Leakage of the Dominant Mode on Stripline with a Small Air Gap

David Nghiem, *Member, IEEE*, Jeffery T. Williams, *Member, IEEE*, David R. Jackson, *Member, IEEE*, and Arthur A. Oliner, *Life Fellow, IEEE*

***Abstract*—In addition to the expected bound (proper) dominant mode, an independent *leaky* (improper) dominant mode has been found to exist on a conventional stripline that has a small air gap above the conducting strip. Such an air gap often occurs during the fabrication process, and has in the past been suspected as the cause of spurious performance. This newly discovered leaky dominant mode leaks into the fundamental TM_0 parallel-plate mode of the background structure, which is a parallel-plate guide with an air gap. Furthermore, it is found that the leaky dominant mode, *not* the bound dominant mode, is the continuation of the stripline TEM mode that exists with no air gap. Hence, it is the *leaky* mode that is excited predominantly by a conventional feed for the small air-gap structure. The general properties of both the bound and leaky dominant modes are obtained by using a full-wave spectral-domain approach. The primary purposes of this paper are to discuss the nature of the leaky dominant mode, and to show that its presence is indeed responsible for spurious transmission-line performance, such as unexpected loss and crosstalk, and interference between the bound and leaky dominant modes. These conclusions are verified experimentally.**

I. Introduction

It is well known that a conventional stripline with no air gap (homogeneous stripline) supports the TEM mode as the fundamental mode. This TEM mode is bound, meaning that the fields decay in the transverse directions away from the conducting strip. At all frequencies, the longitudinal (along the strip) propagation wavenumber of the TEM mode is equal to the substrate wavenumber. In practice, however, a small air gap often occurs during the fabrication process. The air gap introduces an inhomogeneity in the stripline dielectric, and has been suspected in the past as the reason for unexpected and spurious transmission-line performance.

It is shown here that, in addition to the bound dominant mode, an independent *leaky* (improper) dominant mode exists on a conventional stripline with a small air gap above the conducting strip. The existence of this leaky mode was first reported in [1]. This new leaky mode is called a *dominant* mode because it has a current distribution on the conducting strip that is similar to that for the TEM mode on homogeneous stripline, as opposed to *higher-order* modes that have very different current distributions [2]. This leaky dominant mode leaks energy away from the strip at an angle into the TM_0 parallel-plate mode, resulting in increased insertion loss, crosstalk with adjacent circuit elements, and interference with the bound dominant mode.

This study also reveals another surprising new result: for *small* air gaps, the fields of the bound mode resemble those of the TM_0 parallel-plate mode, while the fields of the dominant leaky mode resemble those of the homogeneous stripline TEM mode. Two very interesting consequences follow from these results. First, a conventional feed structure will excite the leaky mode much more strongly than the bound mode; and second, as an air gap is introduced, the leaky mode, *not* the bound mode, is the continuation of the stripline TEM mode that is present when there is no air gap. It is also found that, as the air gap is made larger, the bound-mode fields change character and become more like those of the stripline mode.

In this paper, the main goals are to discuss the general properties of the bound and leaky dominant modes on the small air-gap structure, and to show that the leaky dominant mode can indeed be responsible for spurious transmission-line effects. Numerical results for the propagation wavenumbers of both the bound and leaky dominant modes are presented, showing the dependence on air-gap thickness, frequency, strip width, strip location, and dielectric constant of the substrate. The formulation used to obtain the propagation constants is a standard spectral-domain moment method, with the path of integration in the spectral-domain chosen differently for the bound and leaky solutions. Experimental evidence which confirms the spurious transmission response due to the excitation of the leaky mode is also presented.

II. Formulation

The analysis of the multiple-layered stripline structure in Fig. 1 is based on standard spectral-domain techniques [3]–[5]. As seen in Fig. 1, an air gap of thickness δ is located above the conducting strip of width w. This air gap is sandwiched between two substrates with dielectric constant ϵ_r and thickness h. To simplify the analysis, it is assumed that the structure is infinite along the x and z coordinates, and that the strip is infinitesimally thin. A standard spectral-

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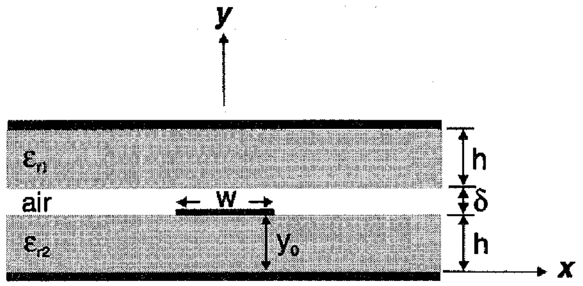


Fig. 1. A stripline structure with an air gap above the strip.

domain moment-method analysis is first used to formulate a determinantal equation for the unknown propagation constant. After this, a discussion is given about the different paths of integration used to solve for the bound and leaky solutions.

A. Moment-Method Procedure

The current on the conducting strip is represented as

$$\mathbf{J}_s(x,z) = [\hat{\mathbf{x}} J_x(x) e^{-jk_{z0}z} + \hat{\mathbf{z}} J_z(x) e^{-jk_{z0}z}] \tag{1}$$

where $k_{z0} = \beta - j\alpha$ is the unknown propagation wavenumber in the z direction. The terms $J_x(x)$ and $J_z(x)$ represent the transverse variations of the x- and z-directed currents, respectively, which are approximated by the expressions

$$J_x(x) \simeq \sum_{n=1}^{N} C_n J_{xn}(x) \tag{2}$$

and

$$J_z(x) \simeq \sum_{m=1}^{M} D_m J_{zm}(x). \tag{3}$$

The basis functions used here, which satisfy the edge conditions for the currents J_x and J_z, are

$$J_{xn} = \left(\frac{2}{\pi w}\right) \frac{\sin(2n\pi x/w)}{\sqrt{1-(2x/w)^2}} \quad |x| \le \frac{w}{2} \tag{4}$$

and

$$J_{zm} = \left(\frac{2}{\pi w}\right) \frac{\cos(2(m-1)\pi x/w)}{\sqrt{1-(2x/w)^2}} \quad |x| \le \frac{w}{2}. \tag{5}$$

A Galerkin testing procedure is applied in the spectral domain to yield the linear set of equations

$$\sum_{n=1}^{N} C_n \int_{-\infty}^{\infty} \tilde{J}_{xk}(-k_x) \tilde{G}_{xx}(k_x, k_{z0}) \tilde{J}_{xn}(k_x) dk_x + \sum_{m=1}^{M} D_m \int_{-\infty}^{\infty} \tilde{J}_{xk}(-k_x) \tilde{G}_{xz}(k_x, k_{z0}) \tilde{J}_{zm}(k_x) dk_x = 0 \tag{6}$$

and

$$\sum_{n=1}^{N} C_n \int_{-\infty}^{\infty} \tilde{J}_{zl}(-k_x) \tilde{G}_{zx}(k_x, k_{z0}) \tilde{J}_{xn}(k_x) dk_x + \sum_{m=1}^{M} D_m \int_{-\infty}^{\infty} \tilde{J}_{zl}(-k_x) \tilde{G}_{zz}(k_x, k_{z0}) \tilde{J}_{zm}(k_x) dk_x = 0 \tag{7}$$

where $k = 1,2,3,\ldots,N$ and $l = 1,2,3,\ldots,M$. The terms G_{zx} and G_{zz} are components of the one-dimensional spectral-domain Green's function, which are functions of k_{z0}. These functions have poles in the complex k_x-plane at $\pm k_{xp}$, where $k_{xp}^2 = k_{pp}^2 - k_{z0}^2$ and k_{pp} is the propagation wavenumber of the individual parallel-plate modes of the background structure (it is assumed here that the substrate is thin enough so that only the TM_0 mode is above cutoff, with a propagation wavenumber $k_{pp} = k_{TM_0}$). For nontrivial solutions of (6) and (7), the system matrix $[Z]$ of the above system must be singular. Hence, the propagation wavenumber k_{z0} is the solution of the equation

$$\det[Z(k_{z0})] = 0. \tag{8}$$

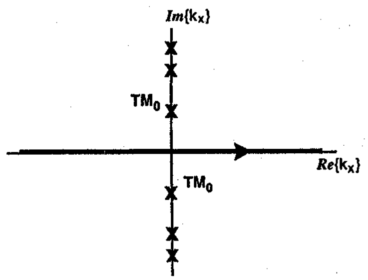
The solution of this equation is obtained by employing a complex root finding algorithm, such as the secant method or Muller's method.

B. Choice of the Integration Path

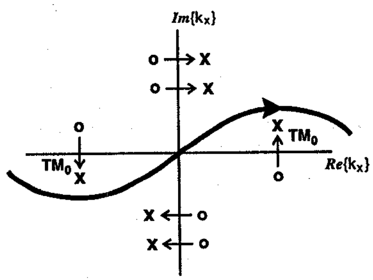
A proper (bound) modal solution, for which the fields decay away from the strip, is obtained by integrating along the real axis in (6) and (7). This solution has $\alpha = 0$ (for lossless materials) and satisfies $\beta > k_{TM_0}$. All of the poles of the integrand, including the TM_0 poles, lie on the imaginary axis in this case, as shown in Fig. 2(a).

Of course, it is possible that improper (leaky-mode) solutions also exist. To help explain the path of integration used to find a leaky-mode solution, it is convenient to initially assume a field with a real-valued propagation wavenumber ($\alpha = 0$) where $\beta < k_{TM_0}$, and assume that there is a slight amount of material loss in the structure. In this case the TM_0 poles lie off the real axis in the second and fourth quadrants. When a leakage loss is then introduced ($\alpha > 0$) and increased until it dominates the material loss, the TM_0 poles cross the real axis from the second and fourth quadrants and enter into the third and first quadrants, as shown in Fig. 2(b). The poles corresponding to the higher-order modes then cross the imaginary axis, as shown in the figure, where the poles are denoted by circles when there is no leakage and by crosses when there is leakage. Therefore, the appropriate path of integration becomes one that is deformed around the TM_0 poles [6]–[8], as shown in Fig. 2(b). This path will recover a leaky solution that leaks into the TM_0 parallel-plate mode. This path is equivalent to the real-axis path plus paths that encircle the TM_0 poles (resulting in residue contributions), as seen in Fig. 2(c). These residue contributions are responsible for the improper nature of the leaky-wave field, which increases exponentially in the $\pm x$ directions. After the TM_0 poles have crossed the real axis, the value of β may increase and become greater than k_{TM_0}, without any further change to the path shown in Fig. 2(b). Therefore, it is important to realize that the path shown in Fig. 2(b) can be used to find leaky solutions regardless of whether or not $\beta < k_{TM_0}$.

It is important to comment briefly on the physical significance of leaky-mode solutions. It is well known that leaky-mode solutions may be physically significant, despite their improper nature [9], [10]. This is because the total fields



(a)



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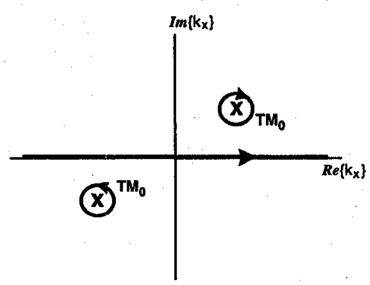


(c)

Fig. 2. (a) An integration path used to obtain k_{z0} for the proper modal solution. Also shown are poles corresponding to k_{TM_0} and higher-order parallel-plate modes. (b) An integration path used to obtain k_{z0} for the improper modal solution. Also shown are poles corresponding to the parallel-plate modes. (c) An equivalent path for the integration path of (b).

near the guiding structure that a practical source would excite may, under certain conditions, be strongly dominated by the fields of the leaky mode alone. The dominance of the leaky mode requires that it is excited with a sufficiently strong amplitude. In the case of stripline, common stripline feeds are designed to excite modes that have a quasi-TEM field distribution, resembling the usual TEM mode that exists on stripline with no air gap. Thus, a leaky mode on a stripline structure would be strongly excited only if it has a quasi-TEM field distribution.

A quasi-TEM field distribution is not, by itself, sufficient to guarantee that the fields near the stripline structure will resemble those of the leaky mode. The value of the phase constant β is also important. When $\beta < k_{\mathrm{TM}_0}$, the leaky mode is a fast wave with respect to the TM_0 parallel-plate mode. In this region, it is universally regarded as being physically meaningful. In this region it is possible to give a simple phase-matching argument to show that the leakage corresponds to the TM_0 mode being launched at an angle of approximately $\theta \approx \cos^{-1}(\beta/k_{\mathrm{TM}_0})$ from the strip axis. When $\beta > k_{\mathrm{TM}_0}$, however, the leaky mode lies within the "spectral-gap" region [11]. As the leaky mode enters this region, it begins to lose physical significance in the sense that the total fields excited by a finite source (such as a feed) lose resemblance to those of the leaky-wave mode alone.

The question of physical significance for a leaky-mode solution is separate from the issue of mathematical existence. A leaky-wave solution found using the path of integration shown in Fig. 2(b) represents a mathematically valid solution that is independent of the bound mode solution, regardless of the phase constant β. Such a solution may be continuously tracked as a particular parameter (such as frequency or air-gap thickness) changes. It is possible that the solution may have $\beta < k_{\mathrm{TM}_0}$ for a certain range of the parameter, and $\beta > k_{\mathrm{TM}_0}$ for another range. Thus, the physical significance of the mode may change as the parameters of the structure change.

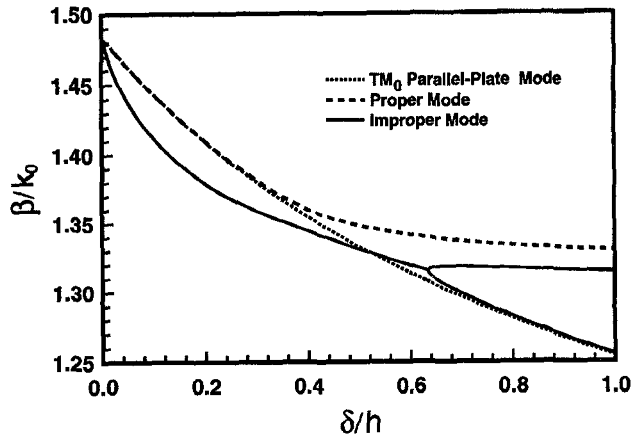
For a lossless structure, it can be shown that k_{z0}^* will also represent a valid solution to (8), provided an integration path is used that is the conjugate of the one shown in Fig. 2(b). For a complex k_{z0}, the conjugate solution represents a modal field that increases in the direction of propagation, and thus is not physical. The conjugate solution merges with the k_{z0} solution at the point where the complex improper solution becomes a real improper solution.

III. Numerical and Experimental Results

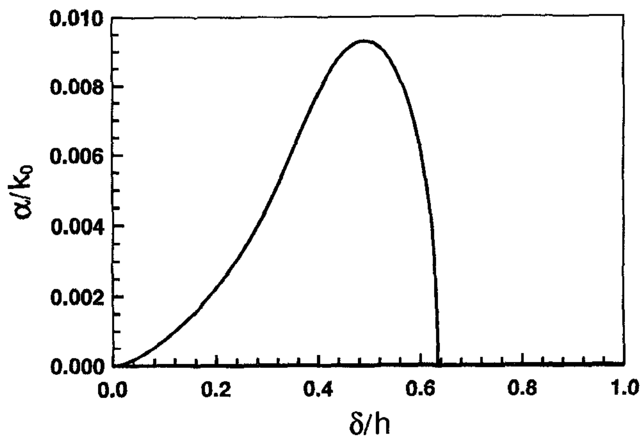
A. Numerical Results

Air gaps are inherent in the construction of many practical stripline structures, and have been suspected as the cause of unexpected and spurious transmission line performance. It is therefore useful to investigate how air gaps above the strip conductor affect the propagation constant k_{z0} of the stripline. For this investigation the structure shown in Fig. 1 is considered, where both the strip width w and the layer thickness h are equal to 0.1 cm and $y_0 = h$, unless otherwise specified. The propagation wavenumbers for both the proper and improper solutions as functions of air-gap thickness δ, frequency, strip width w, dielectric constant ϵ_r, and strip location y_0 are presented.

First, the effects of the *air-gap thickness* δ on the propagation wavenumber for the air-gap structure (Fig. 1) are studied. At an operating frequency of 3 GHz, the normalized parallel-plate wavenumber k_{TM_0}/k_0 and the normalized propagation wavenumber k_{z0}/k_0 (β/k_0) for the proper solution versus δ are shown by the dotted and dashed curves in Fig. 3(a), respectively. As seen in this figure, both k_{TM_0} and the proper solution k_{z0} decrease with increasing δ. For a zero-thickness air gap ($\delta = 0$), k_{z0} for the proper solution is seen to be equal to k_{TM_0}, which in turn becomes equal to $k_0\sqrt{\epsilon_r}$ in that limit. That value is of course also the well-known solution for the propagation wavenumber of a homogeneous stripline. For nonzero δ, k_{z0} for the proper solution is always greater than k_{TM_0}, as expected, although it is almost identical to it for small air gaps. However, this dominant mode solution is not the only one for this stripline structure. Using the integration path of Fig. 2(b), an improper solution with a different k_{z0}



(a)



(b)

Fig. 3. (a) β/k_0 for the proper (bound) and improper (leaky) solutions and k_{TM_0}/k_0 (parallel-plate mode) for the lowest parallel-plate mode, versus the normalized air-gap thickness δ/h, and (b) α/k_0 for the improper solution versus δ/h, for the stripline of Fig. 1, at 3 GHz ($w/h = y_0/h = 1$ and $\epsilon_r = 2.2$).

is found. The real part of k_{z0} for this solution, β/k_0, is shown by the solid curve in Fig. 3(a). For $\delta/h < 0.634$, the improper solution is complex. In this range, the attenuation constant $\alpha = -\mathrm{Im}(k_{z0})$ is nonzero, as shown in Fig. 3(b). The conjugate solution k_{z0}^* also exists in this range, with the same β as shown in Fig. 3(a), and with α the negative of the value shown in Fig. 3(b). When the point $\delta/h = 0.634$ is reached, the k_{z0} and k_{z0}^* solutions merge. As δ increases further these solutions split into two distinct real-valued solutions, which are no longer conjugates of each other. (These real-valued solutions, as well as the k_{z0}^* solution, are nonphysical, as pointed out in Section II.)

This behavior is more readily interpreted by examining the solution locus in the steepest-descent plane. Fig. 4 shows the improper k_{z0} solution locus of Fig. 3 in the steepest-descent ζ-plane, where $k_{z0} = k_{\mathrm{TM}_0} \sin\zeta$. In the ζ-plane, the k_{z0}^* solution is the mirror image, about the $\pi/2$ line, of the k_{z0} solution, when $\alpha > 0$ [9]. When the improper k_{z0} and k_{z0}^* solutions become real, the solution loci meet along the $\frac{\pi}{2}$-line in the complex ζ-plane and split into two curves along the $\frac{\pi}{2}$-line,

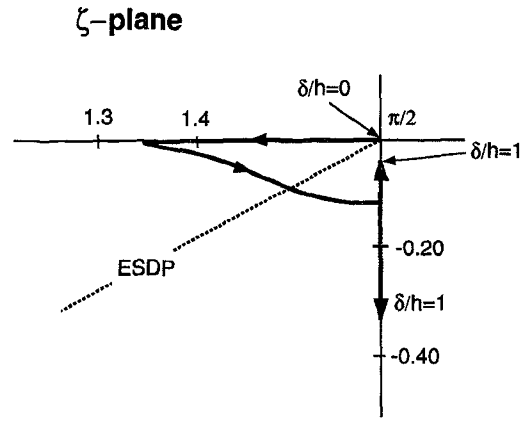
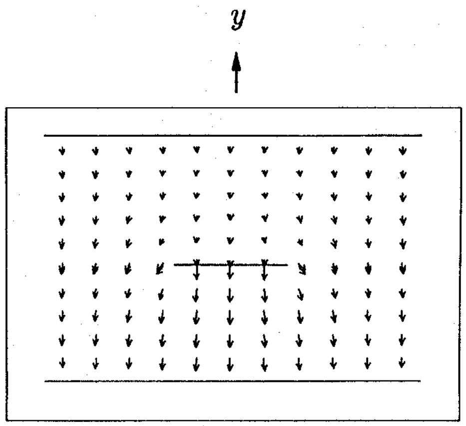


Fig. 4. The locus for the improper k_{z0} solution of Fig. 3 in the steepest-descent ζ-plane. The portion of the steepest-descent plane near the point $(\pi/2, 0)$ is shown magnified for clarity. The arrows indicate the direction of increasing air-gap thickness δ. The extreme steepest-descent path (ESDP) is also shown.

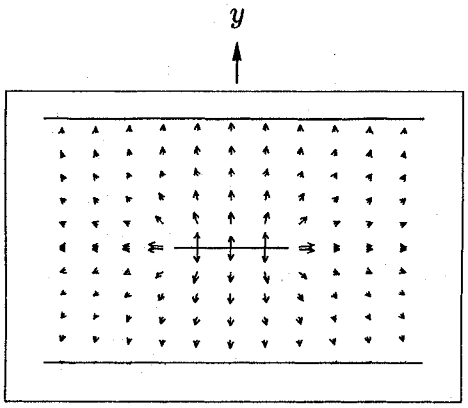
as shown in Fig. 4. After merging, the pole corresponding to the original k_{z0} solution travels down along the $\frac{\pi}{2}$-line, while the pole corresponding to the k_{z0}^* solution travels up. These directions were determined by examining the solution loci (not shown) corresponding to a slightly lossy stripline structure, in which the k_{z0} and k_{z0}^* solutions remain separate and distinct. The behavior in the steepest-descent plane as the air-gap thickness changes is typical of the behavior observed on other guiding structures when frequency is varied [11], [12].

The previous results demonstrate conclusively that both proper and improper dominant mode solutions for the propagation wavenumber exist in the stripline structure of Fig. 1. To further characterize these two solutions, it is desirable to examine their *electric field* ($\bar{E}$) distributions. Computer plots of the real part of $\bar{E}$ ($\mathrm{Re}\{\bar{E}\}$) for both the proper and improper solutions in the $z = 0$ plane are shown in Fig. 5(a) and (b) for the air-gap structure having the same substrate dimensions as in Fig. 3, with a small air-gap thickness δ =0.01 cm ($\delta/h = 0.1$). As seen in these figures, the field distributions are quite *different*. The field distribution for the improper (leaky) solution corresponds to that generally associated with the conventional TEM stripline mode, whereas that for the proper solution more closely resembles the field of the TM_0 parallel-plate mode. This leads to the conclusion that, for striplines with small air gaps, it is the *improper* modal solution that is the continuation of the conventional TEM stripline mode that exists when no air gap is present. A plot of the imaginary part of $\bar{E}$ ($\mathrm{Im}\{\bar{E}\}$) for the improper solution is shown in Fig. 5(c). For striplines with small air gaps, the imaginary part of $\bar{E}$ is, in general, small compared to $\mathrm{Re}\{\bar{E}\}$. The plots in Fig. 5 are normalized with respect to the maximum value of the electric field ($E_{\max}$) in each respective plot. For Fig. 5(c), $E_{\max}$ is approximately 0.013 of the $E_{\max}$ value of Fig. 5(b). The imaginary part of the field of the improper mode closely resembles that of the parallel-plate mode, the mode into which the leakage occurs.

Next, the *frequency dependence* of the propagation wavenumber k_{z0} for the air-gap structure is investigated, for a structure having the same substrate dimensions and air-



(a)



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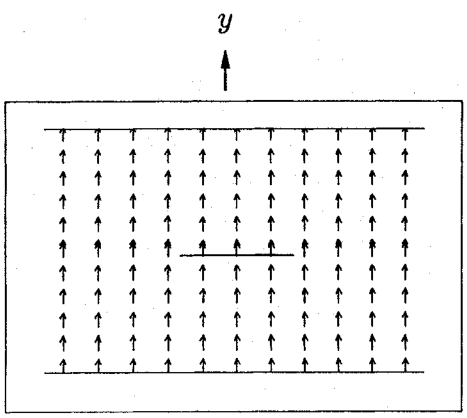


(c)

Fig. 5. The real part of the E-field for (a) the proper (bound) solution and (b) the improper (leaky) solution, and (c) the imaginary part of the E-field for the improper solution, for δ =0.01 cm (a small air gap). The field plots are shown in a rectangular window 0.2 cm × 0.3 cm around the center strip of width 0.1 cm, for the stripline of Fig. 1, at 3 GHz ($\epsilon_r = 2.2$, $h = w = y_0 = 0.1$cm). For the improper k_{z0} solution, $\mathrm{Im}\{E\}_{\max}/\mathrm{Re}\{E\}_{\max} = 0.013$.

gap thickness (0.01 cm) as in Fig. 5. The frequency response (up to 40.0 GHz) of β/k_0 for both the proper and improper solutions, along with a plot of k_{TM_0}/k_0, is shown in Fig. 6. A plot of α/k_0 versus frequency for the improper solution is also provided in Fig. 6. An important observation is that the improper solution remains leaky, with a nearly constant value of β/k_0, as the frequency decreases to zero for this

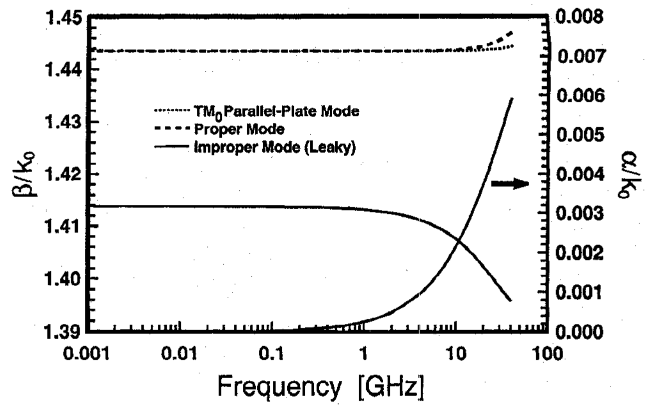


Fig. 6. β/k_0 and k_{TM_0}/k_0 (parallel-plate mode) versus frequency, and α/k_0 versus frequency, for the stripline of Fig. 1, with $\delta = 0.01$ cm ($\epsilon_r = 2.2$, $h = w = y_0$ =0.1 cm), for both the bound (proper) mode and the leaky (improper) mode.

case of small air-gap thickness (although the leakage constant approaches zero as the frequency tends to zero). The value of β/k_0 for the proper (bound) solution is seen to be almost identical with that for the TM_0 parallel-plate mode, consistent with the electric-field behavior in Fig. 5(a). Other results (not shown) for much larger air-gap thicknesses show that β for the leaky-mode solution increases and crosses the k_{TM_0} dispersion curve as the frequency is lowered, and a splitting point occurs at a lower frequency [13]. Below this splitting-point frequency only two real improper modal solutions exist, similar to the situation in Fig. 3(a) for larger air-gap thicknesses. Hence, the dominant quasi-TEM mode remains leaky down to zero frequency only when the air gap thickness is small.

To investigate further the air-gap problem, the effects of the strip width w, the dielectric constant ϵ_r, and strip location y_0 are presented. At an operating frequency of 3 GHz, plots of k_{TM_0}/k_0 and β/k_0 versus the *strip width* are shown in Fig. 7 for the air-gap structure having the same substrate parameters and air-gap thickness (0.01 cm) as in Fig. 5. A plot of α/k_0 for the improper solution is also provided in Fig. 7. As the strip width varies, β/k_0 for the proper solution is quite constant. However, β/k_0 for the improper solution varies substantially, especially for small strip widths. The leakage constant α for the improper solution increases almost linearly with increasing strip width. In general, the improper solution has been found to be sensitive to the strip width, whereas the proper solution is not. The latter observation is consistent with the field distribution of the proper mode in Fig. 5(a), which is mainly that of the parallel-plate mode and therefore relatively independent of the strip.

A plot of normalized attenuation constant α versus thickness δ for striplines with several different *relative permittivity* ϵ_r values is given in Fig. 8, for the air-gap structure having the same substrate and strip dimensions as in Fig. 5. This figure shows that the leakage increases with increasing ϵ_r. The corresponding plots of normalized phase constant β versus the air-gap thickness δ are similar to that shown in Fig. 3(a), and hence not shown.

Plots of k_{TM_0}/k_0 and β/k_0 for both the bound and leaky modes versus the *strip location* y_0 are shown in Fig. 9. The

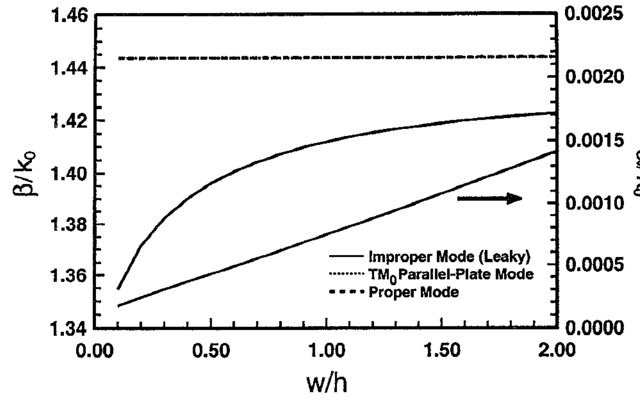


Fig. 7. β/k_0 and k_{TM_0}/k_0 (parallel-plate mode) versus the normalized strip width, and α/k_0 versus the normalized strip width, for the stripline of Fig. 1 at 3 GHz with δ =0.01 cm ($\epsilon_r = 2.2$, $h = y_0 = 0.1$ cm).

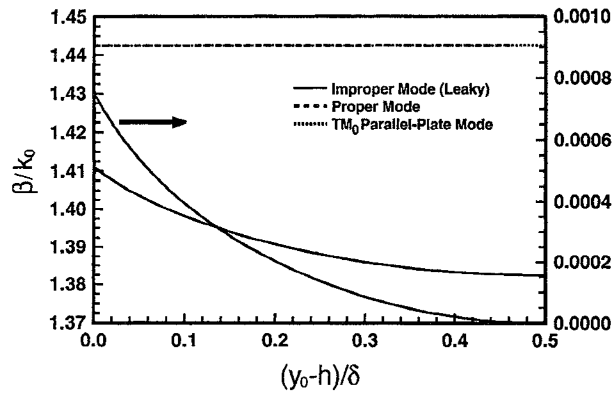


Fig. 9. β/k_0 and k_{TM_0}/k_0 (parallel-plate mode) versus the strip location, and α/k_0 versus the strip location, for $\delta = 0.01$ cm ($\epsilon_r = 2.2$, $h = w = 0.1$ cm), for the stripline of Fig. 1, at 3 GHz. The strip is centered in the air gap when $y_0 = h + \delta/2$.

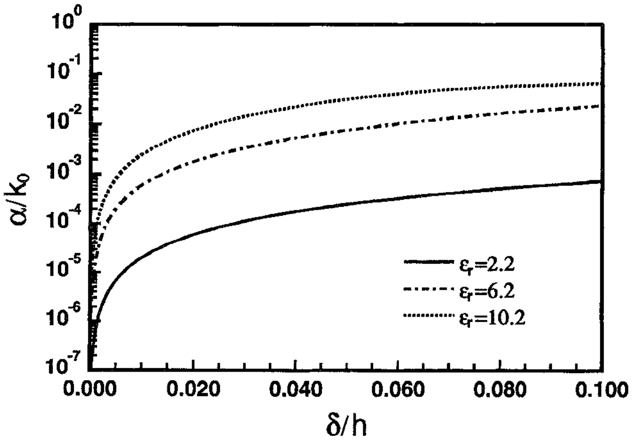


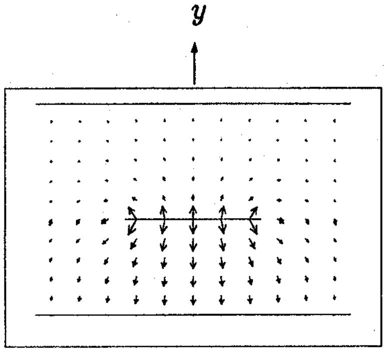
Fig. 8. α/k_0 versus δ/h for various ϵ_r, for the stripline of Fig. 1, at 3 GHz ($h = w = y_0 = 0.1$ cm).

substrate parameters, air-gap thickness, and strip width are the same as in Fig. 5. A plot of α/k_0 for the improper (leaky) solution is also included in Fig. 9. As the strip location moves upward to a position at the middle of the structure, β and α for the improper solution decrease, while β for the proper solution is essentially constant and nearly equal to k_{TM_0}. For a symmetric air-gap structure ($(y_0 - h)/\delta = 0.5$) the leakage constant becomes zero and the improper solution becomes purely real. This result is due to the inability of the symmetrically positioned strip current to excite the TM_0 parallel-plate mode (the longitudinal electric field, E_z, of the TM_0 mode is zero in the center of the symmetric structure). It is also interesting to note that as the strip location y_0 approaches the mid-line of the symmetric parallel-plate guide, the proper stripline mode degenerates into the TM_0 parallel-plate mode. When the strip is in the center of the symmetric parallel-plate structure it does not perturb the electric field of the TM_0 mode. Hence, for the proper mode of the symmetric stripline $\beta = k_{\mathrm{TM}_0}$. When the strip is exactly in the middle of the air gap ($y_0 = h + \delta/2$), there is numerical difficulty finding the proper solution. This is because $\beta = k_{\mathrm{TM}_0}$ and the poles $\pm k_{xp}$ in the k_x-plane approach the origin, near the path of integration. To overcome this difficulty, results for the symmetric structure were obtained by using a slightly asymmetric structure and taking the limit as y_0 approached $h + \delta/2$.

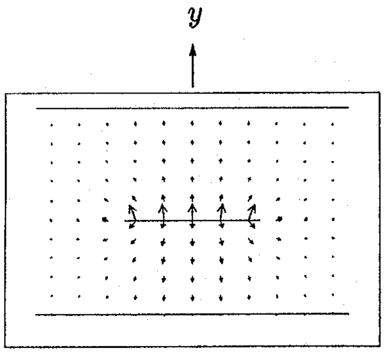
Finally, plots of the *field distributions* for the real part of the proper and leaky modes for the case of a *larger* air-gap thickness are shown in Fig. 10(a) and (b), respectively (the ratio δ/h for this case is about twice the value for Fig. 5). In this case the substrate relative permittivity and frequency was chosen to be slightly different (2.6 instead of 2.2 and 3.8 instead of 3.0 GHz) to match the values used in the experiment (plexiglas). These small differences are not significant, however. The important observation here is that when the air gap is thicker the fields of the proper mode change character and more closely resemble those of the improper (leaky) mode. Thus, when the air-gap thickness is larger, it is likely that both the proper mode *and* the leaky mode, and not just the leaky mode, will be strongly excited by a conventional stripline feed. Because the proper and leaky modes have different phase velocities, it is anticipated that a strong interference may occur between these two modes as they propagate down the line. An experimental observation of this is presented below, to show the type of spurious performance that can result from this interference when the leaky mode is excited.

B. Experimental Results

In order to provide experimental evidence for the existence of the leaky dominant mode, measurements were performed on a stripline structure having the same parameters as in Fig. 10, and also for one having the same substrate parameters but with no air gap. The substrate was fabricated with plexiglas boards ($\epsilon_r = 2.6$, loss tangent = 0.0058) having a length of 121.9 cm (along the strip) and a width of 91.4 cm. An adjustable air gap was realized by using plastic washers between the plexiglas boards, with nylon screws holding the assembly together. Two 50 Ω coaxial launchers were used for the coax-to-stripline transitions at both ends of the conducting strip. The strip width was chosen to give a characteristic impedance of 50 Ω for a zero-thickness air gap. An HP8510B analyzer was used to

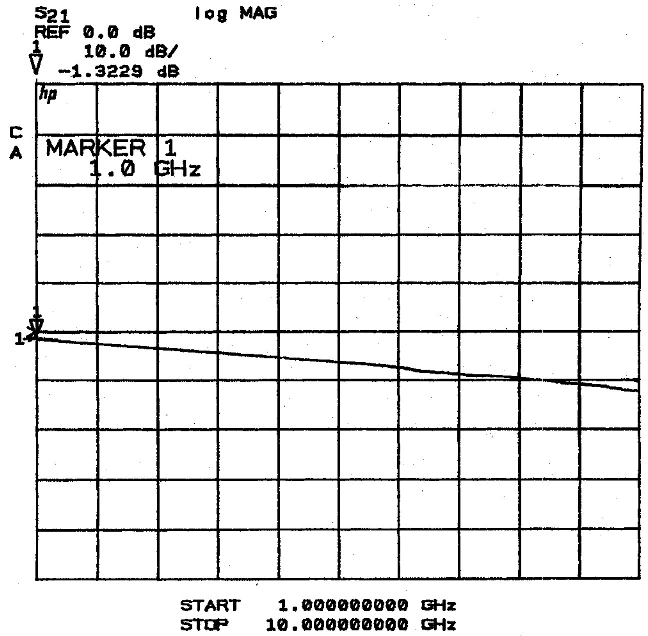


(a)

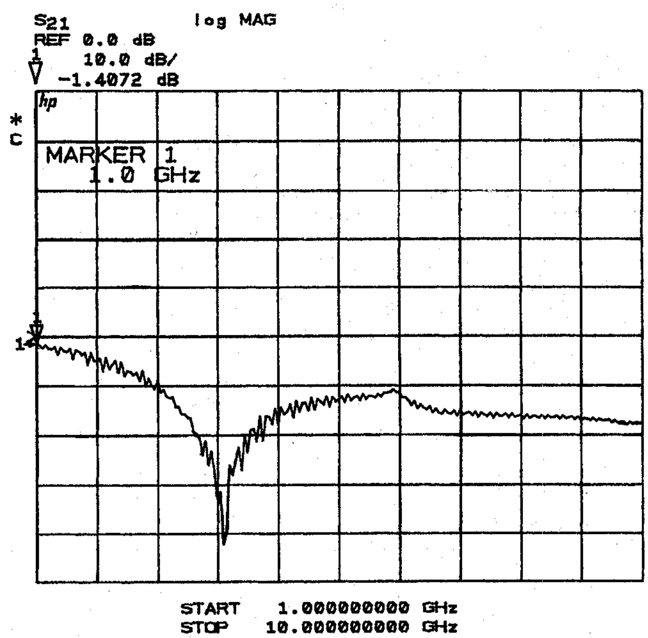


(b)

Fig. 10. The real part of the electric field distribution for (a) the proper solution and (b) the improper (leaky) solution, in a rectangular window of 0.89 cm × 1.34 cm around the strip (w = 0.64 cm), for the geometry of Fig. 1 (δ = 0.08 cm, h = 0.45 cm, ϵ_r = 2.6, and f = 3.8 GHz). The relative air-gap thickness δ/h is larger here than in Fig. 5, and consequently the fields for the proper solution have changed character.



(a)



(b)

Fig. 11. Measured values of $|S_{21}|$ versus frequency for the stripline structure of Fig. 1 with h = 0.45 cm, w = 0.64 cm, and ϵ_r = 2.6. (a) Homogeneous stripline (δ = 0). (b) Stripline with an air gap of δ = 0.08 cm.

obtain the magnitude of S_{21} over a wide frequency range (1 GHz–10 GHz) for both $\delta = 0$ and $\delta = 0.08$ cm.

Fig. 11(a) shows the frequency response of $|S_{21}|$ for the *homogeneous* stripline ($\delta = 0$). As seen in Fig. 11(a), there is only a small amount of attenuation in the transmission response, that increases with frequency. This attenuation is due primarily to the dielectric loss of the substrate. The homogeneous stripline exhibits a smooth $|S_{21}|$ response, as expected, since only a single mode is present.

For the *inhomogeneous* stripline ($\delta = 0.08$ cm), the measured $|S_{21}|$ frequency response is provided in Fig. 11(b). Comparing Fig. 11(a) and (b), it is seen that the overall attenuation in the air-gap structure is greater than that in the homogeneous structure. The increase in measured attenuation is ascribed to the excitation of the leaky dominant mode in the air gap structure. Even more importantly, there is a very pronounced dip at about 3.8 GHz in Fig. 11(b). This dip is attributed to destructive interference between the bound and leaky dominant modes. Because time-gating was used in the measurements, this interference dip is not due to the interference between waves that are reflected from the boundaries. It is interesting to note that the measured $|S_{21}|$ response in Fig. 11(b) flattens out at high frequencies. This is due to the fact that only the proper mode reaches the output port since the leakage constant is much larger at higher frequencies.

IV. Conclusion

A general and rigorous spectral-domain formulation for the analysis of an arbitrary multiple-layer stripline has been used to determine the propagation wavenumber and corresponding fields for the dominant modes in a stripline structure (the modes that have a quasi-TEM current distribution on the conducting strip). For a conventional stripline with a small air gap above the conducting strip, it has been demonstrated that a leaky (improper) dominant mode exists independently of, and in addition to, the conventional bound (proper) dominant mode. This newly discovered leaky mode has leakage into only the fundamental TM_0 parallel-plate mode of the background structure, and exists even at very low frequencies (down to zero frequency). For relatively small air gaps, the leaky dominant mode, not the bound dominant mode, has fields (around the strip) resembling those of the conventional TEM stripline mode. Thus, the leaky dominant mode, not the bound dominant mode, is the continuation of the conventional TEM stripline mode when a small air gap is introduced. Because of this, the leaky mode is expected to be excited more strongly by conventional stripline feeds than the bound mode when the air gap is small. The presence of this leaky mode causes additional loss and spurious transmission-line effects along the stripline because it radiates power and therefore interacts with other circuit components, and also because it interferes directly with the fields of the bound dominant mode. This spurious behavior has been confirmed experimentally.

ACKNOWLEDGMENT

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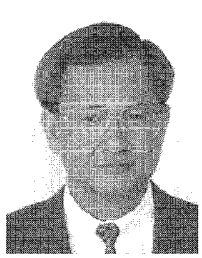

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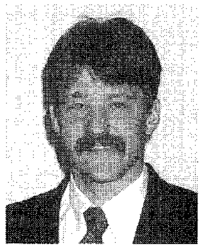

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