Leaky Mode Missing From EM Simulators for Planar Circuits

Mikio Tsuji and Hiroshi Shigesawa
Department of Electronics, Doshisha University
Kyotanabe, Kyoto, 610-0321, Japan

Abstract - Most commercial EM simulators offer us solutions satisfactorily only for the purely bound mode at low frequencies. If we continue to seek modal solutions at high frequencies above a critical frequency, the existing modes become leaky modes. Indeed, they are meaningful only mathematically, but they influence strongly the performance of MIC and MMIC under a right condition. Therefore, this paper discusses whether a commercial EM simulator is practically useful for designing transmission lines and circuits in millimeter-wave range.

I. INTRODUCTION

On an open-planar transmission line, the dominant mode used in MMICs is purely bound only at low frequencies, while in almost all cases the dominant mode becomes leaky at high frequencies (especially in millimeter-wave range) [1]-[4]. Such a leaky mode has an improper nature, and its field increases transversely to infinity. In this sense, the leaky-mode solution is a "hidden solution" locating on the improper (wrong) Riemann sheet. Nevertheless, it can exhibit a serious effect on MMIC performance, and it is very important to have the efficient analytical methods or numerical one. Analytically, the spectral-domain method (SDM) and the mode-matching method (MMM) are basically useful methods. In this case, the key point to be successful in obtaining the expected solution depends on how we select a suitable path of integration (in SDM) or suitable modal functions (in MMM) before seeking solution. Otherwise, we cannot have the expected solution.

On the other hand, commercial EM simulators are now popular to solve properties of modes on printed-circuit transmission lines. They might be mostly based on the finite-element method (FEM), so that a transmission line must be put into a package box covered by appropriate boundary, when we use simulators. Even in such a case, the bound mode that exists below a critical frequency is less influenced by package box, because of the mode fields concentrated around the guide central region. Therefore, simulators can offer us bound-mode solutions with satisfactory approximation. However, the bound mode changes into a leaky mode at high frequencies, and it leaks power while propagating with an angle to the line axis. For such a case, we use here the "Radiation" boundary on trial, which is installed in most of commercial EM simulators, though it is presumed that such a boundary is almost not effective to absorb perfectly the leaky-wave power. Instead, the significant reflection of the leaky mode occurs at the top and side walls. In this paper, therefore, this paper discusses whether a commercial EM simulator is practically useful for designing transmission lines and circuits in millimeter-wave range.

II. SPECTRAL-DOMAIN METHOD TO OBTAIN THE STANDARD BEHAVIORS OF EIGENVALUES

A. Bound- and Surface-Wave Leaky-Mode Solutions

We calculate the wavenumber behaviors of modes on the conductor-backed coplanar strips (CBCPS) without package box by using the Spectral-Domain Method (SDM). The results are shown in Fig. 1, and the cross-sectional view of the structure is shown in it. The bound-mode solution (blue curve) is obtained by selecting the integration path along the real axis on the transverse wavenumber k_x plane as shown in Fig. 2. This solution ends at the critical frequency f_{cr1}, and continues to improper-real solution (green curve), which turns back to low frequencies at another critical frequency f_{cr2}. The path of integration shown in Fig. 3 obtains this solution. The dominant leaky mode (LM_1) that is obtained by the

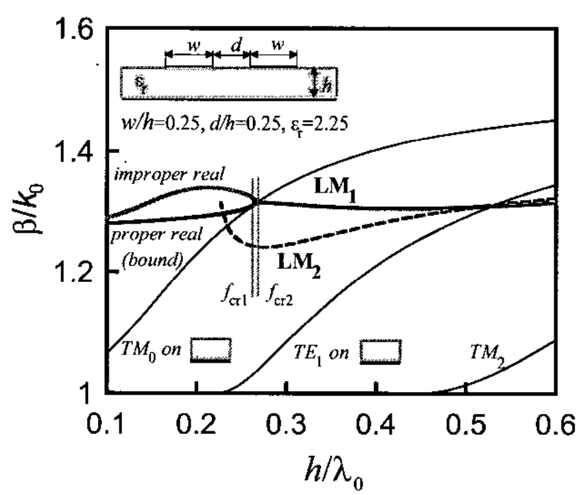

Fig. 1. Dispersion curves of different four types

0-7803-7695-1/03/$17.00 © 2003 IEEE
2003 IEEE MTT-S Digest

integral path shown in Fig. 4 begins from f_{cr2}, and continues towards higher frequency as shown by the red curve in Fig. 1. The improper-real and the LM_1 solutions are obtained by modifying intentionally the path of integration to express the growing up TM_0 surface-wave field in the transverse direction. Such a path captures the TM_0 surface-wave pole only by the path of integration shown in Figs. 3 and 4. In Fig. 1, we have also the first higher-order leaky mode (broken red curve) indicated by LM_2. This solution is obtained when the path of integration is intentionally selected so as to capture both the TM_0 and TE_1 surface-wave poles simultaneously as shown in Fig. 5. It should be noted that we could select two kinds of solutions at a frequency. Such solutions are never derived from the same eigenvalue equation. Thus the integration path should be selected according to the solution to need.

B. Space-Wave Leaky-Mode Solutions

In addition to the surface-wave leaky mode, the power leakage can occur in the form of the space-wave leaky mode under a right condition. This mode is physical in the region, in which the leakage occurs simultaneously in both the space-wave and the surface-wave forms. Therefore, the complex wavenumber is obtained by taking the path of integration on the k_x plain as shown in Fig. 6, where a part of the integration path runs on the improper Riemann sheet as shown by the broken red curve. On that Riemann sheet, the imaginary part of the complex wavenumber normal to the dielectric-air interface is positive. Another selection of the integration path is to take it for the outgoing wave on the k_y plane. Thus, we again encounter the problem of the selection of the integration path even in either case. That is the selection of the proper and the improper sheets, or the selection of the outgoing and the incoming sheets. A typical example of the space-wave dispersion curve for CBCPS is shown in Fig.7. To reference sake, the dispersion plots for other solutions are also included.

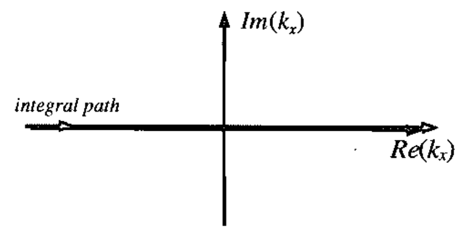

Fig. 2. Integration Path for bound mode.

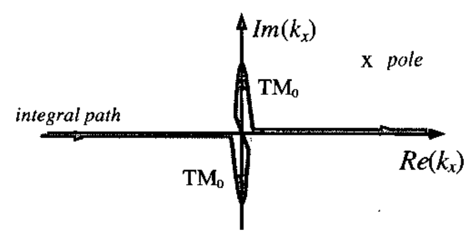

Fig. 3. Integration Path for TM_0 surface wave. (improper-real solution)

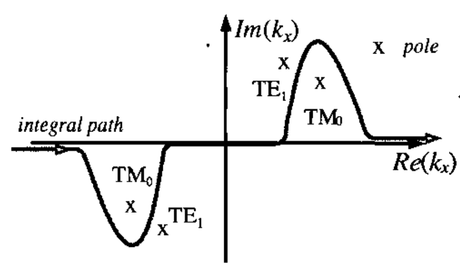

Fig. 4. Integration Path for TM_0 surface-wave leakage. (improper-complex solution)

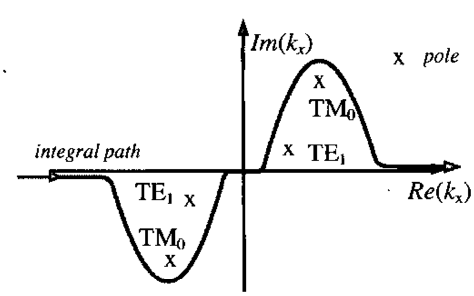

Fig. 5. Integration Path for simultaneous leakage by both TM_0 and TE_1 surface waves. (improper-complex solution)

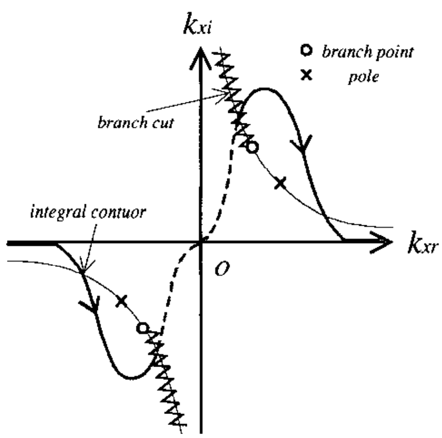

Fig. 6. The paths of integration for space-wave leaky mode.

III. Commercial EM Simulators — Its Power and Defect —

A. *Effects of Package by perfectly conducting walls*

Commercial EM simulators might be mostly based on the finite-element method (FEM), and a transmission line (e.g., CBCPS) must be put into a package box covered by appropriate boundary as shown in Fig. 8. The simulator result (the solid red curve in Fig. 9) for the fundamental bound mode seems to be a duplicate of the result obtained by SDM (the broken blue curve). The fundamental size of CBCPS used here is shown in the inset of Fig. 1. The size of the package box of perfect conductor is H/h=2.5, W/h=10 @ h=5mm. Figure 9 also includes additional curves shown by the brown and blue curves, which are the spurious-package and SWL modes[5]. The separation of the dispersion curves of the package modes between neighboring ones depends simply on the width of the side walls. These modes are certainly proper, and they can propagate on real transmission lines. When the height H/h is increased from 2.5 to 4.0, while keeping W/h=10, we can find (not show here) that the dispersion curves of most package modes overlap, except around the cutoff frequencies. Therefore, the key point to be deeply investigated will be the dynamic cross-talk problems in the package box. Otherwise, commercial EM simulators become a powerful tool to discuss packaged planar circuits and transmission lines in the frequency range below f_{cr1}.

B. *Effects of Package by "Radiation" Boundary*

We next assume the package walls made by the so-called "Radiation" boundary installed in most commercial EM simulators. Although this boundary is usually used for discussing the field behavior radiated from aperture antennas, we try to apply the radiation boundary to the side walls and the top wall. The size of the package box is again H/h=2.5, W/h=10 @ h=5mm. Fig. 10 shows the results from an EM simulator. The bound-mode solution by simulator indeed follows the result of SDM up to f_{cr1} as seen in Fig. 9, but the spurious-package modes similar to those of Fig. 9 are also observed as seen in Fig. 10. This means that the radiation boundary reflects the leaky wave almost perfectly like a perfect conductor. However, those package modes cannot exist actually on real transmission lines, because they are not the modes produced by reflection from the existing boundary.

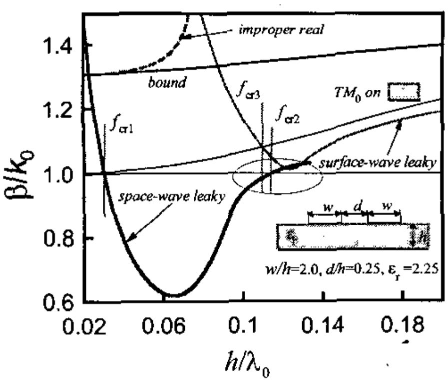

Fig. 7. Dispersion curve of the space-wave leaky mode and other related modes.

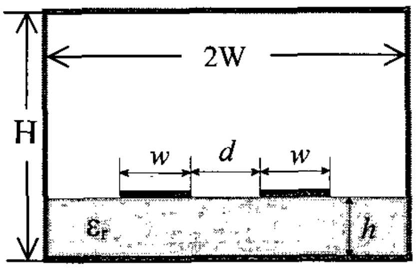

Fig. 8. The CBCPS is packaged with top and side walls, which are perfect conductor or radiation boundary.

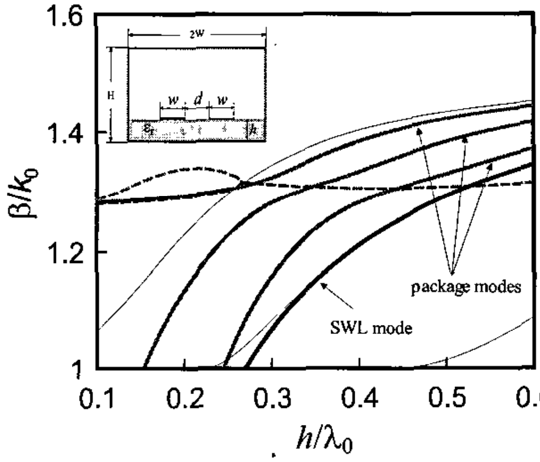

Fig. 9. Dispersion curves of CBCPS calculated by the EM simulator. The top and side walls are the perfect conductor.

IV. CONCLUSIONS

Commercial EM simulators are indeed powerful to discuss transmission-line characteristics and/or to design high frequency circuits, but However, they are effectively used only for the frequency range, in which only the fundamental bound mode can propagate. Further, it is also considered that we often encounter the leakage phenomena at high frequencies, so we have to consider the proper use of either the simulator approach at low frequencies or the analytical one at high frequencies at present.

AKNOWLEDGMENT

This work was supported in part by a Grant-in Aid for Scientific Research (C) (13650439) from JSPS and by Grants from the Research Center, Doshisha University.

REFERENCES

[1] H. Shigesawa, Guest Edit., "Special Issue on Recent Developments on Guided-Wave Problem," Trans. on Electronics, vol.. E83-C, No. 5, May 2000.

[2] M. Tsuji and H. Shigesawa, "Leaky-Wave Phenomena and Their Unfavorable Effect in Millimeter-Wave Circuit Devices (Invited)," Proc. of APMC '01, vol. 1, pp.55-58, Dec. 2001.

[3] M. Tsuji, H. Shigesawa and A. A. Oliner, "New Physical Effects When Leakage on Printed-Circuit Lines Occurs Into More Than One Surface Wave," *Radio Science*, vol.35, pp.557-565, March/April 2000.

[4] M. Tsuji, S. Ueki and H. Shigesawa, "Significant Contribution of Nonphysical Leaky Solution to the Field Excited by a Practical Source in Printed-Circuit Transmission Lines," 2002 IEEE/MTT-S Intern'l Microwave Symp. Digest, W3E-4, June 2002.

[5] A. A. Oliner, "Types and Basic Properties of Leaky Modes in Microwave and Millimeter-Wave Integrated Circuits (Invited)," Trans. on Electronics, vol.. E83-C, No. 5, pp. 675-686, May 2000.

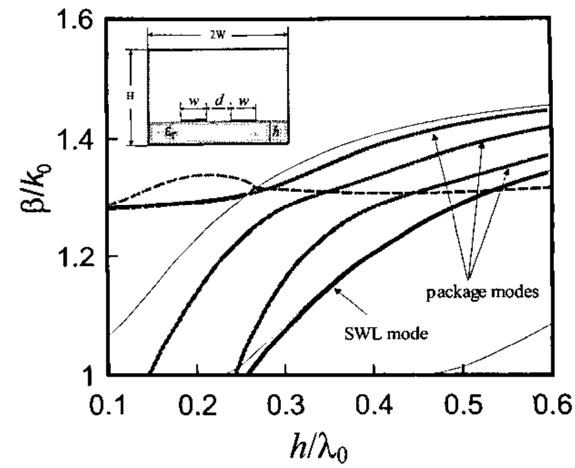

Fig. 10. Dispersion curves of CBCPS calculated by the EM simulator. The top and side walls are radiation boundary.