Mode Conversion and Leaky-Wave Excitation at Open-End Coupled-Microstrip Discontinuities

Joseph L. Cina and Lawrence Carin, *Member, IEEE*

Abstract—**The method of moments (MoM) is used to study mode conversion and leaky-wave excitation at an asymmetric coupled-microstrip discontinuity. The results show that significant mode conversion can occur at such discontinuities and that dominant leaky-wave modes can be excited strongly. Numerical issues with regard to the MoM analysis of such discontinuities are addressed as well, and for some examples it is shown that inclusion of a complete-domain basis function for the leaky mode improves numerical stability dramatically.**

I. Introduction

OVER the last several years leaky modes supported by planar transmission lines have been the subject of significant interest [1]–[12]. A transmission-line mode leaks energy when it is a fast wave with respect to a wave or mode supported by the surrounding medium. Since planar transmission lines are usually fabricated on dielectric layer(s), energy is often leaked into the layer(s) in the form of a surface wave [1]–[6]; however, energy can also be leaked into parallel-plate modes [7]–[10] and space waves [1]–[5], [9]. For example, Oliner [3] has shown that all higher-order microstrip modes are leaky over some frequency range, with energy leaked in the form of surface and space waves; similarly, Boukamp and Jansen [7] have shown that over appropriate frequencies higher-order modes supported by microstrip with a top cover leak energy in the form of parallel-plate modes (the leakage over appropriate frequencies associated with these particular higher-order modes is a general property of all higher-order planar-transmission-line modes). Additionally, it has been demonstrated that several structures support fundamental modes (characterized by no cutoff frequency and often referred to as "quasi-TEM") which are leaky over appropriate frequencies, e.g., slot line [1], [8], [9], microstrip on a properly oriented uniaxial anisotropic substrate [6], coplanar-strip waveguide [1], [9], and broad-side coupled microstrip [10].

Most of the previous studies of leaky modes supported by planar transmission lines have been two dimensional in nature, with an emphasis on calculating the complex wavenumber and the transverse field profile; there has been little work on the effects of such leaky modes on practical three-dimensional planar circuits [13]. Recently the finite difference time domain method has been used to investigate the leakage-induced distortion of pulses propagating on transmission lines which support leaky modes [12]. However, we are not aware of any previous work on the effects of leaky-mode excitation at transmission-line discontinuities; this is the topic of the present paper. In particular, we investigate the excitation of zero-cutoff-frequency leaky transmission-line modes at open-circuit coupled-microstrip discontinuities.

A spectral-domain MoM [13]–[16] analysis is applied to model discontinuities involving coupled microstrip lines in a structure with a top cover. Such discontinuities have been studied [14] in the context of microstrip filters, where a spectral-domain MoM analysis was applied. However, that study considered boxed (shielded) microstrip and therefore did not consider the effects of leaky-wave excitation. Further, since that study focused primarily on the scattering parameters of the filter, mode conversion at coupled-microstrip discontinuities was not addressed. Mode conversion has been investigated by Jackson [16] using the MoM for the case of coplanar waveguide terminated in a short and open circuit; however, that study also did not address the excitation of leaky modes. Although discontinuity-induced leaky-mode excitation has not been investigated directly in these previous studies, it has been addressed indirectly since, from the above discussion, all higher-order transmission-line modes excited are leaky over some frequency range. However, these modes usually damp strongly and therefore only affect currents in the immediate vicinity of the discontinuity (they excite surface waves, space waves, and/or parallel-plate modes which originate near the discontinuity and propagate power into the surrounding media, away from the discontinuity). Here we emphasize the excitation of leaky fundamental transmission-line modes, for which the rate of leakage is often substantially weaker than for higher-order modes.

The explicit problem considered is represented schematically in Fig. 1; a single even (longitudinal currents are the same on each strip) coupled-microstrip mode is incident upon an asymmetric open-circuit discontinuity and we investigate the scattered currents. It is well known that an N-conductor transmission line supports $N-1$ zero-cutoff-frequency modes and therefore the structure we have selected supports three fundamental modes (see Fig. 2). Under appropriate conditions one or more of these modes can be leaky [10], and we address the excitation of such modes at the discontinuity. This work is similar to that of Jackson [16] in that we address discontinuity-induced mode conversion in over-moded planar transmission lines; however, our work differs significantly in

Manuscript received September 16, 1994; revised May 25, 1995.

J. L. Cina is with the Department of Electrical Engineering, Polytechnic University, Brooklyn, NY 11201 USA.

L. Carin was with the Department of Electrical Engineering, Polytechnic University, Brooklyn, NY 11201 USA; he is now with the Department of Electrical Engineering, Duke University, Durham, NC 27708 USA.

IEEE Log Number 9413417.

0018–9480/95$04.00 © 1995 IEEE

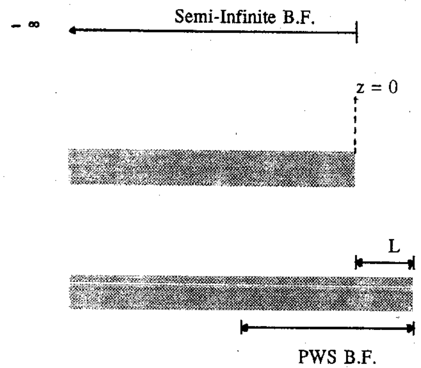

Fig. 1. Schematic of coupled microstrip terminated in an asymmetric open-circuit discontinuity. The scattering problem is analyzed using a Method of Moments (MoM) algorithm in which the fundamental modes are expanded in terms of semi-infinite basis functions (BF) which extend over $z \in (-\infty, 0]$. Piecewise sinusoidal (PWS) subsectional basis functions are used in the vicinity of the discontinuity to account for the excitation of higher-order coupled-microstrip modes.

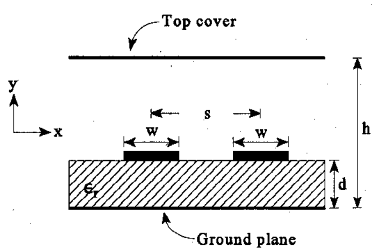

Fig. 2. Cross-sectional view of a coupled-microstrip transmission line with a top cover. The top cover, ground plane, and dielectric substrate are assumed in the analysis to be of infinite transverse extent.

that we consider situations in which mode conversion occurs into one or more fundamental modes which are leaky. In addition to this phenomenological issue, we also demonstrate that these modes may impact the numerical stability of the MoM algorithm.

The remainder of the paper is organized as follows. The numerical procedure used to model the discontinuity is reviewed in Section II; although the MoM analysis of such discontinuities is well known, we mention briefly several important issues relevant in the consideration of leaky-wave excitation. In Section III, results are presented which demonstrate that significant mode conversion can take place at coupled-microstrip discontinuities, and highlight the excitation of leaky fundamental modes. Conclusions and implications of this work are addressed in Section IV.

II. Analysis

For the discontinuity in Fig. 1, we apply a spectral-domain MoM analysis similar to that developed by Jackson and Pozar [13]. Only the longitudinal component of current is considered since the transverse component is negligible for the line widths and frequencies of interest here.

The longitudinal current density is expanded in two types of basis functions [13]–[16]: 1) semi-infinite complete-domain basis functions representing the single incident mode and the multiple reflected fundamental modes, and 2) piece-wise sinusoidal (PWS) subsectional basis functions in the vicinity of the discontinuity (see Fig. 1). The PWS basis functions model the complicated current density around the discontinuity, and therefore they account for higher-order (in general, highly leaky) transmission-line-mode excitation.

The longitudinal variation of the semi-infinite basis functions is represented by $\exp(\gamma_i z)U(-z)$, where $\gamma_1 = -j\beta_1$ for the incident mode (an $\exp(j\omega t)$ time dependence is assumed and suppressed), $\gamma_i = j\beta_i + \alpha_i$ for each of the three reflected fundamental modes ($\alpha_1 = 0$), $U(z) = 1$ for $z > 0$, and $U(z) = 0$ for $z < 0$. The wavenumbers γ_i for the three fundamental modes supported by the coupled microstrip are calculated via a standard two-dimensional spectral-domain MoM analysis, with proper deformation of the spectral integration path for the leaky modes [9]. In that analysis a single basis function $f(x - x_c) = \{1 - [2(x - x_c)/w]^2\}^{-1/2}$ is used to represent the transverse (x) variation of the current, where w is the strip width and x_c locates the strip center; this transverse variation of the longitudinal current density models the edge singularity and is included as well in all basis functions applied to analyze the discontinuity. The unknown basis-function coefficients for the reflected modes and the PWS are determined using a Galerkin testing procedure [13]–[16].

In our MoM analysis, the expansion and testing functions are expressed in the spectral domain. Because the excitation of leaky fundamental transmission-line modes is an important new aspect of the present paper, we demonstrate how such modes are modeled by semi-infinite basis functions. Assuming the wavenumber $\gamma = j\beta + \alpha$ ($\beta > 0$ and $\alpha > 0$), the basis function's longitudinal variation for propagation in the $-z$ direction is expressed as

$$\exp[(j\beta + \alpha)z]U(-z) = \exp(\alpha z)[\cos(\beta z) + j\sin(\beta z)]U(-z) \tag{1}$$

where as discussed in [13] it is convenient to represent the basis function in terms of real trigonometric functions. For an arbitrary function $g(z)$ we define the transform pair

$$g(z) = \frac{1}{2\pi}\int_{-\infty}^{\infty} \hat{g}(k_z)\exp(-jk_z z)\,dk_z \leftrightarrow \hat{g}(k_z) = \int_{-\infty}^{\infty} g(z)\exp(jk_z z)\,dz \tag{2}$$

and from simple residue calculus

$$\exp(\alpha z)\cos(\beta z)U(-z) \leftrightarrow \frac{1}{2j}\left[\frac{1}{k_z + \beta - j\alpha} + \frac{1}{k_z - \beta - j\alpha}\right] \tag{3}$$

where the integration path in the k_z plane is along the real axis, with a similar result for $\exp(\alpha z)\sin(\beta z)U(-z)$. For nonleaky modes ($\alpha = 0$) the semi-infinite sinusoidal basis functions introduce poles along the real k_z axis, and for leaky modes these poles become complex and reside in the upper half of the complex plane. In the evaluation of the spectral-domain integrals required for the elements of the MoM matrix, the integral in the immediate vicinity of real-

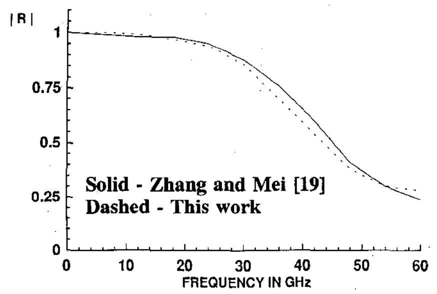

Fig. 3. Reflection coefficient magnitude as a function of frequency for a microstrip open-circuit discontinuity. Parameters: $\varepsilon_r = 9.6$, dielectric thickness $d = 0.6$ mm, and strip width $w = 0.6$.

axis poles (associated with surface-wave poles in the spectral Green's function and nonleaky transmission-line-mode poles in the spectral-domain basis functions) is evaluated using residue calculus [17], [18], while the remainder of the integral is evaluated via Gauss–Legendre numerical integration. Thus, for the consideration of leaky-wave excitation only a relatively minor change is required to previous MoM procedures [13]–[16].

III. Results

We are not aware of any previous results for an isolated coupled-microstrip discontinuity but have made extensive tests with previous results for the open-circuit microstrip discontinuity [13], [19], [20], an example of which is shown in Fig. 3 for dielectric constant $\varepsilon_r = 9.6$, strip width $w = 0.6$ mm, and dielectric thickness $d = 0.6$ mm. In our calculations two semi-infinite basis functions were applied (one each for the incident and reflected microstrip mode) and PWS basis functions were used in the vicinity of the discontinuity to model the effects of all other modes excited. The computer code used to calculate these results, which are in close agreement with those of Zhang and Mei [19], was also applied for all coupled-microstrip discontinuities considered below (with the modifications discussed in Section II).

To demonstrate mode conversion and leaky-mode excitation at an open-circuit coupled-microstrip discontinuity, we consider the following operating conditions (see Fig. 2): frequency $f = 2.55$ GHz (wavelength $\lambda = 11.76$ cm), strip width $w/\lambda = 0.034$, strip separation $s/\lambda = 0.068$, dielectric thickness $d/\lambda = 0.034$, and dielectric constant $\varepsilon_r = 2.55$. As shown below, by varying the cover height h we consider different scattering phenomena at the discontinuity. In Section III-A we consider an example for which the top cover is distant from the strips and semi-infinite basis functions are only used for the zero-cutoff-frequency modes that would be present in the absence of the top conductor. However, in subsequent examples, considered in Section III-B, the top cover is brought close to the strips; in these cases we use semi-infinite basis functions for all fundamental modes, since now the effects of the top cover have a significant impact on the discontinuity. For such cases one or more of these fundamental modes have been found to be leaky [10], and therefore these examples allow us to examine the excitation strengths of leaky transmission-line modes at realistic discontinuities.

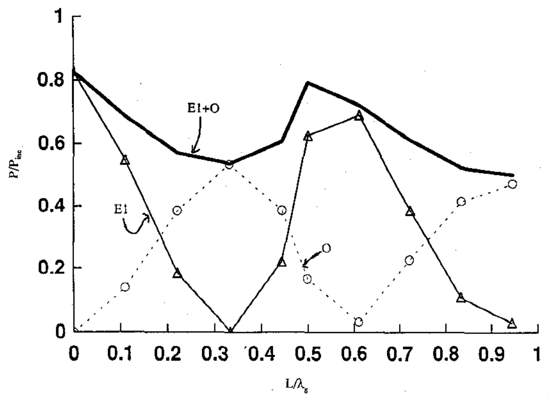

Fig. 4. Relative excitation power P/P_{inc} of the even (E1) and odd (O) coupled-microstrip modes due to the incidence of mode E1 (incident power P_{inc}) upon the discontinuity in Fig. 1. Also shown is the total power reflected in the form of the even and odd modes (E1 + 0). Operating conditions (see Fig. 2): frequency $f = 2.55$ GHz (wavelength $\lambda = 11.76$ cm), $w/\lambda = 0.034$, $s/\lambda = 0.068$, $d/\lambda = 0.034$, $h/\lambda = 0.17$, and $\varepsilon_r = 2.55$.

A. Mode Conversion

Our first example corresponds to a situation in which the top cover is distant from the strips ($h = 5d$) and therefore provides minimal perturbation to the fields in the strip vicinity. Thus, although there are $N = 4$ conductors, there are only two zero-cutoff-frequency modes of importance: the even and odd coupled-microstrip modes, each of which is perturbed weakly by the presence of the top cover. The third mode (referred to as mode E2) corresponds to the parallel-plate mode—which is weakly perturbed by the presence of the strips—and is associated more with the top and bottom conductors than with the strips (the justification for excluding this mode in the complete-domain basis function expansion is discussed further in Section III-C).

The even coupled-microstrip mode (mode E1) is assumed incident on the open-circuit discontinuity and we examine the relative excitation strengths of the even and odd (mode O) modes. As mentioned above, the first step in the numerical procedure is to solve a two-dimensional problem for the modal wavenumbers, which for the geometry considered here are $\beta_{even}/k_o = 1.47$ and $\beta_{odd}/k_o = 1.37$ (for this case both modes are nonleaky and therefore have purely real wavenumbers). Although modes E1 and O are nonleaky, this example allows us to examine their relative excitation strengths at the asymmetric open-circuit discontinuity in Fig. 1 and will provide a vantage point for comparison when the excitation of fundamental leaky modes is considered below. The excitation strengths of modes E1 and O are shown in Fig. 4 as a function of the length extension L/λ_g, where $\lambda_g/\lambda = 1.43$ is the guide wavelength of an isolated microstrip line of width w in the same inhomogeneous parallel-plate waveguide.

From simple transmission-line theory, we anticipate that for $L/\lambda_g = 0.25$ the input impedance at $z = 0$ for the extended strip is approximately that of a short circuit while the input impedance on the other strip is close to an open. Thus, for this length extension the reflected current density on the two strips should be of nearly opposite polarity and thus the odd mode should be excited strongly; the same arguments apply for $L/\lambda_g \approx 0.75$. However, when $L = 0$ the symmetry of the discontinuity precludes excitation of the odd mode; this also leads to the anticipation that the odd mode will be excited weakly for $L/\lambda_g \approx 0.5$. This simple theory explains the oscillatory numerical results as a function of L/λ_g for the excitation strengths of the odd and even modes. However, the situation in the actual scattering problem is much more complicated than in the simplified transmission-line model (the discontinuities are not perfect open circuits, the transmission lines should actually be described by coupled transmission-line theory rather than by isolated lines, etc.), and therefore the lengths L/λ_g computed in the numerical calculations are shifted slightly from the values anticipated from the simplified theory.

We see from Fig. 4 that the total power reflected in the form of modes E1 and O is less than the power in the incident mode. This power loss is attributed to parallel-plate-mode excitation [13] at the end of the discontinuity; the parallel-plate modes so excited travel away from the discontinuity in the form of cylindrical wavefronts. Analogous effects have been demonstrated by Harokopus *et al.* [21] for the case of an open structure (no top cover), for which space waves and surface waves are excited.

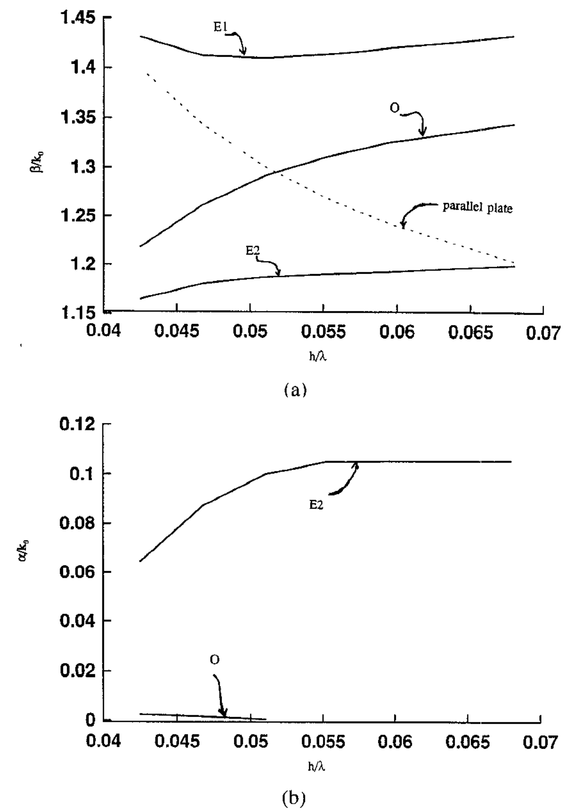

Fig 5 Wavenumbers for the three zero-cutoff-frequency modes supported by the structure in Fig. 2 for frequency $f = 2.55$ GHz (wavelength $\lambda = 11.76$ cm), $w/\lambda = 0.034$, $s/\lambda = 0.068$, $d/\lambda = 0.034$, and $\varepsilon_r = 2.55$. Also shown (dashed) is the wavenumber of the parallel-plate mode. (a) Real part of the wavenumber, (b) imaginary part of the wavenumber.

B. Leaky-Wave Excitation

We next consider scenarios for which the top cover in Fig. 2 is brought relatively close to the strips. Because the cover plays a significant role in these cases, all three fundamental modes are expanded by semi-infinite basis functions. Perhaps of more importance, it has been shown in a previous publication that if the cover height is made low enough the fundamental modes can become leaky [10]. Thus, these examples give an opportunity to examine the excitation strengths of fundamental leaky modes at realistic discontinuities.

We consider cover heights in the range $h/\lambda = 0.042$ to $h/\lambda = 0.068$, and the wavenumbers for the three corresponding fundamental modes are plotted in Fig. 5. For these cover heights one of the even modes (mode E1) is never leaky, the other even mode (mode E2) is always leaky, and the odd mode (mode O) is leaky for some cover heights and nonleaky for others. The schematic field profiles in Fig. 6 indicate that modes E1 and O are respectively the even and odd coupled-microstrip modes perturbed by the presence of the top cover (the two modes considered in Section III-A), and mode E2 is the parallel-plate mode perturbed by the presence of the two strips. These schematic field profiles have been confirmed numerically and have been plotted in Fig. 6 only in the vicinity of the strips; the fields of the leaky modes do not vanish as one moves along the transverse direction away from the strips but rather grow exponentially [10].

As in Section III-A, mode E1 is assumed incident upon the discontinuity, and we investigate the excitation strengths of all the fundamental modes (E1, E2, and O). Results are shown in Fig. 7 for the case in which the cover height is $h/\lambda = 0.0552$ and the amplitude of mode O is normalized by the factor $(Z_o/Z_e)^{1/2}$, where $Z_e = 102\Omega$ and $Z_o = 75\Omega$ are the characteristic impedances [22], [23] of modes E1 and O, respectively; we do not normalize the amplitude of mode E2 since it is leaky and a meaningful characteristic impedance cannot be defined for such a mode. However, the cross-sectional dependence of the current densities for modes E1 and E2 have similar form and therefore their relative amplitudes do reflect meaningfully on their relative excitation strengths. As in Fig. 4, the odd mode is not excited for $L = 0$ and is weakly excited for $L/\lambda_g \approx 0.6$, with strong excitation for $L/\lambda_g \approx 0.35$. However, for values of L for which E1 was excited strongly in Fig. 4, both modes E1 and E2 are excited strongly (in fact, E2 is actually excited more strongly than E1 for many values of L). Since for this cover height modes E1 and O are nonleaky while mode E2 leaks strongly, at sufficient distances from $z = 0$ only modes E1 and O will be present on the strips since all the energy in mode E2 will have leaked away (see Section III-C below).

The final example we consider is for a cover height $h/\lambda = 0.051$ (Fig. 8) for which both modes E2 and O are leaky. In this case mode E2 is excited even more strongly than mode E1 was in Fig. 7, and the odd mode is also excited strongly where expected from Figs. 4 and 7. In Fig. 8 none of the modal amplitudes are normalized with respect to modal characteristic impedance since both modes E2 and O are leaky. However, the modal current densities for the three modes are similar, except that for the even modes the strip current densities have

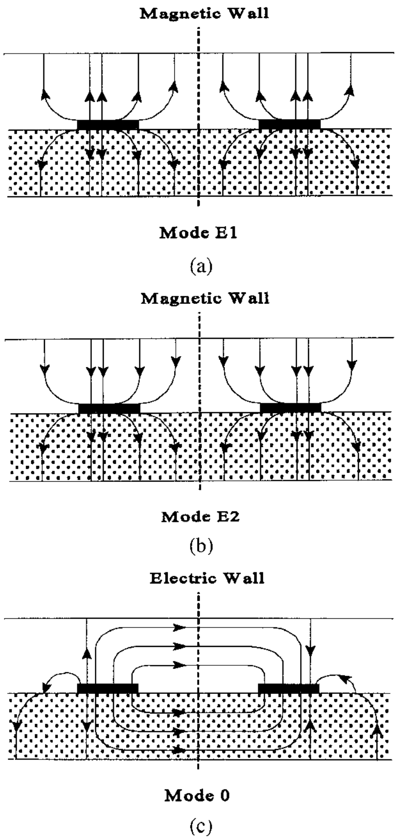

Fig. 6. Schematic electric-field plots for the three fundamental modes (two even modes: E1 and E2, and one odd mode: O) supported by the structure in Fig 2. The fields are plotted only in the vicinity of the strips; for the leaky modes, the fields grow exponentially as one moves away from the strips in the x-direction.

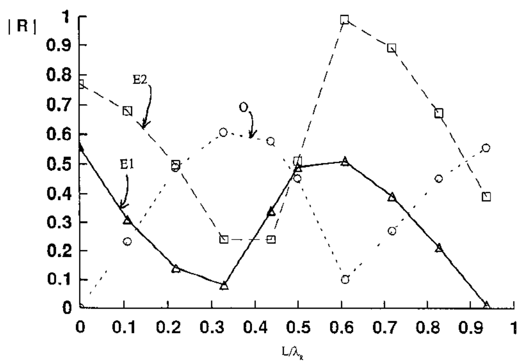

Fig. 7. Magnitude of modes E1, E2, and O excited at the asymmetric coupled-microstrip discontinuity in Fig. 1. The geometrical parameters are as in Fig. 4, except that $h/\lambda = 0.0552$.

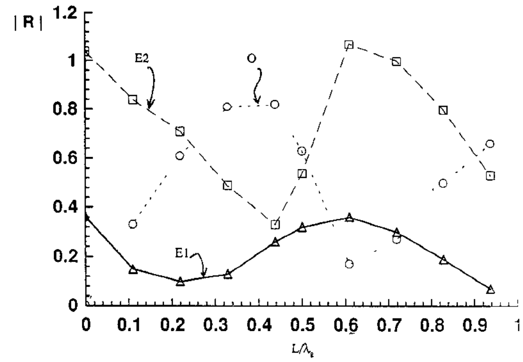

Fig. 8. Magnitude of modes E1, E2, and O excited at the asymmetric coupled-microstrip discontinuity in Fig. 1. The geometrical parameters are as in Fig. 4, except that $h/\lambda = 0.051$.

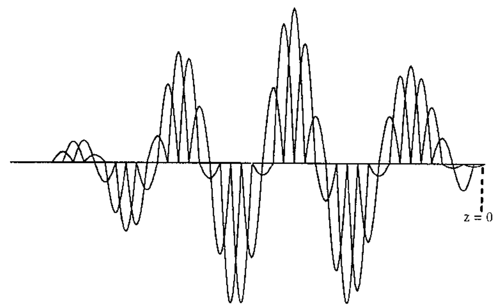

Fig. 9. Piece-wise sinusoidal (PWS) basis functions used to model the currents excited by the discontinuity in Fig. 7 for the case $L = 0$, using PWS to represent mode E2.

even polarity while mode O has odd polarity. Thus, the relative excitation strengths in Fig. 8 should be meaningful.

C. Importance of Mode E2 and Numerical-Stability Issues

As indicated in Fig. 5, mode E2 is leaky for the cover heights considered in Figs. 7 and 8. Thus, at a sufficient distance from the discontinuity mode E2 will contribute negligibly to the total strip current, with this distance determined by the rate of leakage. Therefore, in principle the currents from mode E2 could be represented by a finite number of PWS which extend over the region for which its currents are appreciable. Such an analysis would be analogous to the procedure used for the calculations in Fig. 4, for which semi-infinite basis functions were only used for the fundamental modes which would be present in the absence of the top conductor. However, if the rate of leakage for mode E2 is small one may require a large number of PWS, increasing the size of the MoM matrix and possibly compromising numerical stability. This issue is addressed by reconsidering the example in Fig. 7, but now semi-infinite basis functions are only included for modes E1 and O. The contributions from the PWS are plotted in Fig. 10 for this example, and it is seen that collectively they correspond approximately to a damped sine wave; the wavelength of which is close to that of mode E2. Unfortunately these calculations tended to be unstable and unreliable (as a function of the number of PWS expansion functions used), especially the results for mode E1. As a contrast, we plot in Fig. 10 the PWS associated with the calculations in Fig. 7, in which semi-infinite basis functions were used for all three fundamental modes; it can be seen that for this case the PWS contribution decays rapidly compared to Fig. 9. More importantly, the calculations in Fig. 7 were found to be very stable numerically.

Returning to the results in Fig. 4, the above discussion demonstrates that the accuracy of those results does not hinge upon the assumption that a complete-domain basis function

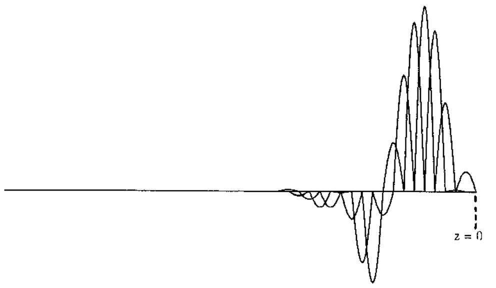

Fig. 10. Piece-wise sinusoidal (PWS) basis functions used to model the currents excited by the discontinuity in Fig. 7 for the case $L = 0$, using a semi-infinite basis function to model mode E2.

can be excluded for mode E2 (as it was for that example). If this assumption were invalid, the PWS basis functions would attempt to model the currents associated with the excluded mode and, based on our experience, the numerical results would tend to be unstable. However, the high level of numerical stability we witnessed in computing the results in Fig. 4—along with the fact that, for that example, the PWS modes decayed quickly away from the discontinuity—give us confidence that our original assumption with regard to the exclusion of a semi-infinite basis function for mode E2 was appropriate (in this case mode E2 is accounted for by the PWS).

IV. Conclusion

A spectral-domain MoM algorithm has been used to investigate asymmetric coupled-microstrip discontinuities. Several examples were considered as a function of cover height. In all cases the asymmetry of the discontinuity introduced significant mode conversion; e.g., for particular examples the reflected power was represented almost entirely in the form of an odd mode, despite the fact that the incident mode was even.

For cases in which the top cover was close to the strips, at least one of the zero-cutoff-frequency modes was leaky. This, for the first time, allowed an examination of the excitation strength of leaky modes at realistic planar-circuit discontinuities. By examining the excitation strength of the modal currents, it was shown that for many cases the leaky mode(s) can be excited more strongly than the nonleaky modes. The energy of such leaky modes is eventually converted into parallel-plate modes which leak away from the transmission line. If not accounted for, such leakage may cause significant cross talk, undermining circuit performance.

In addition to the phenomenological issues discussed above, this study also afforded an opportunity to examine the effects of leaky-wave excitation on the conventional spectral-domain MoM analysis of planar-circuit discontinuities. Since the leaky modes only contribute significantly to the total strip current for a finite distance from the discontinuity, in principle they can be represented by a finite number of PWS basis functions. However, if the leakage rate is small, the PWS expansion must extend for a significant distance from the discontinuity, increasing the number of unknowns and deteriorating numerical stability. Thus, for such cases, we have found that it is more efficient—and the numerical results are more stable—if the weakly decaying leaky-mode currents are represented in terms of complete-domain, semi-infinite basis functions.

References

[1] D. B. Rutledge, D. P Neikirk, and D. P. Kasilingam, "Integrated circuit antennas," in *Infrared and Millimeter Waves,* vol. 10, K. J. Button, Ed. New York: Academic, 1983, pp. 1–87.

[2] A. A. Oliner, "Scannable millimeter wave arrays," vol. II, chaps. IX–XII, Final Report on RADC F19628-84-K-0025, Sept. 30, 1988.

[3] ——, "Leakage from higher modes on microstrip line with application to antennas," *Radio Sci.,* vol. 22, pp. 907–912, Nov. 1987.

[4] A. A. Oliner and K. S. Lee, "The nature of leakage from higher order modes on microstrip line," in *IEEE MTT-S Int. Symp. Dig.,* Baltimore, MD, June 2–4, 1986, pp. 119–122.

[5] K. A. Michalski and D. Zheng, "Rigorous analysis of open microstrip lines of arbitrary cross section in bound and leaky regimes," *IEEE Trans. Microwave Theory Tech.,* vol. 37, pp. 2005–2010, Dec. 1989.

[6] M. Tsuji, H. Shigesawa, and A. A. Oliner, "Printed-circuit waveguide with anisotropic substrates: A new leakage effect," in *IEEE MTT-S Int. Symp. Dig.,* Long Beach, CA, June 13–15, 198, pp. 783–7869.

[7] J. Boukamp and R. H. Jansen, "Spectral domain investigation of surface wave excitation and radiation by microstrip lines and microstrip disk resonators," in *Proc. European Microwave Conference,* Nurnberg, Germany, Sept 5–8, 1983.

[8] H. Shigesawa, M. Tsuji, and A. A. Oliner, "Conductor-backed slotline and coplanar waveguide: Dangers and full-wave analyses," in *IEEE MTT-S Int. Symp. Dig.,* New York, NY, May 25–27, 1988, pp. 199–202.

[9] N. K. Das and D. M. Pozar, "Full-wave spectral-domain computation of material, radiation, and guided wave losses in infinite multilayered printed transmissions lines," *IEEE Trans. Microwave Theory Tech.,* vol. 39, pp. 54–65, Jan. 1991.

[10] L. Carin and N. K. Das, "Leaky waves on broadside-coupled microstrip," *IEEE Trans. Microwave Theory Tech.,* vol. 40, pp. 58–66, Jan. 1992.

[11] L. Carin, A. A. Oliner, G. W. Slade, and K. J. Webb, "Packaged printed transmission-line modal phenomena and relation to leakage," in *1993 IEEE MTT-S Int. Symp. Dig.,* pp. 1195–1199.

[12] M. Tsuji, M. Taniguchi, and H. Shigesawa, "The feature of the narrow-pulse transmission on conventional coplanar waveguides when power leakage is present," *IEEE Trans. Microwave Theory Tech.,* vol. 41, pp. 1017–1023, June/July 1993.

[13] R. W. Jackson and D. M. Pozar, "Full-wave analysis of microstrip open-end and gap discontinuities," *IEEE Trans. Microwave Theory Tech.,* vol. 33, pp. 1036–1042, Oct. 1985.

[14] P B. Katehi and N. G. Alexopoulos, "Frequency-dependent characteristics of microstrip discontinuities in millimeter wave integrated circuits," *IEEE Trans. Microwave Theory Tech,* vol. 33, pp. 1029–1035, Oct. 1985.

[15] R. W. Jackson, "Full-wave finite element analysis of irregular microstrip discontinuities," *IEEE Trans. Microwave Theory Tech.,* vol. 37, pp. 81–89, Jan. 1989

[16] ——, "Mode conversion at discontinuities in finite-width conductor-backed coplanar waveguide," vol 37, pp. 1582–1590, Oct. 1989.

[17] D. M. Pozar, "Input impedance and mutual coupling of rectangular microstrip antennas," *IEEE Trans. Antennas Propagat.* vol. AP-30, pp. 1191–1196, Nov. 1982.

[18] N. K. Uzunoglu, N. G. Alexopoulos, and J. G. Fikioris, "Radiation properties of microstrip dipoles," *IEEE Trans. Antennas Propagat.,* vol. AP-27, pp. 853–858, Nov. 1979.

[19] X. Zhang and K. K. Mei, "Time-domain finite difference approach to the calculation of the frequency-dependent characteristics of the microstrip discontinuities," *IEEE Trans. Microwave Theory Tech.,* vol. 36, pp. 1775–1787, Dec. 1988.

[20] R. H. Jansen, "Hybrid mode analysis of end effects of planar microwave and millimeter wave transmission lines," *IEE Proc. Pt. H,* vol. 128, pp. 77–86, Apr. 1981.

[21] W. P. Harokopus, L. P. B. Katehi, W. Y. Ali-Ahmad, and G. M. Rebeiz, "Surface wave excitation from open microstrip discontinuities," *IEEE Trans. Microwave Theory Tech.,* vol. 39, pp. 1098–1107, July 1991.

[22] L. Weimer and R. H. Jansen, "Reciprocity related definition of strip characteristic impedance for multiconductor hybrid-mode transmission lines," *Microwave and Optical Tech. Lett.,* vol. 1, pp. 22–25, Mar. 1988.

[23] L. Carin and K. J. Webb, "Characteristic impedance of multi-level, multiconductor hybrid mode microstrip," *IEEE Trans. Magnetics,* vol. 25, pp. 2947–2949, July 1989.

Joseph L. Cina was born in Palermo, Sicily on Oct. 15, 1962. He received the B.S. degree in 1986 in electrical engineering, and the M.S. degree in 1987, and the Ph.D. degree in 1995 in electrophysics from Polytechnic University in Brooklyn.

Presently, he is an Academic Administrator, and Adjunct Faculty Member at Polytechnic University. His current research interests center around numerical modeling of electromagnetic fields.

Lawrence Carin (S'86–M'89) was born Mar. 25, 1963 in Washington, DC, and received the B.S., M.S., and Ph.D. degrees in electrical engineering at the University of Maryland, College Park, in 1985, 1986, and 1989, respectively.

In 1989, he joined the Electrical Engineering Department at Polytechnic University, Brooklyn, as an Assistant Professor, and was promoted to the rank of Associate Professor in 1994. In 1995, he joined the Electrical Engineering Department at Duke University, where he is an Associate Professor. His current research interests include quasi-planar transmission lines, short-pulse scattering and propagation, and ultra-fast optoelectronics.

Dr. Carin is a member of the Tau Beta Pi and Eta Kappa Nu honor societies.