LEAKY DOMINANT MODES AND MICROWAVE CIRCUIT COUPLING IN LAYERED SYMMETRIC COUPLED LINES

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ABSTRACT

The leaky dominant modes on symmetric coupled microstrips with and without super-strate have been investigated in details, which indicate that the generic mode spectra of the leaky dominant modes are rather similar to those of much simpler guided-wave structure such as a microstrip line. The rigorous full-wave mode-matching analyses take into account the conductor losses and finite metal thickness. Measured results of a special test circuit clearly reveal that the leaky dominant modes are responsible for circuit coupling at a higher frequency range beyond certain threshold frequency that separates the spectral gap region (nonphysical) and the leaky dominant mode region (improper but physical).

I. Introduction

In analogy to the complex modes existing in an electrically shielded microstrip as reported in [1], the open microstrip exhibits a variety of leaky waves of complex propagation constants, which carry the electromagnetic energy away from the metal strip when the leaky waves are excited [2-4]. The completeness of mode spectra in the dispersion characteristics of such open microstrip mandates the inclusion of these leaky waves (modes). To date two types of leaky waves have been found. The first category, named as conventional leaky waves, lends itself to the following scenario. Certain bounded dominant mode or bounded higher-order modes convert themselves to leaky waves at frequencies above or below certain threshold frequencies [3-7]. The second category belongs to the leaky dominant modes, which, on the other hand, are the *additional* modes with respect to the conventional leaky modes converted from the bounded dominant modes or the bounded higher-order modes [2,8]. The less familiar leaky dominant modes deserve more attention.

The aim of the paper is then twofold. First, we wish to learn whether the leaky dominant modes existing just on the special occasions reported in [2,8], or they are generic in nature for more complicated guided-wave structures, e.g., the multi-layered coplanar strips. Such investigation is accomplished by studying the propagation characteristics of the symmetric coplanar strips embedded in multi-layered substrates as shown in Fig. 1. The theoretic results will be discussed in Section II. After knowing the fact that the mode spectra of the leaky waves resemble those of the simpler guided-wave structure [2], our next interest is to examine the impact of leaky waves on microwave circuit coupling by experiments. A test circuit , consisting of a SMA launcher, coplanar waveguide (CPW), CPW-to-coplanar strips transition, symmetric coupled lines, terminations to the coupled lines, and four microstrip probes, is devised for measuring the circuit coupling through leaky waves. The experimental setup will be described in Section III, together with the test results and the corresponding physical interpretations.

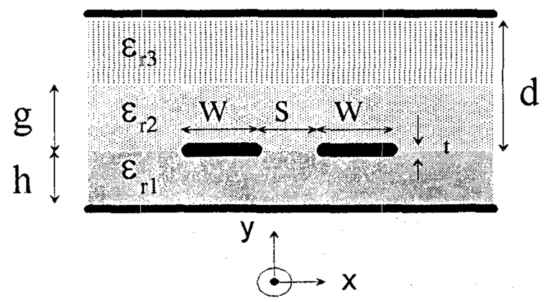


Fig. 1 Cross-sectional view of generic symmetric multi-layered coplanar strips with a top cover.

II. Leaky Dominant Modes

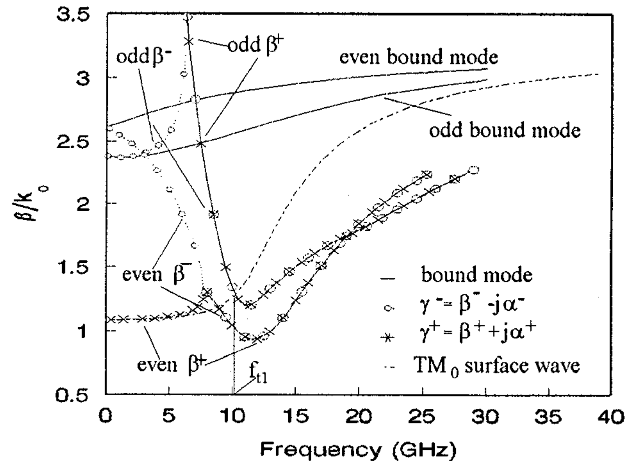
II-1. Theory and Validity Check

The hybrid network representation of full-wave mode-matching method had been successfully implemented for analyzing the leaky waves in coupled microstrip lines considering the effects of finite substrate width and finite metal thickness of finite conductivity [9]. Here we extend the same technique to analyze the structure shown in Fig. 1. The solutions of the leaky dominant modes obtained by our method considering the finite metal thickness and top cover agree well with those reported in [2,8]. Limited by the space, only parts (a) and (b) of Fig. 2 are reported. Fig. 2 shows the dispersion characteristics of the symmetric coupled microstrips printed on a single substrate of relative dielectric constant equal to 10.2. Fig. 2(a) presents the normalized phase constants β/k_0 for both even and odd symmetries versus frequency, whereas Fig. 2(b) shows the corresponding normalized attenuation constants α/k_0. Both even and odd leaky dominant modes are reported in addition to the even and odd bound modes. A pair of complex solutions denoted by $\gamma^+ = \beta^+ + j\alpha^+$ and $\gamma^- = \beta^- - j\alpha^-$ will be adopted hereinafter, where β^+, α^+, β^-, α^- are all positive real numbers. Throughout the paper, the factors $e^{j\omega t}$ and $e^{-j\gamma z}$ are assumed, and $\gamma = \beta - j\alpha$.

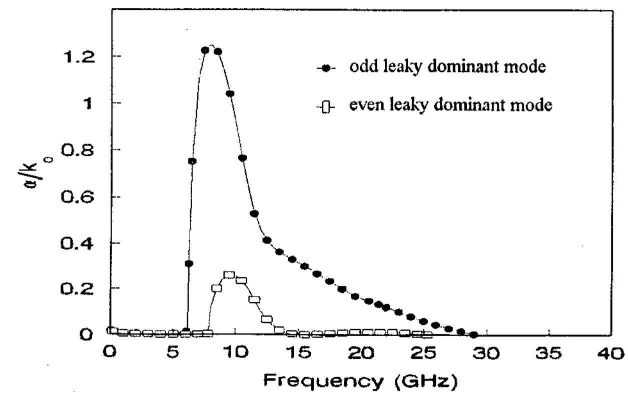
In the case of even symmetry, and at lower frequencies, there are two improper (lossy) complex solutions, which are purely real when the conductivity is assumed infinity, with relatively very small imaginary parts arising from the conductor losses. One of them has small positive imaginary part, indicated by γ^+, and the other has small negative one, indicated by γ^-. The normalized phase constants of these improper complex solutions are asymptotic to the TM_0 surface wave curve for the lower half (denoted by cross symbols) and to the bound mode solution for the upper half (denoted by circle symbols), respectively, when frequency decreases. As frequency increases, these two improper solutions nearly intersect, then they become a pair of improper (leaky) complex modes, which are still nonphysical until they intersect with the dispersion curve of the TM_0 surface wave (γ^+ is always nonphysical). Notice that the complex solutions γ^+ and γ^- always split and they do not form a complex conjugate pair, since finite conductor losses are considered in the analyses. However, their distinction can not be distinguished obviously from Fig. 1.

For the odd symmetry case, the real parts β^- of the nonspectral γ^- solutions in the lower frequency region become asymptotic to the odd bound mode. Notice also that the β^+ curve increases rapidly when frequency decreases slightly. Otherwise the rest of the dispersion curves for the leaky dominant modes resemble the even symmetry case.

II-2. Leaky Dominant Modes in symmetric Coupled Microstrips with Substrate-superstrate Configuration



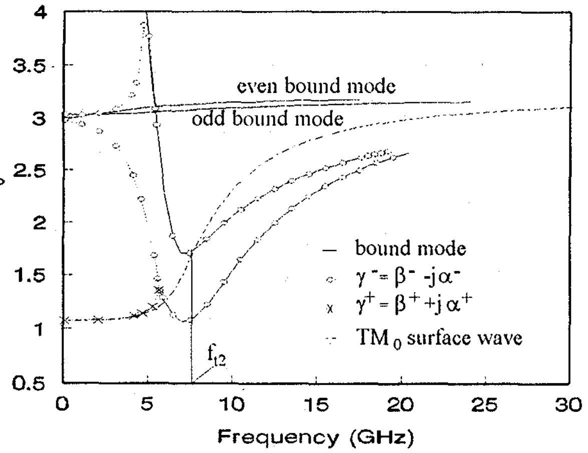
(a) The normalized phase constants versus frequencies.



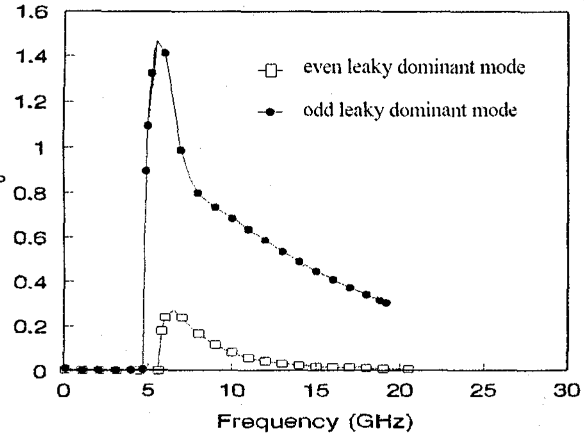
(b) The normalized attenuation constants of the leaky dominant modes (only α^- values are presented)

Fig. 2 The modal solutions of the covered coupled microstrip lines as shown in Fig. 1, where the structural parameters are h=1.905 mm, $\varepsilon_{r1}=10.2$, $\varepsilon_{r2}=\varepsilon_{r3}=1.0$, w/h=0.75, s/h=1, d/h=5, strip thickness t=0.05h, and strip conductivity σ=5.8x107 (mhos/m). α^-, α^+, β^-, and β^+ are all positive real numbers in the plots.

In the previous section II-1, we have shown that the characteristics of the leaky dominant modes for the even-symmetric microstrip line [2] and for the odd-symmetric coplanar strips [8] have indeed been preserved for the particular case study. Now we wish to investigate whether the same preservation can be maintained for a more complicated symmetric coupled microstrips with substrate-superstrate configuration. The resultant dispersion curves are plotted in Fig. 3(a) and Fig. 3(b) for β/k_0 and α/k_0, respectively. When comparing Fig. 2 and Fig. 3, the two leaky dominant mode spectra show great similarity, e.g., (1) the asymptotes such as TMo, even bound mode, and odd bound mode are similar, (2) the spectral gaps are also similar, and (3) the shapes of various curves for γ^+ and γ^- are similar. Fig. 3 shows that the spectral gap region moves toward the low frequency side by adding the super-strate layer.



(a) The normalized phase constants versus frequencies. Some β^+ curves are not displayed for clarity.



(b) The normalized attenuation constants α^- of the leaky dominant modes.

Fig. 3 The modal solutions of the covered coupled microstrip lines with a super-strate as shown in Fig. 1, where the structural parameters are the same as those in Fig. 2, except that ε_{r2} =10.0 , g/h=0.667 , d/h=10.

III. Experimental Results

Notice that the conventional leaky waves are not shown in Fig. 2 and Fig. 3. When the first higher-order leaky waves occur, they leak below certain cutoff frequency [3]. On the other hand, the leaky dominant modes reported in Fig. 2 and Fig. 3 leak above certain cutoff frequencies. It is therefore of highly interest to investigate the circuit coupling through the combined leaky waves for a much broader spectrum. An experimental setup to serve this purpose is shown in Fig. 4, where a CPW-coupled lines transition is launched by the SMA connector at one end of the CPW, and the other ends of the coupled lines are terminated by resistive loads obtained in the same way as reported in [10], for minimizing the reflections. Four open-ended microstrip lines are located at distance D away from both sides of the coupled lines. The distance is kept long enough to prevent reactive coupling. The CPW is conventional one (without back plating) and with finite side plane width. An air bridge is used to suppress the coupled slot line modes. The test circuit of Fig. 4 will excite both even mode and odd mode of the coupled lines. When the leaky dominant mode is excited to propagate along the guiding structure, power will leak in the form of predominantly TM_0 surface wave at an angle measured from the longitudinal z axis. As the surface wave reaches the open end of the microstrip line, any one of the four short microstrip lines will pick up the signal and behaves like a probe. Thus we may measure the two-port S-parameter. Port 1 is defined at the SMA connector launching into the CPW and CPW-coupled lines transition. Port 2, however, is chosen to be the SMA connector launched to one of the four microstrip open-ended probes.

Fig. 5 shows the superimposed plots of the $|S_{21}|$ transmission parameters for the symmetric coupled lines with and without the super-strate layer. The structural parameters and material constants of the coupled lines are one-to-one correspondence to those given in Fig. 2 and Fig. 3. The magnitude of S_{21} stands for the amount of coupling between port 1 and port 2. The measured results shown in Fig. 5 are highly correlated to the theoretic results for the odd leaky dominant modes in Fig. 2 and Fig. 3, respectively. For the case without super-strate, Fig. 5 shows stronger coupling above f'_{t1}, which is very close to the threshold frequency f_{t1} of the spectral gap of Fig. 2. Likewise, for the case with super-strate, Fig. 5 shows stronger coupling above f'_{t2}, which is lower than f'_{t1} and is also very close to the threshold frequency f_{t2} of Fig. 3.

Notice that the coupling between port 1 and port 2 is predominantly due to the leaky waves. Fig. 5 clearly shows that the leaky dominant modes affect the high frequency coupling. In the lower frequency region down to DC, below f'_{t1} or f'_{t2}, the effect of conventional leaky modes on the microwave circuit coupling is not as influential as the leaky dominant modes in our particular test setup.

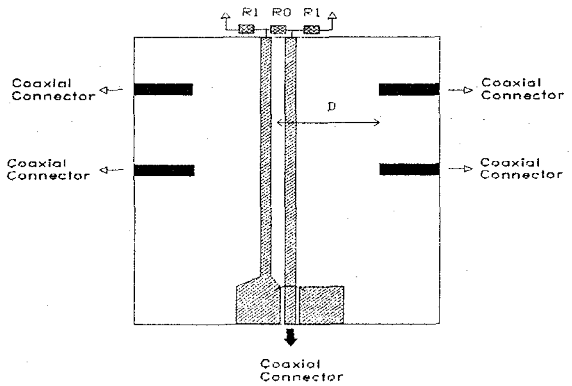


Fig. 4 Top view of the measurement setup for the investigation of the leaky dominant modes, where the coupling lines have the structural parameters as illustrated in Fig. 2 and Fig. 3. D=20mm.

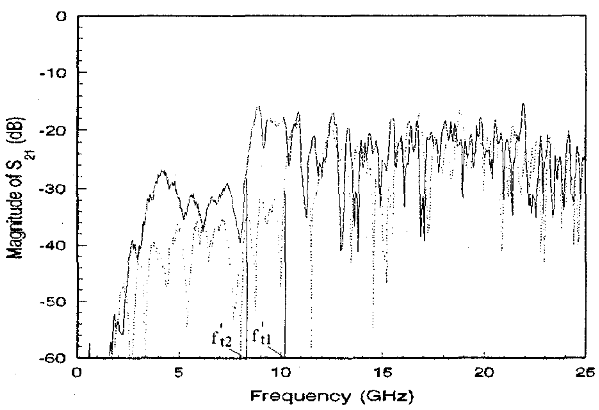


Fig. 5 Measured results showing the amount of coupling in the test circuit as shown in Fig. 4. The experimental data corresponding to Fig. 2 and Fig. 3 are represented by the dotted lines and the solid lines, respectively. f'_{t1} and f'_{t2} are the threshold frequencies above which the magnitudes of $|S_{21}|$ become larger indicating the excitations of the leaky dominant modes.

IV. Conclusion

Experiments have been carried out to show the existence of leaky dominant modes and their effect on the microwave circuit coupling by using a specially designed test fixture described in Fig. 4. The leaky dominant modes result in stronger coupling above certain higher threshold frequency that can be accurately determined by obtaining the dispersion characteristics resulted from full-wave method. The effect of super-strate on the even and odd leaky dominant modes of the coupled microstrips is investigated thoroughly. The theoretic results show that the dispersion curves of the leaky dominant modes are all very similar. Thus the leaky dominant modes are generic in a sense that we may believe that they exist in most multiple-coupled transmission lines on multi-layered substrates. Therefore the leaky dominant modes are realistic and they can cause serious problems at higher frequencies when tight specification on circuit coupling is necessary for proper operation of microwave components or module design.

Acknowledgement

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References

[1] W. -X. Huang and T. Itoh, "Complex modes in lossless shielded microstrip lines," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-36, pp. 163-165, Jan. 1988.

[2] D. Nghien, J. T. Williams, D. R. Jackson, and A. A. Oliner, "Existence of a leaky dominant mode on microstrip line with an isotropic substrate: theory and measurement," *IEEE MTT-S Int. Microwave Symp. Dig.*, vol. 3, pp. 1291-1294, 1993.

[3] A. A. Oliner and K. S. Lee, "The nature of the leakage from higher modes on microstrip line," *IEEE MTT-S Int. Microwave Symp. Dig.*, pp. 57-60, 1986.

[4] M. Tsuji, H. Shigesawa, and A. A. Oliner, "Printed-circuit waveguides with anisotropic substrates: a new leakage effect," *IEEE MTT-S Int. Microwave Symp. Dig.*, pp. 783-786, 1989.

[5] H. Shigesawa, M. Tsuji, and A. A. Oliner, "Conductor-backed slot line and coplanar waveguide: dangers and full-wave analyses," *IEEE MTT-S Int. Microwave Symp. Dig.*, pp.199-202, 1988.

[6] P. Lampariello, F. Frezza, and A. A. Oliner, 'The transition region between bound-wave and leaky-wave ranges for a partially dielectric-loaded open guiding structure," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-38, pp. 1831-1836, Dec. 1990.

[7] N. K. Das, and D. M. Pozar, "Full-wave spectral-domain computation of material, radiation, and guided wave losses in infinite multilayered printed transmission lines," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-39, pp. 54-63, Jan. 1991.

[8] M. Tsuji, H. Shigesawa, and A. A. Oliner, "Simultaneous propagation of both bound and leaky dominant modes on conductor-backed coplanar strips," *IEEE MTT-S Int. Microwave Symp. Dig.*, pp. 1295-1298, 1993.

[9] C. -C. Tien, C. -T. C. Tzuang, and S. T. Peng, "Effects of the metal thickness and finite substrate width on leaky waves in coupled microstrip lines," *IEEE MTT-S Int. Microwave Symp. Dig.*, pp. 499-502, 1992.

[10] J. -T. Kuo and C. -K. C. Tzuang, "A termination scheme for high speed pulse propagation on a system of tightly coupled coplanar strips," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-42, pp. 1008-1015, 1994.