LEAKAGE OF THE STRIPLINE DOMINANT MODE PRODUCED BY A SMALL AIR GAP

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ABSTRACT

Stripline may have an inhomogeneous dielectric medium, due to inadvertent air gaps. For such inhomogeneous stripline, *two* dominant modes are generally present, a *proper* (bound) mode and an improper complex (*leaky*) mode; the properties of both dominant modes have been obtained by using a full-wave spectral-domain approach. Of these two dominant modes, we find that it is the *leaky* mode that is the continuation of the conventional stripline mode when a very small air gap is introduced. This presentation discusses the nature of this leaky dominant mode, and shows that the leaky mode may be responsible for spurious transmission-line effects in stripline. In addition, under certain conditions interference effects can occur between the two dominant modes. These conclusions are confirmed by measurements.

I. INTRODUCTION

It is well known that a lossless strip transmission line (stripline), uniformly filled with a homogeneous dielectric material, supports the TEM mode as the fundamental mode. This TEM mode is a proper (bound) mode, meaning that the fields decay in the transverse direction away from the strip. At every frequency the longitudinal propagation constant k_{xo} of the TEM mode is equal to the substrate wavenumber k. In practice, however, when stripline is constructed, the dielectric material between the ground planes is often no longer homogeneous. This may happen inadvertently. for example. when a small air gap is introduced in the middle of the dielectric, as shown in Fig. 1. For this inhomogeneous structure, the dominant modes of propagation are quasi-TEM, with zero cutoff frequency. A dominant mode on the inhomogeneous stripline (as opposed to a higher mode) has a current variation across the strip that is similar in form to that for the TEM mode of homogeneous stripline.

Recently, it was discovered that more than one dominant mode can exist on inhomogeneous stripline [1]. One of the dominant modes is a proper mode, which has a real propagation constant (assuming lossless stripline). In addition to the proper mode, there exists an *improper* dominant mode on the stripline, which has fields that increase with transverse distance from the strip. The proper mode is a bound mode, whereas the improper mode is a *leaky mode* for which power leaks away from the strip at an angle to it. The goal of the present study is to examine the nature of the improper mode on one of the most important inhomogeneous stripline structures: a conventional stripline with a small air gap above the strip. Due to the leakage, the presence of the improper mode on this structure can produce unexpected spurious transmission-line effects, such as increased attenuation along the line and crosstalk between adjacent striplines in integrated circuits. Such spurious behavior is demonstrated experimentally, and is discussed in Sec. III.

II. GENERAL PROPERTIES OF THE IMPROPER (LEAKY) MODE

For lossless stripline with a small air gap, it has been found [1] that there exists a complex improper modal solution, which is a dominant mode solution separate from the proper solution. The complex improper mode has a phase constant β which is usually less than the propagation constant k_{TM_0} of the fundamental guided-wave mode of the inhomogeneous parallel-plate structure away from the strip region. Such a complex improper mode is interpreted as a mode that *leaks* power by radiating into the TM_0 parallel-plate mode as it propagates, and hence attenuates longitudinally ($\alpha > 0$) [2], [3].

For a stripline with a small air gap, the improper mode corresponds to a mode that leaks power into the dominant mode of the background parallel-plate guide, and therefore has a complex propagation constant $k_{xo} = \beta - j\alpha$. Furthermore, this leaky improper mode, rather than the proper (bound) mode, has a field configuration closely resembling that normally associated with a conventional homogeneous stripline. In fact, for very small air gaps, the proper mode has a field configuration that resembles that of the TM_0 parallel-plate mode. This leads to the surprising conclusion that of the two dominant modes present when a very small air gap is introduced, it is the *leaky* improper mode that is the continuation of the conventional TEM mode present when there is no air gap. Therefore, the leaky mode is the

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one that should be predominantly excited by a common stripline feed (such as a coaxial launcher). This conclusion is supported by measurements which show that the amplitude of the through response for a stripline ($|S_{21}|$) is reduced when a small air gap is introduced, thus indicating that the transmitted signal experiences a level of attenuation greater than that associated with normal ohmic loss. This additional attenuation is associated with the power loss due to leakage.

Figure 2 shows a plot of normalized β and α versus air-gap thickness δ for the stripline structure of Fig. 1, with a plexiglass substrate ($\epsilon_r' = 2.6$). Results are shown in Fig. 2 for a lossy substrate with a loss tangent of 0.0058 (published value for plexiglass at 3.0 GHz [4, p. 453] and a lossless substrate. The loss tangent does not noticeably affect β (only α). Thus, Fig. 2a is for the lossy case only, while results for both lossy and lossless cases are shown in Fig. 2b. As seen in Fig. 2a, for $\delta < 0.26$ cm the improper solution has a phase constant β is less than $\Re\{k_{TMo}\}$ (the real part of k_{TMo}), so the mode corresponds to *conventional leakage*. For $\delta > 0.26$ cm β is greater than $\Re\{k_{TMo}\}$, so that the improper mode is outside the conventional leakage region; however, k_{xo} is still complex, and hence there is some amount of leakage. As seen in Fig. 2b, the leakage constant α first increases with increasing δ, and then decreases. Near the point of maximum attenuation ($\delta \approx 0.26$ cm), it is noticed that most of the attenuation is due to leakage and not dielectric loss, even for this quite lossy substrate. These results are typical for more common substrate materials, as well.

III. EXPERIMENTAL RESULTS

In order to experimentally demonstrate the existence of the dominant leaky mode, a stripline structure should have a relatively small air-gap thickness so that the leaky mode will be excited more strongly than the proper mode using a common stripline feed. However, the attenuation constant of the leaky mode should be high enough so that the loss is due primarily to leakage; hence the air gap should not be too small. With these constraints, an air-gap thickness of 0.08 cm was chosen for the experiment. For later reference, a plot of the real part of the electric field corresponding to the proper mode and the leaky mode is provided in Figs. 3a and 3b, respectively, for $\delta = 0.08$ cm at 3.8 GHz.

Measurements were performed on a stripline structure having dimensions $h = 0.445$ cm and $w = 0.635$ cm, which was fabricated with plexiglass substrate boards 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 substrate 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 line. The strip width was chosen to give $Z_0 = 50\Omega$ for a zero thickness air gap. Transmission (S_{21}) measurements over a wide frequency range (1 GHz - 10 GHz) were made for $\delta = 0$ and $\delta = 0.08$ cm.

Figure 4a shows $|S_{21}|$ for the homogeneous stripline ($\delta = 0$), and Fig. 4b shows $|S_{21}|$ for the inhomogeneous stripline ($\delta = 0.08$ cm). The theoretical result in Fig. 4a is obtained by assuming that the strip and two ground planes are perfect conductors, and using the previously quoted values for ϵ_r' and loss tangent. As seen in Fig. 4a, there is good agreement between the theoretical and experimental results. This indicates that the attenuation is primarily due to dielectric loss (not conductor loss). The homogeneous stripline exhibits a smooth $|S_{21}|$ response, as expected.

The plot for $\delta = 0.08$ cm shows that for all the measured frequencies the attenuation in the air-gap structure is greater than that in the homogeneous structure. The increase in attenuation is attributed to the excitation of the dominant leaky mode in the air-gap structure, and therefore a loss of power due to leakage. In addition, there is a very pronounced dip at about 3.8 GHz. Since the coaxial connectors and stripline transitions used have low VSWRs (typically less than 1.17), the dip in Fig. 4b is attributed to destructive interference between the proper and leaky modes. From the field distributions shown in Fig. 3, it is expected that the proper mode is excited to some degree by a common stripline feed, but to a lesser extent than the leaky mode. Assuming that the dip is due to interference between the proper and leaky modes (which gives $|S_{21}| = -42.0$ dB at 3.8 GHz), the ratio of the wave amplitudes of the proper mode and the leaky mode at the input port was calculated from the theoretical values of α for the two modes, giving a ratio of 0.12. From the theoretical values of β the phase difference between the two waves at the input port is calculated as 1.11 radians.

From completely independent considerations we can draw two conclusions in connection with the value of $|S_{21}|$ at the high-frequency end, $f = 10$ GHz. First, the value of α/k_o increases monotonically with frequency, so that the power in the leaky mode reaching the output port is computed to be about 85 dB lower than its value at the input end. The corresponding power ratio for the proper mode at that frequency is found to be 9.5 dB down. The first conclusion, then, is that for $f = 10$ GHz the power at the output port is solely that due to the proper mode. For this reason, the experimental curve for $|S_{21}|$ in Fig. 4b flattens out for higher frequencies. Second, it is found that as frequency increases the field distribution for the proper mode becomes more and more like that for the leaky mode, so that the proper mode should be much more strongly excited at the higher frequencies. Working backwards from the experimental value of 18 dB for $|S_{21}|$ at $f = 10$ GHz, we find that the amplitude ratio for the proper to improper modes is 0.48, which is much larger than the value 0.12 that was calculated at $f = 3.8$ GHz, at the large dip.

We then calculated a theoretical plot for $|S_{21}|$ as a function of frequency, assuming that the amplitude ratio at the input port remains at 0.12 from the low-frequency end to the large dip, but then increases linearly from 0.12 there to 0.48 at $f = 10$ GHz. The amplitude ratio is assumed constant below 3.8 GHz since the field distributions for both modes change only slightly in this frequency range. For simplicity, we also assumed that the phase difference between these two modes at the input end remains constant over the frequency range. The resulting computation is shown in Fig. 4b as the dashed curve. The agreement with the measured curve is seen to be fairly good.

IV. CONCLUSIONS

It has been demonstrated that a dominant complex improper (leaky) mode exists in general on a conventional stripline with a small air gap above the strip. This improper mode has a zero cutoff frequency, as does the proper mode. The improper (leaky) mode, rather than the proper mode, is the one that has fields resembling those of the conventional TEM homogeneous stripline mode, and is therefore the mode that is expected to be more strongly excited by a common stripline feed. Its presence may cause spurious transmission-line effects along such stripline, because it leaks power and may therefore interact with other circuit components, as well as interfere directly with the fields of the proper mode. This spurious behavior has been demonstrated experimentally.

REFERENCES

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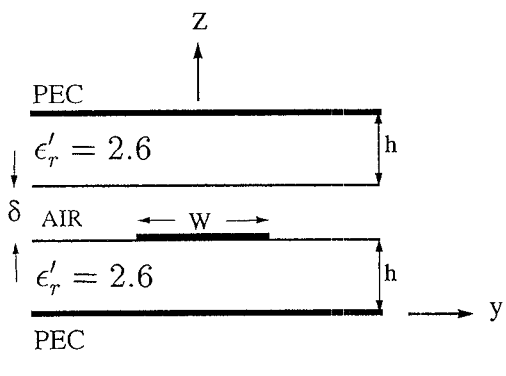


Figure 1: Stripline with an air-gap thickness δ.

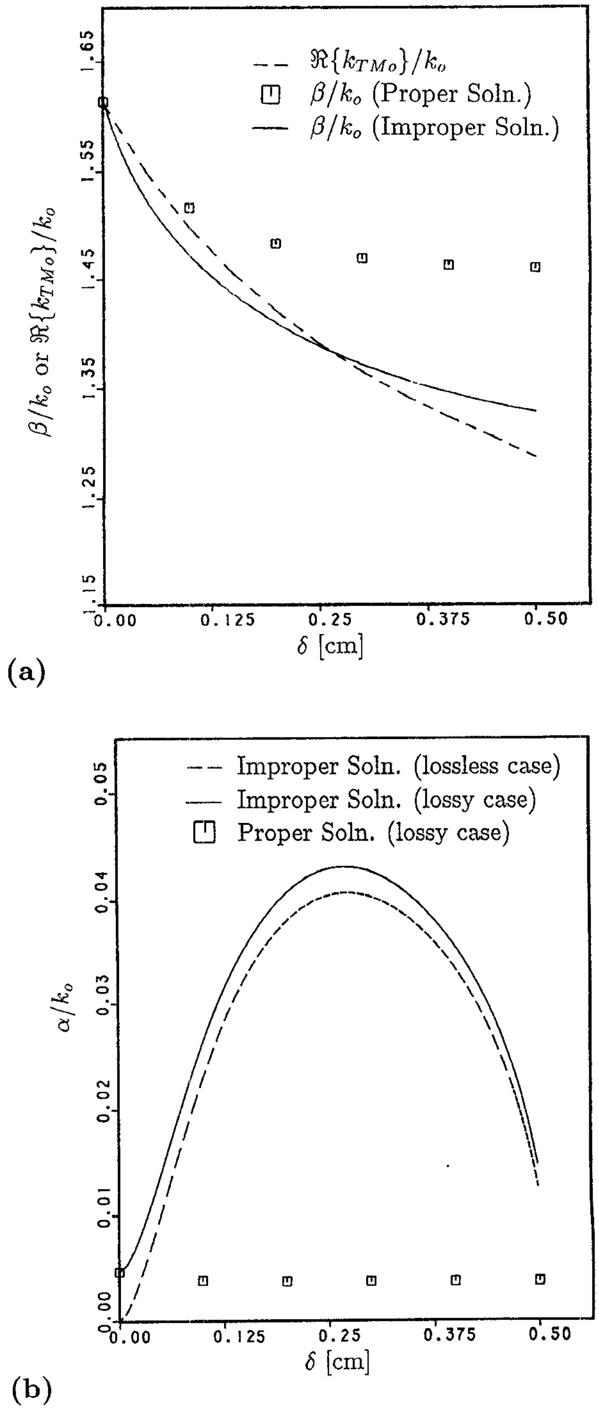
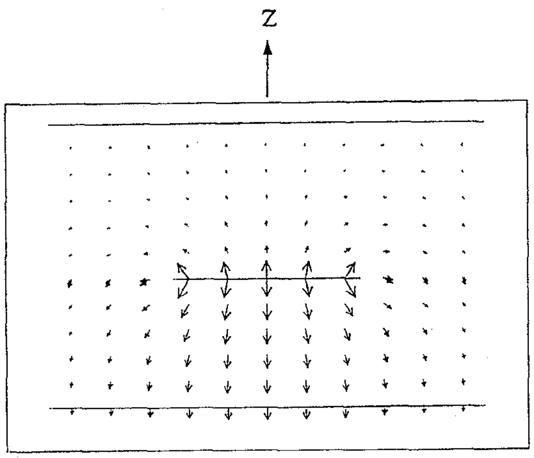


Figure 2: (a) β/k_0 for the proper and improper (leaky) solutions, and k_{TM_0}/k_0 versus the air-gap thickness δ at 3 GHz for the stripline of Fig. 1 with a lossy plexiglass substrate. (b) α/k_0 for the proper and improper (leaky) solutions versus δ at 3 GHz for the stripline of Fig. 1, shown for a lossless substrate and for a substrate with a loss tangent of 0.0058. ($h = 0.445$ cm and $w = 0.635$ cm in both cases)



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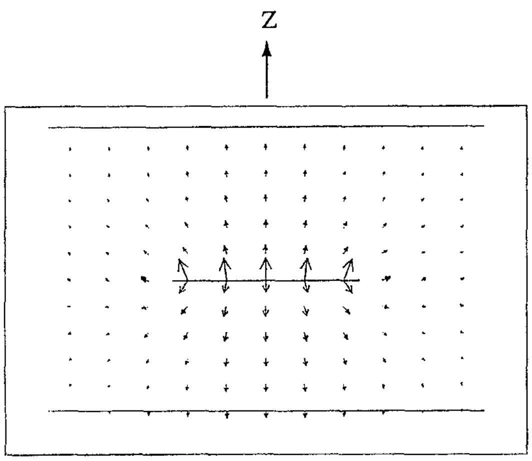
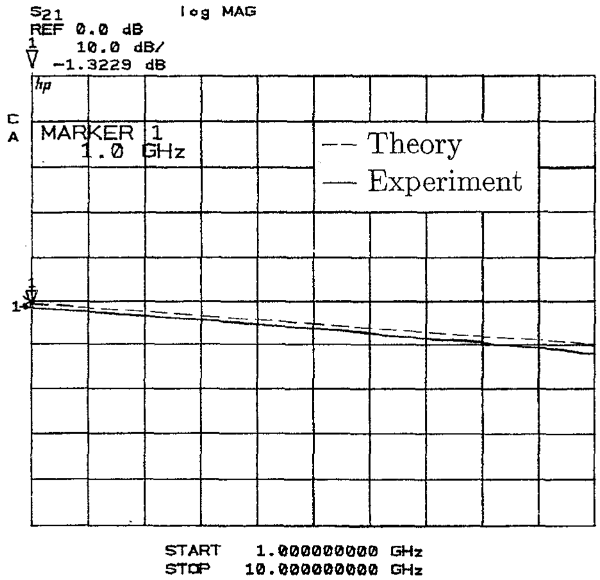
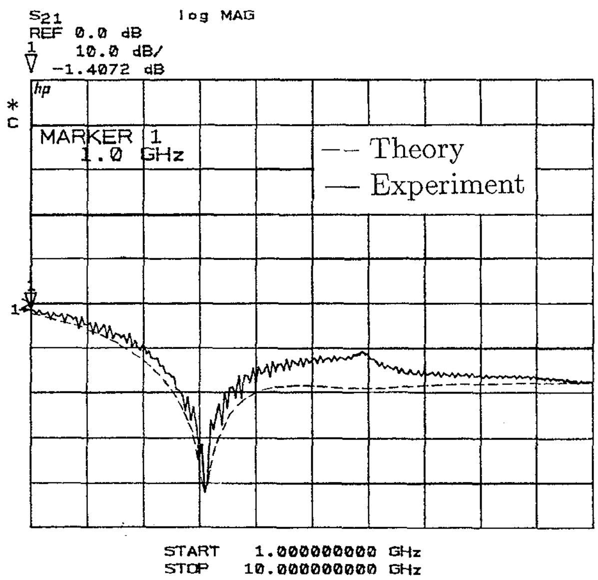


(b)

Figure 3: The real part of the electric field distribution for (a) the proper solution and (b) the improper (leaky) solution, in a rectangular window of 0.889 cm × 1.335 cm around the strip (w = 0.635 cm), for the geometry of Fig. 1 (δ = 0.08 cm, at 3.8 GHz). The field points are calculated at points corresponding to the tails of the arrows.



(a)



(b)

Figure 4: Measured and calculated values of $|S_{21}|$ versus frequency for the stripline structure of Fig. 1 with h = 0.445 cm and w = 0.635 cm. (a) Homogeneous stripline (δ = 0). (b) Stripline with an air gap of δ = 0.08 cm.