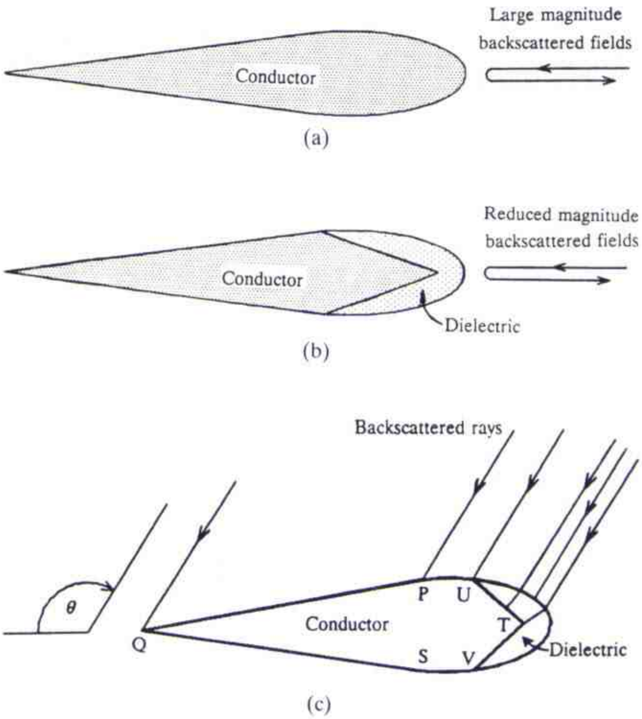

Figure 1 Geometries of conducting and composite wing-shaped structures. (a) Cross section of a conducting structure with large magnitude backscattered fields. (b) Cross section of a composite structure with reduced magnitude backscattered fields. (c) Scattering mechanisms for the UTD calculations.

III. RESULTS

The calculated radar width of a structure with a length of 20 wavelengths from the trailing to the leading edge, a height of 5 wavelengths, and a dielectric with relative dielectric constant ε_r equal to 2 is shown in Figure 2. The tip of the internal wedge (T) was placed very close to the rounded leading edge in order to minimize the magnitude of the fields diffracted from this point. The radar width patterns of the original conducting structure, the conducting part of the new structure, and the composite new structure are compared in Figure 3. It is evident that the proposed modification of the leading edge can reduce the RCS of the original structure by typically more than 10 dB in the direction $\theta = 180°$. In conclusion, the use of lossless dielectric material instead of electromagnetic absorbing material offers a less-expensive and less-involved means of reducing the leading-edge RCS of a wing-shaped conducting structure.