Existence of a Leaky Dominant Mode on Microstrip Line with an Isotropic Substrate: Theory and Measurements

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***Abstract*—A newly discovered *leaky* dominant mode is reported for conventional microstrip line on an isotropic substrate, at higher frequencies. The existence of this leaky mode has been confirmed both numerically and experimentally. This new mode exists independently of, and in addition to, the customary bound dominant mode. It leaks power away from the line into the fundamental TM_0 surface wave of the surrounding grounded substrate, and may therefore be responsible for spurious microstrip circuit performance at higher frequencies. This could have important implications for millimeter-wave circuits.**

I. Introduction

THE existence of leaky modes on various open wave-guiding structures is well known. For conventional microstrip line on isotropic substrates, the *higher-order* microstrip modes become leaky at *lower* frequencies [1], [2]. These higher-order leaky modes leak power away from the line either into space (the space wave) and/or into surface waves, depending on the frequency. These leaky modes also have a current distribution on the conducting strip and a field within the substrate that are quite different from the usual current and field associated with the *dominant* microstrip mode. (In this discussion, the use of the term "dominant" implies that the current on the strip is similar to that of the customary quasi-TEM mode.) Therefore, these higher-order modes will usually not be strongly excited by conventional feeds (such as an end-launch connector), even if these modes are above cutoff.

It was subsequently observed that if the substrate is anisotropic, the dominant mode on a microstrip line could become leaky at higher frequencies [3]. In this *anisotropic* case, the bound dominant mode turns into a leaky mode *above* some critical frequency, and leakage occurs into the TE_1 surface wave of the grounded substrate. It is well known that, for microstrip line on *isotropic* substrates, the conventional dominant mode is bound at all frequencies. Leakage of the dominant mode has also been observed on *stripline* with an *isotropic* substrate, provided the substrate material between the two ground planes is inhomogeneous [4]–[7]. The specific example discussed in [4]–[7] was that of a stripline with a homogeneous substrate and an air gap above the conducting strip, making the overall structure inhomogeneous. Leakage from other types of printed-circuit lines is discussed in [8].

In this paper, it is shown that contrary to general understanding, a *leaky dominant mode* is present at *higher* frequencies on conventional microstrip line with an *isotropic* substrate (Fig. 1). This new dominant mode, which has leakage into the TM_0 surface wave, exists independently of, and in addition to, the usual *bound* dominant mode. An important observation is that near the strip, this new leaky mode has a field distribution that closely resembles that of the bound mode, which is the customary microstrip mode. Hence, both the bound and leaky dominant modes are expected to be excited strongly by conventional microstrip feeds.

All numerical results are obtained using a general formulation, based on standard spectral-domain techniques [9], that accounts for both longitudinal and transverse currents on the conducting strip. The new leaky mode solution is obtained by using a path of integration in the spectral-domain formulation that detours around the poles of the integrand, corresponding to the TM_0 surface wave of the grounded substrate.

Experimental results are presented that confirm in an indirect way the theoretical calculations for the new leaky dominant mode. These measurements demonstrate, for three different strip widths, increased attenuation at higher frequencies in a manner consistent with the calculated frequencies at which leakage is expected to begin for the leaky mode.

II. Formulation

The analysis of the microstrip line is based on standard spectral domain techniques. As seen in Fig. 1, the perfectly conducting strip of width w is located at the interface between a semi-infinite air layer and a grounded isotropic substrate having dielectric constant ϵ_r and thickness h. In this analysis, the conducting strip is assumed to be infinitesimally thin, such that the surface current density $\mathbf{J}_s$ on the strip has components in the x and z directions only.

For fields propagating in the positive z direction, the surface current $\mathbf{J}_s$ is expressed as

$$\begin{aligned}\mathbf{J}_s(x,z) &= \mathbf{J}_{so}(x)e^{-jk_{zo}z}\\ &= [\hat{\mathbf{x}}J_x(x) + \hat{\mathbf{z}}J_z(x)]e^{-jk_{zo}z}\end{aligned} \quad (1)$$

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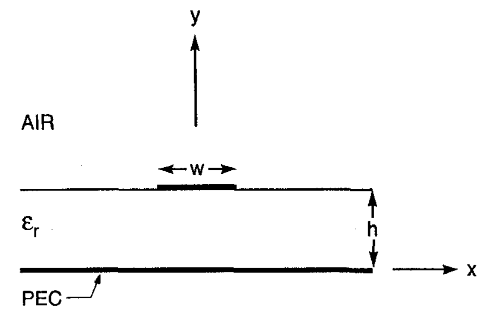

Fig. 1. Geometry of a microstrip line on an isotropic substrate.

where $J_x(x)$ and $J_z(x)$ represent the transverse variations of the x-directed and z-directed currents, respectively. The propagation wavenumber is denoted as $k_{zo} = \beta - j\alpha$, where β is the phase constant and α is the attenuation constant (α is referred to as the leakage constant when there are no metal or dielectric losses, which will be the case for all of the results presented here). The total electric-field vector $\mathbf{E}$ in the plane of the strip ($y = h$) generated by the surface current density $\mathbf{J}_s$, is calculated using the well-known *spectral-domain immittance method* [9], [10].

The transverse current variations $J_x(x)$ and $J_z(x)$ are approximated as

$$J_x(x) \simeq \sum_{n=1}^{N} a_n J_{xn}(x) \quad J_z(x) \simeq \sum_{m=1}^{M} b_m J_{zm}(x) \tag{2}$$

where a_n and b_m are unknown current coefficients, and $J_{xn}(x)$ and $J_{zm}(x)$ are known expansion functions. A commonly used set of expansion functions that enforces the required edge conditions for J_x and J_z are [9]

$$J_{xn} = \left(\frac{2}{\pi w}\right)\frac{\sin(2n\pi x/w)}{\sqrt{1-(2x/w)^2}}, \quad |x| < \frac{w}{2} \tag{3}$$

and

$$J_{zm} = \left(\frac{2}{\pi w}\right)\frac{\cos(2(m-1)\pi x/w)}{\sqrt{1-(2x/w)^2}}, \quad |x| < \frac{w}{2}. \tag{4}$$

The condition of zero tangential electric field on the strip is enforced using Galerkin's method, resulting in a homogeneous system of equations in which the matrix elements are functions of the unknown propagation wavenumber k_{zo}. Nontrivial solutions to this system exist only for values of k_{zo} for which the determinant of the system matrix is equal to zero. These values are obtained using a complex root-finding algorithm such as the secant method. For the dominant modes (both bound and leaky), it has been determined that only one basis function for each current component ($m = 1$ and $n = 0$) is needed to obtain accurate k_{zo} solutions, for the frequency and w/h ranges presented in the next section (this fact is verified numerically in Section III).

The main feature of interest in the spectral-domain analysis is the path of integration used to compute the matrix elements. Since the path is an open contour in the k_x plane, from $-\infty$ to ∞, different solutions for k_{zo} are possible depending upon the choice of the integration contour. The conventional path, which lies along the real axis in the complex k_x-plane (contour C_0 of Fig. 2), yields the solution for the proper (bound) mode. The other two paths C_1 and C_2 in Fig. 2 are used to obtain leaky-mode solutions [2], [11]. These references extend the method originally proposed in [12]. Both paths C_1 and C_2 have been also used in [2] to obtain solutions for leaky higher-order microstrip modes. As seen in Fig. 2, the path C_1 detours around the poles of the integrand in the k_x-plane (denoted with an X) that correspond to the TM_0 surface wave of the grounded substrate, and lies entirely on the top sheet of the k_x-plane, which is the proper sheet for the vertical wavenumber k_y. (In Fig. 2 it is assumed that only the TM_0 surface wave is above cutoff.) This path is used to obtain the solution for a leaky mode that has leakage into only the TM_0 surface wave [4]. In order to yield the solution for a leaky mode that leaks into both the space wave and the TM_0 surface wave, the path C_2 of Fig. 2 is utilized [13], [11]. This path lies partly on the improper sheet of the k_x-plane in the region between the branch cuts. No results using path C_2 are presented in this paper.

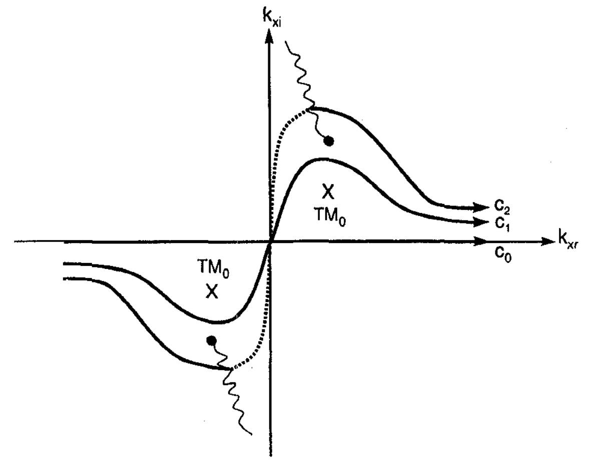

Fig. 2. Paths of integration in the complex k_x-plane used to obtain the propagation wavenumbers for the proper (bound) mode (path C_0); the improper mode that has leakage into the TM_0 surface wave (path C_1); and the improper mode that leaks into both the space wave and the TM_0 surface wave (path C_2).

III. Numerical and Experimental Results

In this section, both numerical and experimental results are presented for the leaky dominant mode that has leakage into only the TM_0 surface wave, and the general properties of this leaky dominant mode are discussed. For the frequencies used in the results, only the TM_0 surface-wave mode with propagation wavenumber k_{TM_0} is above cutoff.

A. Numerical Calculations

First, consider the microstrip structure of Fig. 1 with a substrate of dielectric constant $\epsilon_r = 2.6$, and a ratio of strip width to substrate thickness $w/h = 1.5$. Fig. 3 presents plots of the normalized phase constant β/k_0 and leakage constant α/k_0 versus the normalized frequency h/λ_0, obtained by the spectral-domain method using the paths C_0 and C_1 of Fig. 2

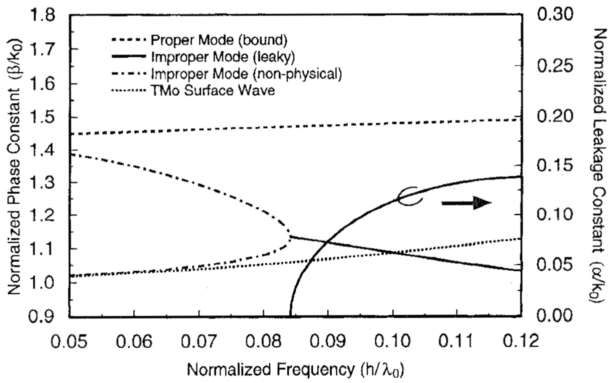

Fig. 3. Calculated values of the normalized phase constant β/k_0 and leakage constant α/k_0 versus the normalized frequency h/λ_0 for the microstrip line in Fig. 1, using a lossless plexiglass substrate: $\epsilon_r = 2.6$, $w/h = 1.5$. Plots of β/k_0 are shown for the proper mode (which is the customary bound mode) and the improper mode calculated from path C_1 (which is leaky at higher frequencies). Also shown is the dispersion curve for k_{TM_0}, the propagation wavenumber of the TM_0 surface wave on the grounded substrate. A plot of α/k_0 is shown on a separate vertical scale (on the right side) for the improper mode.

with only one basis function for the current ($m = 1$, $n = 0$). Two *independent* dominant modal solutions are found, one proper (bounded, from path C_0) and one improper (unbounded, from path C_1). The proper solution, shown with short dashes in Fig. 3, is the customary bound dominant mode, which remains purely real (for lossless structures). The improper solution has two distinct regions. For higher values of h/λ_0, the improper solution is *complex* with $\beta < k_{\mathrm{TM}_0}$, and thus represents a physical *leaky* mode because the propagation constant is consistent with the condition for leakage. The corresponding phase and leakage constants in this region are shown using solid curves in Fig. 3.

As h/λ_0 is decreased (the frequency decreases or the substrate becomes thinner), the phase constant β becomes greater than k_{TM_0}, and the solution enters the "spectral-gap" region [14], [15]. As it enters this region the solution no longer satisfies the condition of leakage for the TM_0 surface wave, and it therefore begins to lose physical significance [15], [16]. As h/λ_0 becomes even smaller, the leakage constant α for the complex solution approaches zero. At the point $\alpha = 0$ (splitting point), the solution splits into two improper real solutions ($\alpha = 0$) that correspond to nonphysical modes and will be ignored in this paper. These improper real solutions are represented by dash-dot curves in Fig. 3. The spectral-gap region is discussed in [14], [15]. The curve composed of a series of dots represents the TM_0 surface wave of the grounded substrate. It should be observed that even though this newly found *leaky mode* does not occur at low frequencies, the frequency or substrate thickness at which it does begin need not be very large; for the parameter values indicated in the caption for Fig. 3, a normalized frequency around $h/\lambda_0 = 0.08$ is sufficient.

Because the modes of interest are *dominant* leaky modes, having a quasi-TEM current distribution, it is expected that the modal solutions are well represented by the use of only the dominant basis function [$m = 1$ and $n = 0$ in (3) and (4)] and that the results for the propagation constant are not sensitive to the number of basis functions. (This is not expected to be the case for higher-order leaky mode solutions, as investigated in [2].) To verify this, Table I shows the convergence of the propagation wavenumber for both the bound and leaky modes for the case of Fig. 3, using a substrate thickness $h/\lambda_0 = 0.20$. An electrically thicker substrate corresponds to a slower convergence, and the value 0.20 is significantly larger than the thickest value in Fig. 3, which is 0.12. Even for this thickness, however, the use of a single basis function gives acceptable accuracy. For all subsequent results, only a single basis function has been used in the calculations.

Figs. 4 and 5 show plots of the normalized *electric fields* near the conducting strip for both the proper (bound) and leaky modes of Fig. 3, using the parameters given in the caption of Fig. 3, with $h/\lambda_0 = 0.12$. The electric field $\mathbf{E}_0(x, y)$ is obtained from a spectral-domain calculation, assuming a normalized real-valued strip current of unity. The field of the proper mode (Fig. 4) is purely real, while the field of the leaky mode is complex. Near the strip, the real part of the field for the leaky mode, shown in Fig. 5(a), is *very similar* to the field of the proper mode. However, away from the strip, in the transverse (x) direction, the field behaviors are quite different in that the field for the proper mode continues to decay whereas that for the leaky mode begins to increase exponentially [this increase is not visible on the scale of Fig. 5(a)]. A conventional microstrip feed, however, would

TABLE I

Convergence of the Propagation Wavenumber Versus the Number of Basis Functions, for Both the Bound Mode and the Improper Mode That Leaks into the TM_0 Surface Wave. $\epsilon_r = 2.6$, $w/h = 1.5$, and $h/\lambda_0 = 0.20$

		Bound	Improper	
m	n	β/k_0	β/k_0	α/k_0
1	0	1.54287	0.97857	4.699×10^{-2}
2	1	1.54573	0.98305	4.436×10^{-2}
3	2	1.54577	0.98310	4.416×10^{-2}
4	3	1.54578	0.98311	4.411×10^{-2}

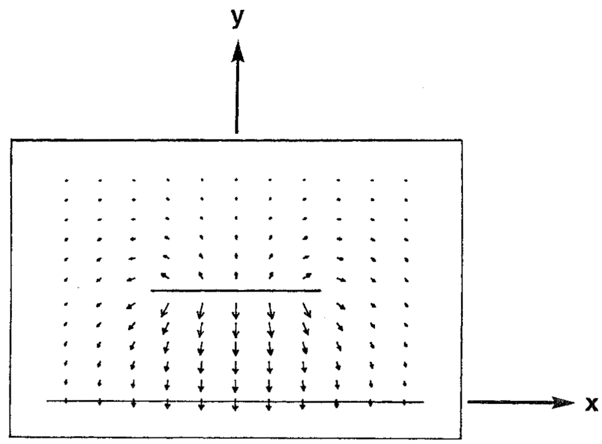

Fig. 4. Plot of the calculated electric field near the conducting strip for the proper (bound) mode on the microstrip line of Fig. 3, using the parameters given in the caption of Fig. 3 with $h/\lambda_0 = 0.12$.

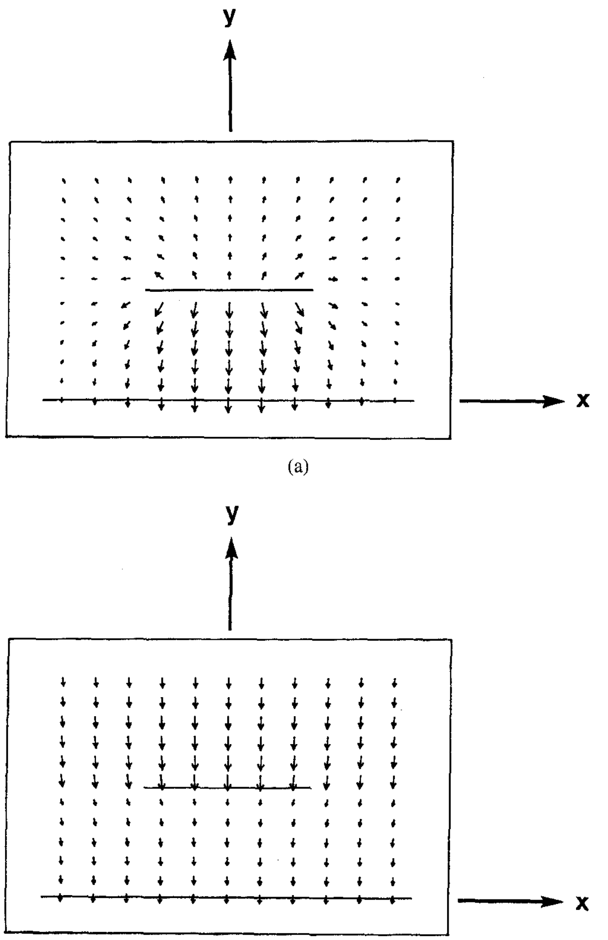

Fig. 5. Plots of the calculated electric field near the conducting strip for the improper mode in the leaky-mode range on the microstrip line of Fig. 3, using the parameters given in the caption of Fig. 3 with $h/\lambda_0 = 0.12$. (a) The real part of the electric field. (b) The imaginary part of the electric field. In this example each plot has been normalized by the maximum field in the plot. The ratio of these maximum values is $\mathrm{Im}(\mathbf{E})_{\max}/\mathrm{Re}(\mathbf{E})_{\max} = 0.99$.

affect only the fields near the strip, so that it would be expected to excite *both* modes strongly. Since the leaky mode leaks power into the TM_0 surface wave, the imaginary part of the leaky-mode field, shown in Fig. 5(b), resembles that of the surface wave. (The lengths of the arrows for the electric field in the air region are larger than those in the dielectric region because $D_y(= \epsilon E_y)$ must be continuous at the air-dielectric interface.) The amplitude of the imaginary part of the field is quite high, comparable to that of the real part, consistent with the large α observed in Fig. 3 for this leaky mode.

Fig. 6 presents a plot of α/k_0 versus h/λ_0 for the same structure considered in Fig. 3, but with *various substrate dielectric constants*. As seen in this figure, as the dielectric constant of the substrate increases, the frequency at which the onset of leakage occurs decreases. This frequency corresponds to the frequency of the splitting point in the β/k_0 plots. (The β/k_0 plots for these cases are similar in appearance to Fig. 3 and therefore have been omitted.) Another important observation is that the maximum leakage constant increases

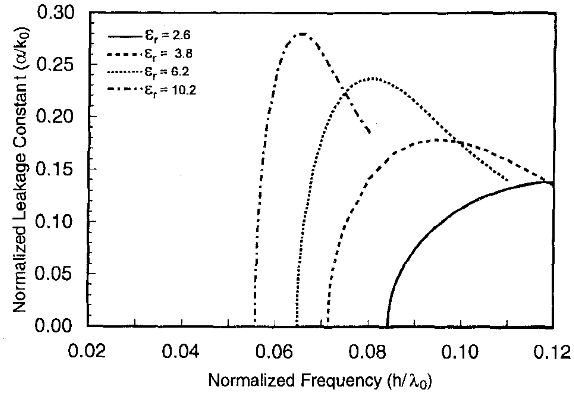

Fig. 6. Plots of α/k_0 for the improper mode in the leaky-mode range versus h/λ_0, for the microstrip structure of Fig. 1 with $w/h = 1.5$ and several different values of substrate dielectric constant ϵ_r.

substantially as the dielectric constant increases. The two curves in this figure that are terminated at the high-frequency end are stopped at the cutoff frequency for the TE_1 surface-wave mode of the grounded substrate.

In order to compare with experimental results, plots of β/k_0 and α/k_0 versus frequency are shown in Fig. 7 for the microstrip structure in Fig. 1 with substrate thickness $h = 0.45$ cm, strip width $w = 0.64$ cm, and substrate dielectric constant $\epsilon_r = 2.6$ (plexiglass). The loss tangent of the plexiglass is approximately 0.0058. For simplicity, however, the calculated numerical results are presented for lossless plexiglass (for a lossy substrate there is no longer a sharp transition between complex and real improper modes, although the calculated differences in both β and α between the lossless and lossy cases are very small). As seen in Fig. 7, the behaviors of β and α are very similar to those in Fig. 3. In the frequency range of interest (1–10 GHz), only the TM_0 surface-wave mode is above cutoff, and the onset of leakage (splitting point) occurs at approximately 5.5 GHz. In addition, a plot of α/k_0 versus frequency for the same structure considered in Fig. 7, but with *various strip widths*, is shown in Fig. 8. The main feature of interest in this figure is that the strip width affects the frequency at which the the onset of leakage occurs and, therefore, the frequency range over which the well-known proper (bound) mode and the new leaky mode are present simultaneously.

B. Measured Results

To experimentally verify the numerical results, transmission measurements were performed on microstrip structures having dimensions $h = 0.45$ cm and $w = 0.32$, 0.64, and 1.27 cm, which were fabricated with a plexiglass board having a width of 25.4 cm (x-direction) and a length of 10.2 cm (z-direction). Two 50 Ω-SMA end-launch connectors were used for the coax-to-microstrip transitions at both ends of the line. The measurements were obtained using an HP8510-B Network Analyzer. Time gating was used to eliminate multiple reflections between the coax-to-microstrip transitions at each end of the microstrip line, and reflections from the edges of

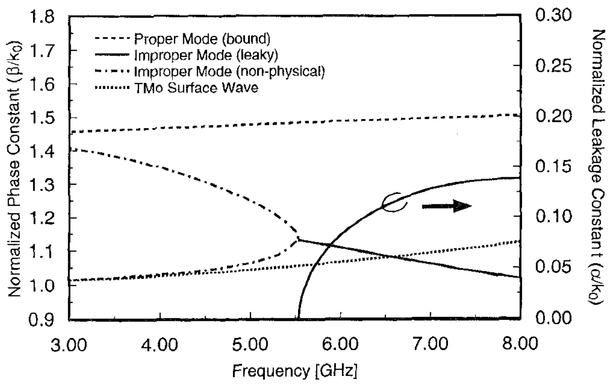

Fig. 7. Calculated values of β/k_0 and α/k_0 versus frequency for the microstrip line in Fig. 1, using a lossless plexiglass substrate: $\epsilon_r = 2.6$, $w = 0.64$ cm, and $h = 0.45$ cm. Plots of β/k_0 are shown for the proper mode and the improper mode. Also shown is the dispersion curve for k_{TM_0}, the propagation wavenumber of the TM_0 surface wave on the grounded substrate. A plot of α/k_0 is shown on a separate scale for the improper mode.

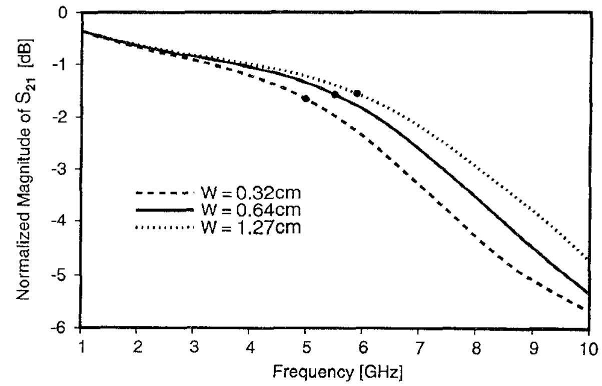

Fig. 9. Measured transmission response $|S_{21}|$ in dB versus frequency for a microstrip line having a length of 10.2 cm, and three different strip widths corresponding to those in Fig. 8 (all three curves are normalized to the same value at 1.0 GHz). The geometry is the same as in Fig. 7, except that the plexiglass substrate used in the measurements has a loss tangent of approximately 0.0058. For each curve, the frequency corresponding to the onset of leakage (from Fig. 8) is shown by a dot for comparison.

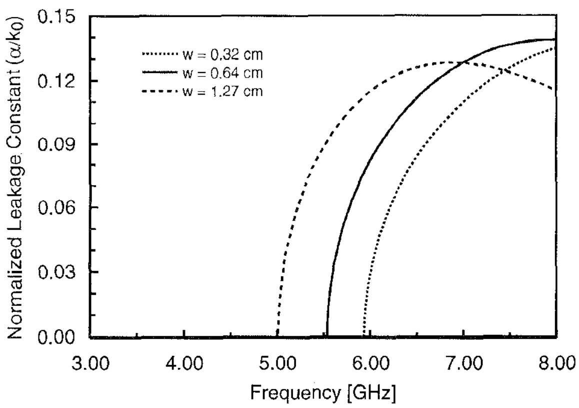

Fig. 8. Plot of α/k_0 versus frequency for the same geometry as in Fig. 7, but with different strip widths. The frequency at which the onset of leakage occurs clearly changes with strip width.

the substrate, thus approximately simulating the response for a matched line on an infinitely wide substrate.

For the transmission measurements to be meaningful, the direct surface-wave and space-wave fields launched by the feed connector and received by the output connector should be small. In order to ascertain the amount of such spurious contributions, we measured the through response *without* the strip present, and we found that the direct transmission from the input to the output connectors was indeed very small.

Fig. 9 shows *experimental* results for the transmission coefficient $|S_{21}|$ through a 10.2 cm length of microstrip line, for the different strip widths used in Fig. 8 (all three curves are normalized to the same value at 1.0 GHz). The main feature in Fig. 9 is that each curve has a distinct change in slope (knee). The frequency at which the knee occurs varies with strip width, and corresponds to the frequency of the onset of leakage predicted in Fig. 8 (for each curve in Fig. 9 the frequency at which the calculated onset of leakage occurs is shown with a small dot for comparison). For frequencies below the onset of leakage the response is consistent with that of the bound mode alone, and demonstrates that the improper mode is not physically significant in this region, as discussed previously. Beyond this point, the slope of the $|S_{21}|$ response becomes much steeper. This behavior is consistent with the calculations that indicate that *both* the bound mode and the leaky mode exist in this region. The increase in attenuation is therefore due to the leakage.

The change in slope at the knee of each curve in Fig. 9 is gradual, for two reasons. First, the leakage rate builds up from zero; second, the actual onset frequency of the leakage lies within the spectral gap, so that its physical meaning asserts itself in a gradual fashion, as mentioned earlier. The measurements are therefore consistent with the theoretical predictions, and the correlation between them is as good as one could expect.

IV. Conclusion

It is shown here that a *leaky* dominant mode exists at high frequencies on microstrip line with an *isotropic* substrate. This new mode exists *independently of,* and *in addition to,* the customary bound dominant mode. For this mode the leakage occurs into the TM_0 surface wave of the surrounding substrate at an angle from the strip itself. The leakage occurs at higher frequencies, or for thicker substrates, with the leakage beginning when the substrate is roughly $0.1\lambda_0$ in thickness; the leakage begins at lower frequencies when the dielectric constant of the substrate is greater or when the strip is narrower. The field distributions near the strip are very similar for both the customary bound mode and the new leaky mode, so that the two modes would be excited with comparable amplitudes by a conventional microstrip feed. The new leaky mode can therefore play a strong role once the frequency is high enough for it to be excited.

Measured results have been presented which support the existence of this new mode, and also show that this mode will be strongly excited at high frequencies by a customary microstrip feed. The presence of this new leaky mode is significant in that it represents a new mechanism for power loss in microstrip circuits. Furthermore, the surface-wave leakage field for this mode can easily extend well beyond the strip in the transverse directions. This leakage field may therefore interact with other components in the microstrip package, accounting for crosstalk or other spurious effects.

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