PACKAGED PRINTED TRANSMISSION LINES: MODAL PHENOMENA AND RELATION TO LEAKAGE

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Abstract - The dispersion curves of the modes on shielded printed transmission lines often interact with the dispersion curves of box (package) guided modes in a classical coupled-mode manner. It is shown here that this effect is related directly to the phenomenon of leakage. We show that the dominant mode associated with a shielded printed transmission line can interact with box guided modes in a coupled-mode manner <u>only if</u> the corresponding dominant mode is <u>leaky</u> when the same transmission line is placed on a substrate of infinite transverse extent. Furthermore, we demonstrate that the modes of a shielded transmission line may support fields that are "leaky" in the sense that they are not confined to the designed guiding region (strip or slot), even though all the modes of the structure have either purely real or imaginary propagation wavenumbers. Numerical and experimental results are presented to show the effects of these phenomena.

I. INTRODUCTION

At first glance, the analysis of leaky waves on printed transmission lines may appear purely academic since, in all cases, it is assumed that the transmission line is fabricated on a substrate of infinite transverse extent into which the surface waves can leak. In this work we show that the study of <u>leaky waves</u> on substrates of <u>infinite</u> transverse extent has important application for the interpretation and prediction of modal phenomena on realistic, <u>packaged</u> transmission lines. Moreover, we show that although a true leaky wave, with a complex propagation wavenumber, cannot exist for realistic transmission on a substrate of finite size, modal effects on such structures such as mode coupling are often best interpreted and predicted in the context of leaky-wave theory.

We choose microstrip line on an anisotropic substrate placed within a rectangular waveguide as a specific example of a shielded printed transmission line; its cross section is shown in Fig. 1. The reasons for this selection are that calculations have been made previously [1] for the guided modes on that shielded transmission line that exhibit interesting mode-coupling behavior, and that the dominant mode on that line when placed on a substrate of infinite lateral extent has been shown to become leaky above some critical frequency [2]. Furthermore, most packages are rectangular in shape, so that our choice provides practicality as well as simplicity.

The mode-coupling behavior found in [1] was recognized to consist of interactions between the guided modes of the partially dielectric-filled rectangular waveguide (the box), but the role of leakage was not understood at that time. Here, we explain clearly why the mode coupling occurs in the manner found earlier and why such coupling effects are possible <u>only</u> when the dominant transmission-line mode would be leaky if the substrate were of infinite lateral extent. The discussion is phrased in general terms because these effects can occur in many other packaged printed circuits, and the explanation presented here applies to all such cases.

<u>Measurements</u> have also been taken to indicate some practical consequences of these mode-coupling effects. The structure under measurement had the same cross-section dimensions as the one for which the calculations were made previously [1], to afford direct correlation with the theory. Measurements of $|S_{21}|$ were made with two different substrates, one <u>anisotropic</u>, with dielectric constant values identical to those in the calculations, and the other <u>isotropic</u>, with a dielectric constant value close to the average of those for the anisotropic case. The reason for choosing the two substrates is that, if the substrate is transversely infinite, the dominant mode can leak when the substrate is anisotropic, but not when it is isotropic [2]. Therefore, mode-coupling effects occur for the anisotropic substrate but not for the isotropic one. The section on theory explains why this is so, and the measurements demonstrate that, for frequencies in the neighborhood of a mode-coupling point, the $|S_{21}|$ values are affected strongly for the anisotropic case but not at all for the isotropic case.

The remainder of this summary is organized as follows. In Sec. II we discuss in general terms the mode coupling between planar transmission lines and box modes, and stress that this effect can occur <u>only if</u> the corresponding mode, on a substrate of infinite extent, is <u>leaky</u>. Experimental results are presented in Sec. III for shielded

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microstrip line on a uniaxial anisotropic and on a similar isotropic one. Conclusions are addressed in Sec. IV.

II. ANALYSIS

For simplicity, we restrict ourselves here to the discussion of shielded printed transmission lines placed in a rectangular waveguide, although we will also consider more-general transverse truncations in the talk.

In shielded transmission lines, classical coupled-mode-like interaction has been calculated previously [1,3,4] between the dispersion curve of the transmission-line dominant mode and those of the box (package) modes. In classical coupled-mode theory [5], one first identifies the (unperturbed) modes associated with two independent guiding structures. The two guiding structures are combined in some fashion and the new (perturbed) modes of the composite structure are described and represented in terms of the unperturbed modes of the original isolated guides. Regions of classical mode coupling in the perturbed modes occur at and near frequencies at which the dispersion curves of the unperturbed modes cross. In the case of a printed transmission line shielded in a rectangular waveguide, the composite structure is the printed transmission line in the presence of the box. The unperturbed modes are those associated with the box in the absence of the strip(s) (box modes) and the dominant mode of the printed transmission line on a substrate of infinite width (no transverse truncation). The perturbed modes are the box modes in the presence of the strip(s) and the transmission-line dominant mode in the presence of the box. The unperturbed transmission-line mode can be leaky and therefore could have a complex propagation wavenumber. However, the imaginary part α of the propagation wavenumber of a leaky transmission-line mode is usually two or so orders of magnitude smaller than its real counterpart β (see references in [3]), and we would therefore expect classical mode coupling in the neighborhood where the real part of the transmission-line mode's propagation wavenumber equals the propagation wavenumber of an unperturbed box mode (always real when propagating).

It is well known that the unperturbed box modes can be represented in terms of pairs of surface waves traveling at an angle to the longitudinal direction [6]. For example, assume that at a particular frequency the conductor-backed dielectric layer supports a surface wave with phase constant β_{sw} and that the box width is a. Then it can easily be shown that there are an infinite number of box modes (with index n) with phase constant $\beta_{box\,n}=\sqrt{\beta_{sw}^2-(n\pi/a)^2}$ that can be represented in terms of the surface wave with phase constant β_{sw} . Each box mode can be associated with a particular surface wave. It is important to note that the box mode will always have a phase constant that is less than that of the surface wave from which it is composed.

According to the condition for leakage, if the unperturbed transmission-line mode is bound (non-leaky), then the phase constant of the transmission-line mode must be greater than that of all surface waves supported by the surrounding dielectric. Thus, if the unperturbed transmission-line mode is bound, the phase constant of this mode will be larger than those of all the unperturbed box modes (from the discussion in the previous paragraph), and therefore the dispersion curves of these two classes of unperturbed modes will never cross. Hence, one can never get mode-coupling behavior between a transmission-line mode and box modes if the unperturbed transmission-line mode is bound (see Fig. 2(a)). However, if an unperturbed transmission-line mode becomes leaky, the real part of its propagation wavenumber (its phase constant) must be less than that of a surface wave on the surrounding medium. In this case it is possible that the real part of the unperturbed propagation wavenumber of the leaky mode could become less than that of an unperturbed box mode. Then, a mode crossing of the dispersion curves of the two unperturbed modes can occur (as seen in Fig. 2(b)), leading to mode coupling. Thus we see that mode-coupling behavior between the perturbed transmission-line mode and the perturbed box mode can occur only if the unperturbed transmission-line mode is leaky.

As discussed above, the phase constant of the nth unperturbed box mode associated with the surface wave with phase constant β_{sw} can be expressed as $\beta_{box\,n}=\sqrt{\beta_{sw}^2-(n\pi/a)^2}$. Note that as the box width a increases, the differences between the phase constants of the various box modes associated with β_{sw} becomes smaller and smaller. Hence, for wide boxes, the crossings of the box mode dispersion curves with that of the unperturbed leaky mode occur close together as a function of frequency. In contrast, for small box widths, the separation in frequency between regions of mode coupling is relatively large.

Finally, we should understand what happens to the fields of the original (unperturbed) leaky mode when the transmission line is placed into the box. The fields that are leaking away in the form of surface waves propagating at an angle become reflected from the side of the box and recombine into the new perturbed transmission-line mode, which now has a purely real wavenumber not much different from the real part of the leaky-mode wavenumber. Although this perturbed transmission-line mode has a real propagation wavenumber, the fields are not bound to the vicinity of the slot or strip. Moreover, the propagating surface waves that compose the fields away from the slot or strip to the perturbed transmission-line mode are the same surface waves into which leakage occurs in the unperturbed case.

III. NUMERICAL AND EXPERIMENTAL RESULTS

As mentioned in the Introduction, in our numerical and experimental studies we have specialized the general discussion above to the case illustrated in Fig. 1, a shielded microstrip line printed on Epsilam-10, a uniaxial anisotropic substrate with $\epsilon_{\parallel}$ =10.3 and $\epsilon_{\perp}$ =13. The reason for that choice is that a microstrip line on Epsilam-10 has been shown to support a leaky fundamental mode, above a critical frequency, if the substrate is assumed to be of infinite transverse extent [2]. The dispersion curves for this shielded line are shown in Fig. 3, where the solid lines represent the perturbed transmission-line mode and three perturbed box modes. We observe, as expected, that at frequencies for which these perturbed modes approach one another, they do not cross, but rather bend away from one another in a classical coupled-mode manner. Inset in Fig. 3 are the dispersion curves of the unperturbed modes, shown by dashed lines in a frequency region in which the perturbed modes display coupled-mode behavior. These dashed lines cross each other, and the crossings are seen to occur near the middle of the coupling region. The calculated curves in Fig. 3 therefore represent a direct example of the behavior explained with the help of Fig. 2(b).

The substrate material, strip width, and dielectric thickness chosen for this calculation correspond exactly to the dimensions used for the investigation of leaky waves in [2]. As indicated by the discussion in Sec. II, the leakage associated with the microstrip line printed on an idealized substrate of infinite transverse extent implies that mode coupling is expected for the realistic case of such a transmission line housed in a rectangular waveguide. Also, as discussed above and shown in Fig. 2(b), the mode coupling will occur only at frequencies above which the leakage occurs in the unperturbed case. We may also note that in Fig. 3 the first region of mode coupling occurs just above the onset of leakage calculated in [2]. This is because the box width used in these calculations is fairly large; as the box width decreases, the regions of mode coupling will occur at higher frequencies.

The goal in the experiment is to determine whether or not the presence of a coupling region will affect the transmission of power in some significant way. Since the fields associated with a coupling region become some combination of the microstrip line dominant mode and the box mode with which it is coupling, the fields within a coupling region will be distributed throughout the box rather than concentrated near the microstrip itself. As a result, we would expect that the transmission of power along the microstrip line would be severely reduced within a coupling region.

For the measurements, we built two test structures. One consisted of microstrip line on Epsilam-10, and the second structure was identical to the first, except that we used Rogers Duroid (ϵ_r~11) instead of Epsilam-10 as a substrate. Both structures were shielded by rectangular waveguide, and the geometrical parameters employed in the experiments corresponded to the dimensions used in Fig. 3 (and in [2] where leakage was studied) with substrate-layer thickness t=5.08 mm. This isotropic substrate was chosen because it has a dielectric constant which is close to both of the dielectric constants associated with the uniaxial anisotropic substrate. Since the dominant mode on microstrip line on an anisotropic substrate of infinite transverse extent is leaky (under the conditions chosen for Fig. 3), but the corresponding mode on an isotropic substrate is known to be purely bound at all frequencies, we would expect, based on the discussion in Sec. II, that within a coupling region on the dispersion curves in Fig. 3 the transmission of power from input to output along a length of line would be seriously modified for the anisotropic substrate but not for the isotropic one.

The measurements were performed with an HP8510B network analyzer. The measured results are shown in Fig. 4 for the transmitted signal $|S_{21}|$ for the microstrip line on the Epsilam-10 and Rogers Duroid substrates. The length L of the microstrip line in both cases was $L=10h$. Over most of the measured bandwidth, the $|S_{21}|$ values associated with the Rogers Duroid substrate are relatively small and frequency independent. However, for the microstrip line on Epsilam-10, a sharp dip in $|S_{21}|$ is observed very near $t/\lambda_o=0.24$, which can be seen from Fig. 3 to correspond to the first mode-coupling region between the perturbed microstrip mode and perturbed box mode. At frequencies near this point, there is a strong drop in $|S_{21}|$ associated with the Epsilam-10 substrate, not seen for the Rogers Duroid substrate. This behavior is consistent with what we expected to find on theoretical grounds.

IV. CONCLUSIONS

Mode coupling between shielded transmission-line modes and box (package) modes has been linked directly to the phenomenon of leakage. Experimental results have been presented that show the effects of mode coupling for the case of microstrip line on a uniaxial anisotropic substrate, a transmission line which has previously been shown to support a leaky microstrip mode if the idealized substrate is of infinite transverse extent.

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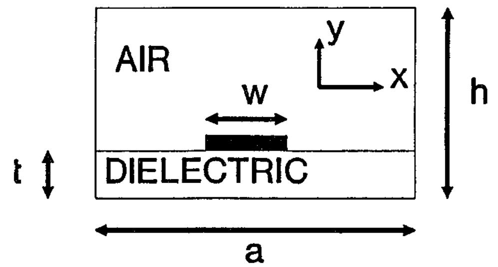

Figure 1. Cross section of a microstrip line shielded in a rectangular waveguide.

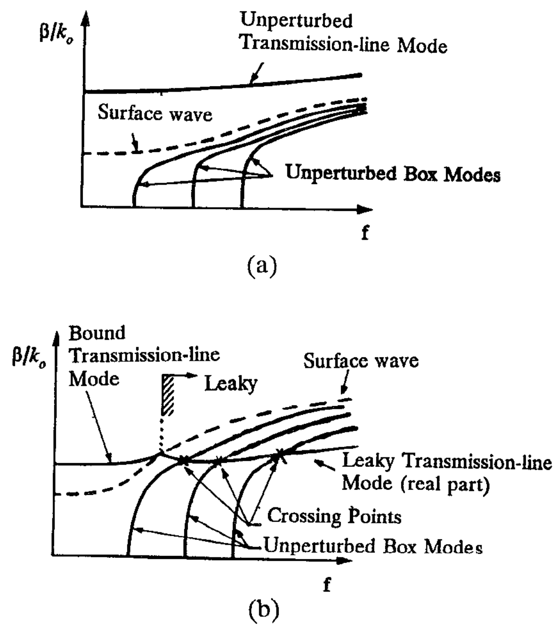

Figure 2. Qualitative examples of dispersion curves for unperturbed dominant transmission-line mode and box modes. (a) The unperturbed transmission-line mode is bound and therefore there are no crossings with the dispersion curves of the unperturbed box modes. (b) The unperturbed transmission-line mode is leaky and there are mode crossings with the dispersion curves of the unperturbed box modes.

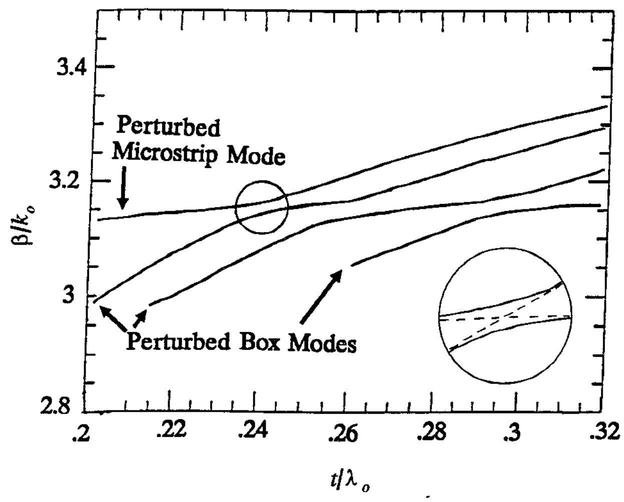

Figure 3. Numerical results for the perturbed microstrip line dominant mode and the perturbed guided box modes. The strip width is $w=t$, the box width is $a=9t$, the box height is $h=5t$, and the substrate thickness is t. The dielectric substrate used in the calculations is Epsilam-10. The solid lines indicate the dispersion curves of the perturbed modes, and within the inset the dashed lines represent the dispersion relation of the unperturbed modes. We note that the dispersion curves of the unperturbed modes cross and that those for the perturbed modes bend away from each other in a coupled-mode fashion.

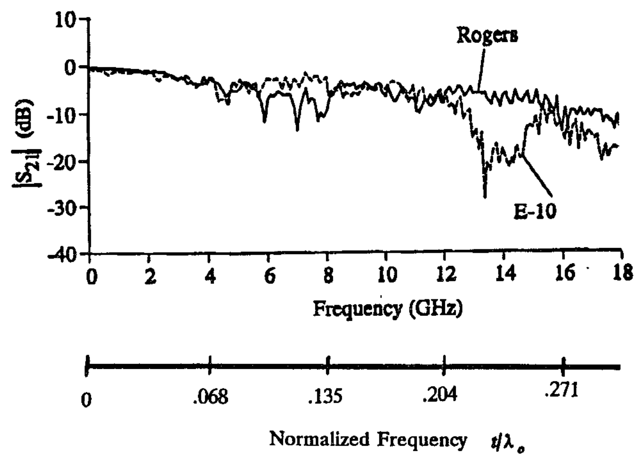

Figure 4. Measured $|S_{21}|$ values for microstrip line printed on the anisotropic substrate Epsilam-10 (E-10) and on an isotropic Roger's Duroid substrate. In both cases, the geometrical parameters selected are the ones used in the calculations for Fig. 3. The physical dielectric thickness used in the measurements was t=5.08 mm. The frequencies shown were those used in the measurements, and they are also presented in normalized form for comparison with Fig. 3. The length of the microstrip lines used in both cases was $L=10t$.