EXISTENCE OF A LEAKY DOMINANT MODE ON MICROSTRIP LINE WITH AN ISOTROPIC SUBSTRATE: THEORY AND MEASUREMENT

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ABSTRACT

We have made the surprising discovery that a leaky dominant mode is present at higher frequencies on conventional microstrip line with an isotropic substrate, and we have confirmed its existence both theoretically and experimentally. The leaky mode exists independently of, and in addition to, the customary bound dominant mode. This new mode leaks power away from the line into the TM_0 surface wave supported by the surrounding grounded substrate, and may be responsible for spurious microstrip performance at higher frequencies. This could have important implications for millimeter-wave circuits.

INTRODUCTION

The existence of leaky modes on various open wave-guiding structures is well-known. For conventional microstrip on isotropic substrates, the higher-order microstrip modes become leaky at lower frequencies [1,2]. These higher-order modes 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* mode, and therefore such modes will usually not be strongly excited by a conventional feed (such as a probe connector). The use of the term "dominant" in this discussion implies that the current on the conducting strip is similar to that of the customary quasi-TEM mode.

It was subsequently discovered that the dominant mode on microstrip may become leaky at higher frequencies if the substrate is anisotropic [3]. In that *anisotropic* case, the bound dominant mode turns into a leaky dominant mode above some critical frequency. For microstrip line on *isotropic* substrates, the conventional dominant mode was found to remain purely 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 [4,5]. The specific example discussed in [4,5] was that of a stripline with a homogeneous substrate and an air gap above the center conductor, making the overall structure inhomogeneous.

In the present work, we show 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 is physically meaningful, and it exists independently of, and in addition to, the usual *bound* dominant mode, in contrast to what was found [3] for microstrip lines on anisotropic substrates.

Both theoretical and experimental results are presented here to confirm the existence of this new dominant mode. An important observation is that, near the strip, the leaky mode has a field distribution that closely resembles that of the bound mode, which is the customary microstrip field. Hence, at high frequencies, both the proper and leaky modes are expected to be excited strongly by conventional microstrip feeds. This feature is verified experimentally in the results that follow.

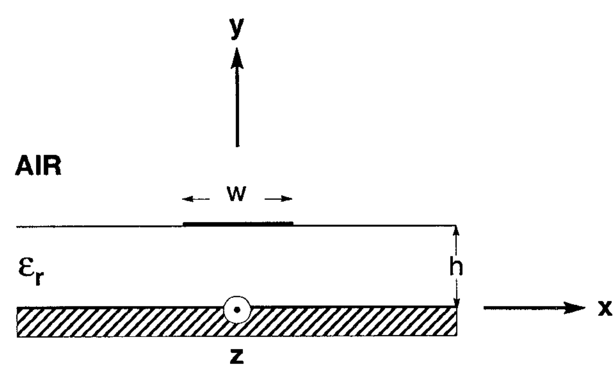

Fig. 1: Geometry of a microstrip line on an isotropic substrate.

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FORMULATION

The formulation of the microstrip eigenvalue problem, in which a transcendental equation for the unknown propagation wavenumber k_{zo} is derived, utilizes the well-known spectral-domain method. Transmission line theory is used in this approach to derive the spectral-domain dyadic Green's function $\tilde{\mathbf{G}}(k_x, k_{zo})$, which represents the Fourier transform (in x) of the electric field produced by a line current of unit strength at $x = 0, y = h$ (see Fig. 1). Because the strip is a perfect conductor, the electric field integral equation applied with Parseval's theorem yields

$$\int_{-\infty}^{\infty} \tilde{\mathbf{J}}(-k_x) \cdot \tilde{\underline{\underline{\mathbf{G}}}}(k_x, k_{zo}) \cdot \tilde{\mathbf{J}}(k_x)\, dk_x = 0, \qquad (1)$$

where $\tilde{\mathbf{J}}(k_x)$ is the Fourier transform of the strip current. A moment method procedure that accounts for x and z directed currents is used for the solution of (1). The main feature of interest in (1) is the path of integration. The conventional path, which lies along the real axis in the complex k_x-plane, yields the solution for the bound (proper) microstrip mode. The solution for the new leaky (improper) mode uses a path which detours around the TM_0 surface-wave poles in the k_x-plane, as shown in Fig. 2. The reasoning for such a path is similar to that for the leaky dominant stripline mode [4].

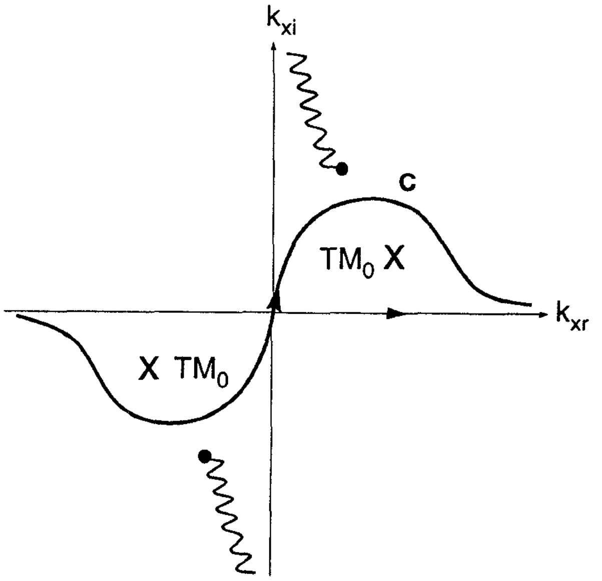

Fig. 2: Paths of integration in the complex k_x-plane used to find the propagation wavenumbers for both the proper microstrip mode (real axis path) and the improper mode (path C).

NUMERICAL AND EXPERIMENTAL RESULTS

Results, both numerical and experimental, are shown below for a microstrip line on a plexiglass substrate ($\epsilon_r = 2.6$). The loss tangent of the plexiglass is approximately 0.0058. However, for simplicity, the numerical results are presented for a lossless plexiglass substrate; the calculated differences in both β and α between the lossless and lossy cases are very small.

Figure 3 presents plots of the normalized phase constant β/k_0 and leakage constant α/k_0 versus frequency, obtained by solving (1). Two independent dominant mode solutions are found, one proper and one improper. The proper solution is the customary dominant mode, which is purely bound at all frequencies, and is shown with short dashes in Fig. 3. The improper solution has two parts. At higher frequencies, the improper solution is complex, and represents a physical *leaky* mode; the phase constant and leakage constant values are shown using solid curves in Fig. 3. At lower frequencies, the improper solution takes the form of a pair of improper real modes (for which the fields increase transversely), which are non-physical and which can therefore be ignored for practical purposes. That range of the improper mode is represented in Fig. 3 by a dashed-dot curve, and lies within the "spectral-gap region", the properties of which are discussed further in [6]. The curve composed of a series of dots represents the TM_0 surface wave on the surrounding grounded substrate.

Figures 4 and 5 show plots of the normalized electric fields near the strip conductor for both the bound and leaky modes of Fig. 3, at $f = 8.0$ GHz. The normalized field of the bound mode (Fig. 4) is purely real, while the field of the leaky mode is complex. The real part of the field for the leaky mode, shown in Fig. 5, is seen to be very similar to the field of the bound mode. Away from the strip conductor, in the transverse (x) direction, the field behaviors are different in that the field for the bound mode continues to decay whereas that for the leaky mode increases. A conventional microstrip feed, however, would affect only the fields near the strip, so that it would be expected to excite both modes strongly. Since the leaky mode leaks power in the form of the TM_0 surface wave, the imaginary part of the leaky-mode field resembles that of the surface wave; due to space limitations imposed on this summary, this field plot is not included here but will be presented during the talk.

Figure 6 presents a plot of α/k_0 versus frequency for the same structure as in Fig. 3, but with different strip widths. The main feature of interest is that the strip width affects the frequency at which the onset of leakage occurs (where the two improper real solutions meet the leaky solution) and, therefore, the frequency range where the well-known bound mode and the new leaky mode are present simultaneously. Figure 7 shows *experimental* results for the transmission coefficient $|S_{21}|$ through a 10.2 cm length of microstrip line, for the three different strip widths shown in Fig. 6 (all three curves are normalized to the same value at 1.0 GHz). These measurements were performed with an HP8510-B Network Analyzer, using a test fixture with end-launch connectors. Time gating was used to eliminate multiple reflections between the coax-to-microstrip transitions, and reflections from the edges of the substrate, thus simulating the response for an infinitely wide substrate. The main feature in this figure is that each curve has a distinct change in slope (or knee). The frequency at which the knee occurs varies with strip width, and for each width the knee corresponds to the frequency of the onset of leakage predicted by Fig. 6 (for each curve the frequency at which the onset of leakage occurs is shown for comparison). For

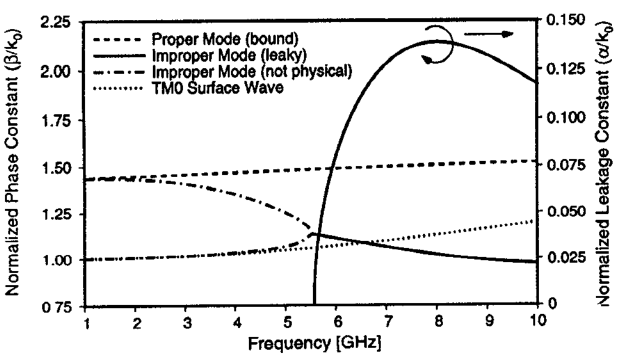

Fig. 3: Calculated values of β/k_0 and α/k_0 versus frequency for the microstrip line in Fig. 1, using a lossless plexiglass substrate: $\epsilon_r = 2.6$, $W = 0.64$ cm, $h = 0.45$ cm. Plots of β/k_0 are shown for the proper mode and the improper mode. Also shown is the dispersion curve for k_{TM_0}, the propagation wavenumber of the TM_0 mode on the grounded substrate. A plot of α/k_0 is shown on a separate scale for the improper mode, when it is leaky.

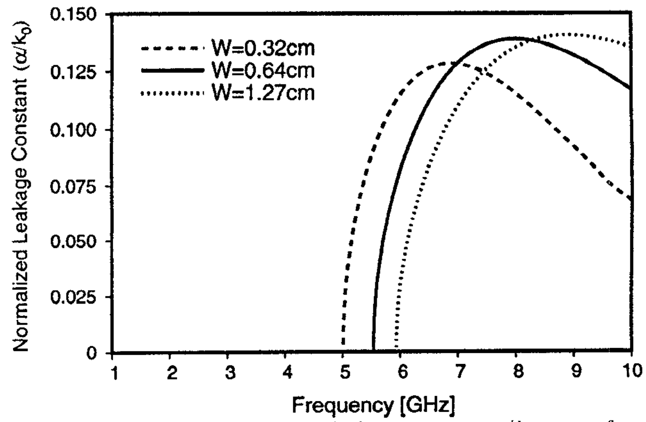

Fig. 6: Plot of the calculated leakage constant α/k_0 versus frequency for the same geometry as that in Fig. 3, but with several different strip widths. The frequency at which the onset of leakage occurs clearly changes with strip width.

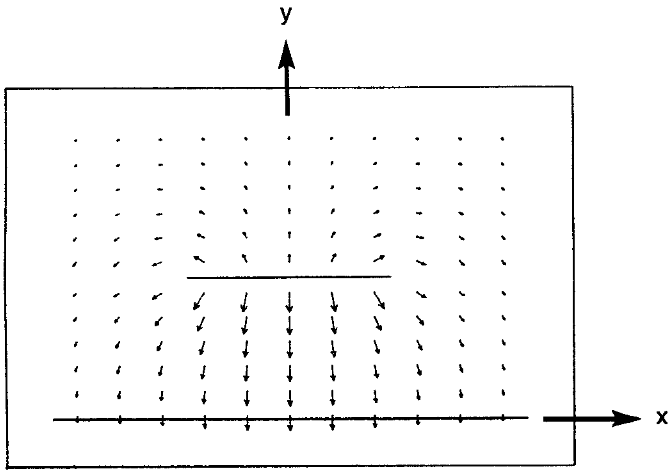

Fig. 4: Plot of the calculated electric field near the strip conductor for the *bound* mode on the microstrip line of Fig. 3, at a frequency of 8.0 GHz.

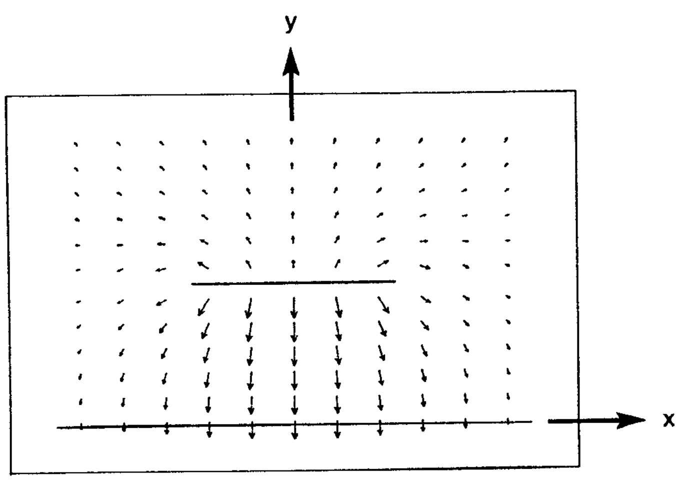

Fig. 5: Plot of the real part of the calculated electric field near the strip conductor for the *leaky* mode on the microstrip line of Fig. 3, at a frequency of 8.0 GHz.

frequencies below the onset of leakage the response is determined by the bound mode only. Beyond the points indicated by the dots the slopes of the $|S_{21}|$ responses becomes much steeper. This behavior is consistent with the assumption that both a bound and leaky mode exist in this region. Therefore, the increased attenuation is attributed to leakage. The overall change in $|S_{21}|$ indicates that the level of the leaky wave is comparable to that of the bound mode at high frequencies.

Measured results are shown in Fig. 8 for a fixed strip width ($W = 0.64$ cm) versus the length of the microstrip line, for several different frequencies. At the two lowest frequencies ($f = 1$ GHz and 4 GHz), the curves are seen to be relatively flat and to decay relatively slowly with increasing line length. This behavior is consistent with the fact that *only* the *bound* dominant mode is present at these frequencies, so that the attenuation rate is small, being due to the metal and dielectric losses. For the remaining frequencies, we observe in Fig. 8 that some pronounced oscillatory behavior occurs at the shorter line lengths, and a more rapid decay at the larger values of line length. To explain such behavior, we first note that at these higher frequencies the *bound* and the *leaky* dominant modes are *both* present simultaneously. We should also appreciate that the oscillations cannot be due to reflections between the ends of the line since reflections are time-gated out. Furthermore, measurements of the direct radiation from the input connector to the output connector indicate that such radiation is too small to produce these oscillations. Thus, the oscillations in the curves must be attributed to the *interference* between the bound and leaky modes received at the output port, since these two modes possess different values of β. As the line length increases, the amplitude of the leaky mode along the line decreases (since power leaks away at an angle in surface wave form), so that the amplitude of the interference-produced oscillations also decreases.

SUMMARY

We have discovered that, in addition to the customary bound dominant mode, a leaky dominant mode exists on microstrip line. Measured results have been presented which confirm the existence of this mode at higher frequencies, and also show that the leaky mode and the bound mode will be excited with comparable amplitudes, at higher frequencies, by conventional microstrip feeds. The presence of this leaky mode is significant in that it represents a new mechanism for power loss in microstrip circuits, by virtue of leakage into the TM_0 surface wave on the supporting substrate. Furthermore, the leakage fields may interact with other components in the microstrip package, accounting for crosstalk or other spurious effects at high frequencies.

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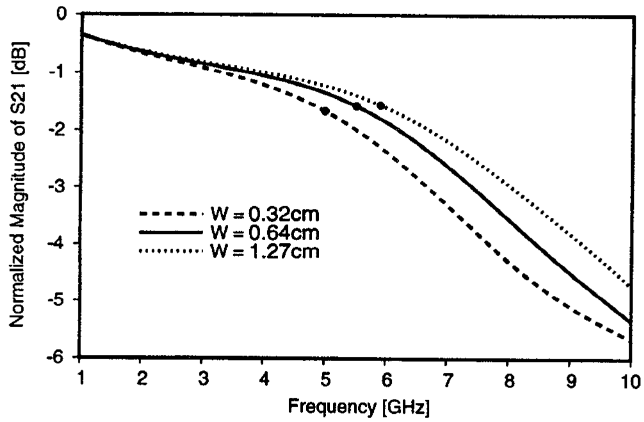

Fig. 7: Measured transmission response $|S_{21}|$ in dB versus frequency for a microstrip line having a length of 10.2 cm, and three different strip widths corresponding to those in Fig. 6 (all three curves normalized to the same value at 1.0 GHz). The geometry is the same as in Fig. 3, except that the 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. 6) is shown by a dot for comparison.

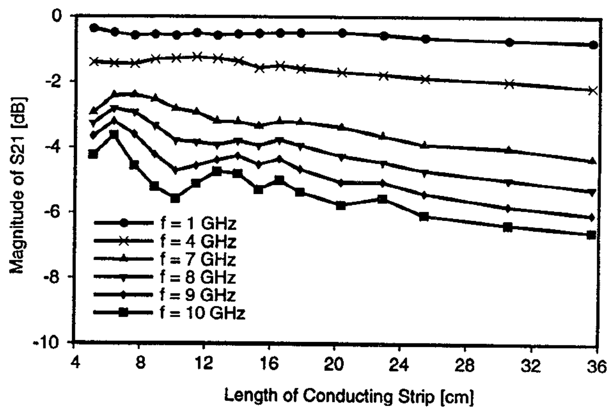

Fig. 8: Measured transmission response $|S_{21}|$ in dB versus length of the microstrip line for several different frequencies. The geometry is the same as in Fig. 7, with a line width W of 0.64 cm.