The Effect of Substrate Anisotropy on the Dominant-Mode Leakage from Stripline with an Air Gap

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***Abstract*—The fundamental properties of dominant leaky modes that exist on stripline structures having a small air gap above the conducting strip and uniaxial anisotropic substrates are investigated. These dominant leaky modes are modes that have a quasi-TEM strip current and are often strongly excited by conventional stripline feeds. The leakage occurs into the TM_0 parallel-plate mode of the background structure and results in undesirable crosstalk and spurious stripline performance. The properties of the leaky modes are examined for substrates that are either positive or negative uniaxial, and new physical effects introduced by the substrate anisotropy are discussed. The effects of replacing the air gap above the strip with an isotropic or uniaxial anisotropic bonding film are also discussed, and it is shown that the leakage may be eliminated by a proper choice of bonding film material, depending on the type of substrate anisotropy.**

I. Introduction

IT WAS RECENTLY REPORTED, [1] and [2] that a dominant leaky mode exists on a stripline transmission line when a small air gap is present above the conducting strip. This leaky mode is referred to as a *dominant* leaky mode because it has a strip current that closely resembles the current of the TEM stripline mode that exists when no air gap is present. This is in contrast to a *higher-order* leaky mode, which has a very different current distribution [3]. Leakage occurs when a small air gap is present because the air gap introduces an asymmetry that causes the TEM parallel-plate mode of the background parallel-plate structure to become a TM_0 mode that has a nonzero horizontal electric field. The TM_0 mode therefore couples to the strip current, so that the stripline mode leaks power in the form of the TM_0 mode of the background structure. The resulting leaky mode will attenuate longitudinally as it propagates, resulting in a complex propagation wavenumber. The leaky mode has fields that are improper (increasing) in the transverse directions away from the strip, and hence excitation of this mode may result in spurious performance, including loss of power and undesirable crosstalk between adjacent lines. The leaky mode is present in addition to a bound (proper) mode, that has fields that decay away from the strip. However, it is the *leaky* mode that has fields that closely resemble the fields of the conventional TEM stripline mode that exists when no air gap is present. In contrast, the bound mode has fields that resemble the TEM parallel-plate mode. Hence, when an air gap is introduced into stripline, the conventional TEM stripline mode becomes a leaky mode, and is strongly excited by a conventional stripline feed. The bound mode, on the other hand, is only weakly excited by a practical stripline feed when the air gap is small. This conclusion has important practical implications, since a small air gap is often introduced inadvertently during fabrication.

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In this paper, the fundamental properties of the leaky mode will be discussed for the more general uniaxial anisotropic structure in Fig. 1, where ϵ_y and ϵ_t denote the normal and transverse relative permittivities, respectively (the y direction is normal to the layers, while the x and z directions are transverse). The properties of the leaky mode will first be briefly reviewed for the case of an isotropic substrate, with $\epsilon_y = \epsilon_t$. The effects of making the substrate uniaxially anisotropic will then be examined in detail and new physical effects will be discussed, including some interesting differences in the dispersion characteristics that arise because of the anisotropy. It will be demonstrated that a *positive* uniaxial substrate ($\epsilon_y > \epsilon_t$) tends to enhance leakage, while a *negative* uniaxial substrate ($\epsilon_y < \epsilon_t$) tends to suppress leakage. Finally, the effects of replacing the air gap with a bonding film will be examined. It will be shown that a bonding film of the proper permittivity can always be selected to eliminate the leakage. However, the physical mechanism by which the leakage is eliminated is different for the cases of positive and negative uniaxial substrates.

II. Formulation

The propagation wavenumber ($k_{z0} = \beta$) of the bound mode is determined by standard spectral-domain techniques [4]. The

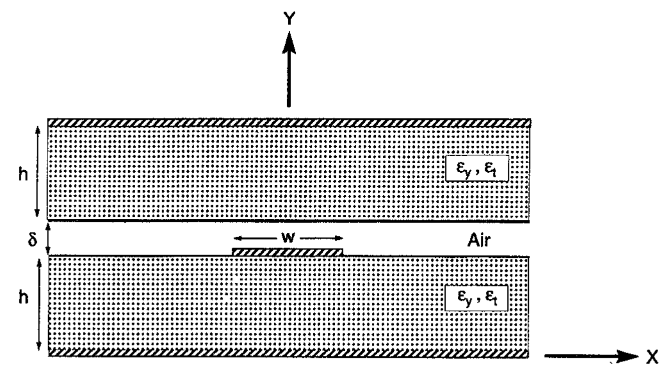


Fig. 1. Geometry of a stripline with uniaxially anisotropic layers, having an air gap above the conducting strip.

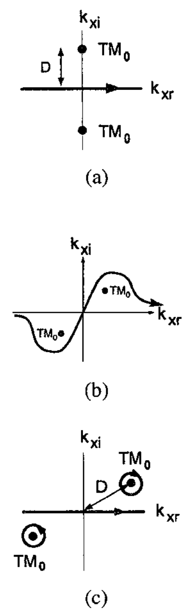


Fig. 2. Integration path in the complex k_x plane used to determine the wavenumber of the propagating modes on the stripline. (a) The real-axis path, used to find the bound-mode solution. (b) The deformed path that is used to find the leaky-mode solution. (c) The real-axis path plus residue contributions from the TM_0 poles, equivalent to the deformed path.

propagation wavenumber ($k_{z0} = \beta - j\alpha$) of the leaky mode is found using the same spectral-domain analysis, except that the path of integration in the spectral domain is deformed around the TM_0 poles of the integrand, as discussed in [2]. In either case, the current is assumed to be z-directed and represented as

$$J_z(x) = \left(\frac{2}{\pi w}\right)\frac{1}{\sqrt{1-(2x/w)^2}}. \tag{1}$$

This simple current representation accurately describes the dominant bound and leaky modes over the range of parameters of interest here. This has been verified by using a complete moment-method expansion, in which both z- and x-directed currents are assumed and represented in terms of full-domain sinusoidal expansion functions that are weighted by appropriate edge-singularity terms [2]. In all cases, negligible differences were found between the propagation wavenumber values obtained by using the complete basis function expansion and by using only the dominant current term (1) above.

A transcendental equation for the unknown propagation wavenumber k_{z0} is derived by enforcing the electric-field integral equation using Galerkin's method. The resulting equation has the form

$$\int_{-\infty}^{\infty} \tilde{J}_z(k_x)\tilde{G}_{zz}(k_x, k_{z0})\tilde{J}_z(-k_x)\,dk_x = 0. \tag{2}$$

In this equation the term $\tilde{G}_{zz}(k_x, k_{z0})$ denotes the spectral-domain Green's function, which is the Fourier transform (in x) of the spatial Green's function $G_{zz}(x, k_{z0})$. The Green's function $G_{zz}(x, k_{z0})$ corresponds physically to the electric field $E_z(x)$ in the plane of the strip, produced by a phased line source of current having a propagation wavenumber k_{z0}. The spectral-domain Green's function has poles in the k_x plane at

$$k_{xp} = (k_{pp}^2 - k_{z0}^2)^{1/2} \tag{3}$$

where k_{pp} is the propagation wavenumber of the pth mode of the background parallel-plate structure at the specified frequency. It will be assumed here that only the fundamental TM_0 mode (with a zero cutoff frequency) is above cutoff for the frequencies of interest. The propagation wavenumber for the bound mode is determined by performing the integration in (2) along the real axis in the complex k_x plane. In this case the poles k_{xp} are located on the imaginary axis, as shown in Fig. 2(a). To find a solution for a leaky mode that leaks into the TM_0 parallel-plate mode, the path of integration is deformed around the TM_0 poles, as shown [2] by the deformed path in Fig. 2(b). This path is equivalent to an integration along the real axis plus a residue contribution from the TM_0 poles, as shown in Fig 2(c). Using either the real-axis path or the one shown in Fig. 2(b), (2) represents a transcendental equation for the unknown propagation wavenumber for the mode of interest, and is solved numerically using a method for finding complex roots such as the secant method.

For the leaky-mode solution, the residue contribution in Fig. 2(c) corresponds to a TM_0 parallel-plate mode that is launched outward at an angle from from strip. Far away from the strip, this will be the dominant field component of the total leaky-mode field. However, the leaky-mode field is stripline-like near the strip. This will be discussed further in the results section.

III. Results

A. Isotropic Stripline

Fig. 3(a) shows the normalized phase constant β/k_0 for the bound (proper) and leaky (improper) modes that exist on a stripline with an isotropic substrate ($\epsilon_r = 10.4$), versus the thickness δ of the air gap above the conducting strip. Also shown for convenience is the normalized wavenumber k_{TM_0}/k_0 of the TM_0 parallel-plate background mode. The normalized leakage constant α/k_0 for the leaky mode is shown in Fig. 3(b). For a zero-thickness air gap the leaky mode and the bound mode are both TEM modes, as is the TM_0

parallel-plate mode. The bound mode becomes identical to the parallel-plate mode in this limiting case, while the leaky mode becomes the customary TEM stripline mode. Both the bound and leaky modes then have a phase constant equal to the wavenumber of the substrate, and the leaky mode has no attenuation ($\alpha = 0$). For small nonzero air gaps the leaky mode has a phase constant that is below that of the TM_0 mode, corresponding to physical leakage. In this region the field of the leaky mode has the form of a stripline-like mode, while the field of the proper mode resembles that of the TM_0 parallel-plate mode [2]. As the air gap increases, the phase constant of the leaky mode becomes larger than that for k_{TM_0}, entering into the "spectral-gap" region [5], where the mode begins to lose physical meaning. For a sufficiently large air gap the leaky mode splits into two improper real modes ($\alpha = 0$), which are nonphysical. The attenuation constant α, shown in Fig. 3(b), increases from zero to a maximum value as the air gap increases, and decreases to zero at the splitting point. The field of the bound mode slowly changes from parallel-plate-like to stripline-like as the air-gap thickness increases, and the bound mode replaces the leaky mode as the physical mode with the stripline-like behavior when the leaky mode enters the spectral-gap region.

In the region of leakage (where the air-gap thickness is less than the value at the splitting point) a second leaky solution also exists [2], but it is nonphysical, with a propagation constant k_z^*. The dispersion curve for this conjugate mode is identical to the one shown in Fig. 3(a) for the physical leaky mode, but it is nonphysical because its field increases in the direction of propagation. Because this conjugate solution is clearly nonphysical, it is not discussed further.

From observations of the field distributions (not shown here, but given in [2]), the field of the proper mode, for small nonzero air-gap thicknesses, is parallel-plate-like (PPL), as labeled on Fig. 3(a). The leaky mode, on the other hand, has a stripline-like (SLL) field for small air-gap thicknesses. This can be explained by considering the residues of the TM_0 poles shown in Fig. 2. The parallel-plate-like behavior of the bound mode is observed because the TM_0 poles in Fig. 2 approach the origin in the k_x plane, corresponding to k_{z0} approaching k_{TM_0}. The residues of each of the two TM_0 poles (they are equal in magnitude) approach zero as δ approaches zero. Nevertheless, the proximity of the poles to the path of integration may result in a significant influence of the poles as δ approaches zero. As the poles approach the origin, the contribution of each pole to the integrand is of the form $Res/(k_x - k_{xp})$, where Res is the residue of the pole and k_{xp} is the pole location. When k_x is at the origin, the magnitude of this term is R/D, where R is the magnitude of the pole residue and D is the distance of the pole from the origin (the same for both poles). It has been found that the term R/D does indeed predict when the field of either a bound mode or a leaky mode will have a parallel-plate-like field or a stripline-like field when k_{z0} approaches k_{TM_0}. The former situation occurs when R/D tends to infinity as the poles approach the origin; the latter situation occurs when R/D approaches zero. The value of R is unique only to within a multiplicative constant, since (2) is homogeneous. It would be necessary to normalize the value of R (for example, by the amplitude of the real axis integration) before any *quantitative* information could be obtained from the R/D ratio. However, in all of the observed cases the ratio either approaches zero or infinity when k_{z0} approaches k_{TM_0}, and therefore the limit is not affected by any normalization. Therefore, the limiting value of the ratio R/D as k_{z0} approaches k_{TM_0} *qualitatively* determines the nature of the field in this limit. The ratio R/D for the bound mode in Fig. 3(a) is shown in Fig. 4(a), while the ratio for the leaky mode is shown in Fig. 4(b). It is seen that the ratio R/D for the bound mode tends to infinity as δ approaches zero, corresponding to a field that is parallel-plate-like. The ratio R/D for the leaky mode tends to zero as δ approaches zero, corresponding to a stripline-like field.

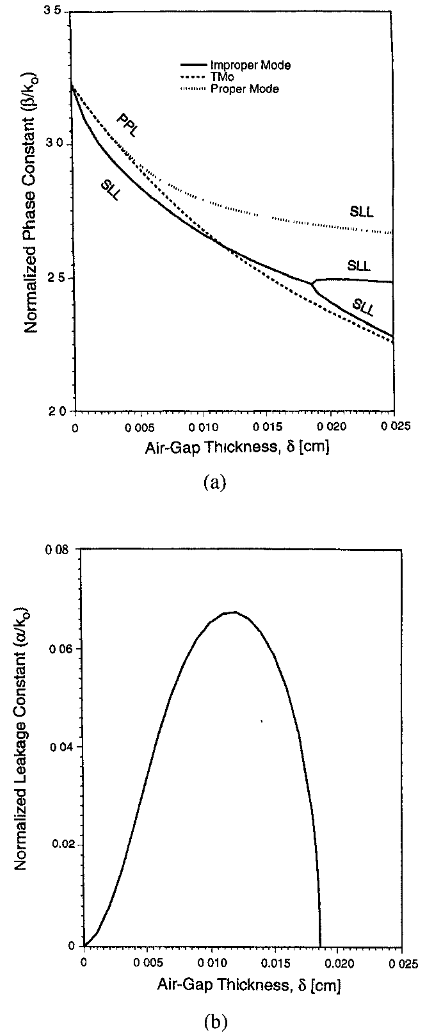
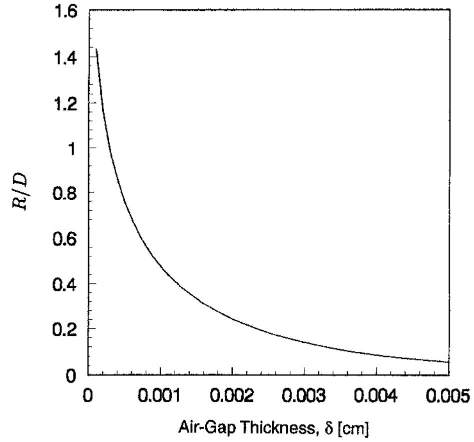
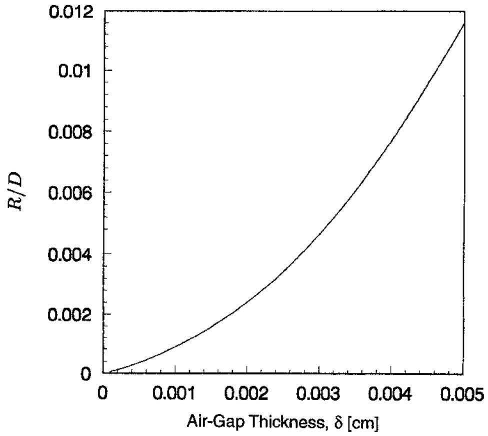


Fig. 3. (a) Normalized phase constant β/k_0 for the proper and improper modes, and k_{TM_0}/k_0, versus the air-gap thickness δ for the stripline structure of Fig. 1 with an *isotropic* substrate, having $w = h = 0.1$ cm and $\epsilon_{ry} = \epsilon_{rt} = 10.4$, at 3.0 GHz. The labels PPL and SLL indicate when the solution has a parallel-plate-like field or a stripline-like field. The improper mode is leaky from $\delta = 0$ up to the splitting point shown; beyond that point the improper mode consists of two nonphysical improper real solutions. (b) The normalized leakage constant α/k_0 versus the air-gap thickness δ for the leaky mode in part (a).

The leaky mode remains stripline-like throughout the range of air-gap thicknesses shown in Fig. 3(a). As δ becomes still larger, the lower improper real solution in Fig. 3(a) continues

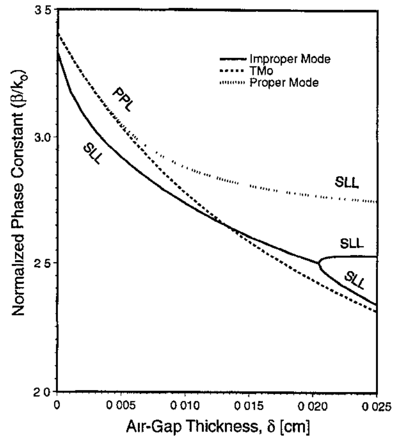


(a)

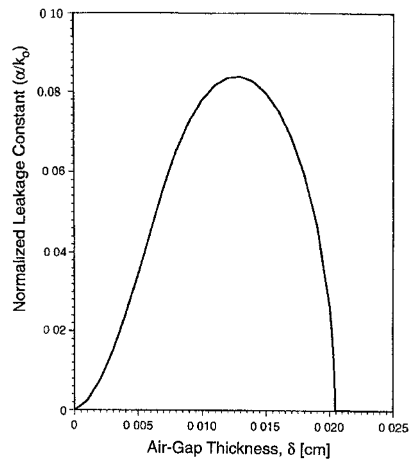


(b)

Fig. 4. (a) A plot of the ratio R/D versus the air-gap thickness δ for the bound mode in Fig. 3(a). This ratio is the magnitude of the TM_0 pole residue divided by the distance of the pole from the origin. (b) A plot of the ratio R/D for the leaky mode in Fig. 3(a).



(a)



(b)

Fig. 5. (a) Normalized phase constant β/k_0 for the proper and improper modes, and k_{TM_0}/k_0, versus the air-gap thickness δ for the stripline structure of Fig. 1 with a *positive uniaxial* (sapphire) substrate, having $w = h = 0.1$ cm and $\epsilon_{ry} = 11.6 > \epsilon_{rt} = 9.4$, at 3.0 GHz. The labels PPL and SLL indicate when the solution has a parallel-plate-like field or a stripline-like field. (b) The normalized leakage constant α/k_0 for the leaky mode in part (a).

to approach the k_{TM_0} curve, which corresponds to the TM_0 poles once again approaching the origin. The magnitude of the residue R approaches infinity in this case (and, therefore, so does the ratio R/D), so that the field of the lower improper real solution eventually becomes parallel-plate like. However, this occurs beyond the range of the air-gap thicknesses shown. Because the leaky mode has a stripline-like field while the bound mode has a parallel-plate-like field for *small* air-gap thicknesses, it is the *leaky* mode, not the bound mode, that would be excited by a practical stripline feed. As the air-gap thickness becomes larger (beyond about 0.012 cm), the bound mode would be the mode that becomes predominantly excited, since its field changes into a stripline field, while the leaky mode enters into the spectral gap region and loses physical meaning.

B. Positive Uniaxial Stripline

Fig. 5 shows the normalized phase constant for a substrate that has a positive ($\epsilon_y > \epsilon_t$) uniaxial anisotropy (sapphire), for which $\epsilon_y = 11.6$ and $\epsilon_t = 9.4$. The normalized leakage constant of the leaky mode is shown in Fig. 5(b). The dispersion curves closely resemble those for the isotropic case, except for small air-gap thicknesses. As in the isotropic case, the proper mode and the TM_0 parallel-plate mode become coincident (as a single TEM parallel-plate mode) as δ approaches zero. However, the phase constant of the leaky mode remains *below* k_{TM_0}. The leaky wave is therefore a fast wave with respect to the TM_0 parallel-plate mode when there is no air gap. However, the leakage constant is zero in this limit, as seen from Fig. 5(b). Because there is no horizontal electric field associated with the TEM parallel-plate mode, there is no coupling between this mode and the strip current when the air-gap thickness is zero. The leaky mode therefore becomes a proper stripline mode that propagates without attenuation in the limit of zero air-gap thickness, as it does for the isotropic case. However, the stripline mode is not TEM when $\delta = 0$, as in the isotropic case. This may be easily proven by assuming $E_z = H_z = 0$ and expanding Maxwell's equations. A contradiction is reached unless $\epsilon_y = \epsilon_t$. The fast-wave property when $\delta = 0$ follows from the fact that the stripline mode has both x and y components of electric field, and thus "sees" an effective permittivity that is between ϵ_t and ϵ_y. However, the TM_0 mode, which is a TEM mode when $\delta = 0$, "sees" only the ϵ_y component of the permittivity. Hence, the stripline mode remains a fast wave with respect to the TM_0 parallel-plate mode in the zero air-gap limit.

Because the leaky mode is stripline-like and the bound mode is parallel-plate-like for small air-gap thicknesses, the field behavior is the same as the isotropic case; hence, it is the leaky mode, not the bound mode, that is excited by a practical stripline feed for small air gaps. For larger air gap thicknesses it is the bound mode that would mainly be excited, for the same reasons discussed in connection with the isotropic case. Also notice that the plot of leakage constant shown in Fig. 5(b) is very similar to the one in Fig. 3(b) for the isotropic case, but the maximum value of the leakage constant is slightly higher for the positive uniaxial case. This demonstrates that the positive uniaxial anisotropy enhances the leakage.

C. Negative Uniaxial Stripline

Fig. 6(a) shows a plot of the normalized phase constant for a substrate that is negative ($\epsilon_y < \epsilon_t$) uniaxial (Epsilam-10), for which $\epsilon_y = 10.3$ and $\epsilon_t = 13.0$. The normalized leakage constant of the leaky mode is shown in Fig. 6(b). The overall dispersion curve in Fig. 6(a) is again similar to that for the isotropic case in Fig. 3(a), except for the behavior for very small air gaps. In this region an additional splitting point occurs, which is in essence a mirror image of the one that occurs for larger air-gap thicknesses. This new splitting point is more easily seen on the magnified plot shown in Fig. 6(c). Below this splitting point, which occurs for $\delta \doteq 0.00105$ cm, there are two improper real solutions. The upper solution approaches the bound mode solution, and coalesces with the bound mode when the air-gap thickness becomes zero. The lower solution approaches the TM_0 dispersion curve, and coalesces with this mode when the air-gap thickness is zero. For the negative uniaxial case the bound-mode and TM_0-mode dispersion curves no longer come together as δ approaches zero, as they do for the isotropic and positive uniaxial cases. Because of this, the ratio R/D for the bound mode remains sufficiently small as δ approaches zero such that the bound mode solution has a stripline-like field for very small air gaps. The R/D ratio for the lower improper real solution tends to infinity as δ approaches zero, and hence the fields of this mode undergo a rapid transition, changing from stripline-like to parallel-plate-like as the air-gap thickness decreases below the value of the lower splitting point.

The improper real solutions that exist for very small air-gap thicknesses (below the first splitting point) are not physical, and hence the only physically meaningful solution in this region is the bound mode, which has a stripline-like field. Hence, it is the *bound* mode that would be excited by a practical stripline feed for very small air gaps when the substrate has a negative uniaxial anisotropy. As the air-gap thickness increases beyond the first splitting point, the improper mode becomes a leaky mode with $\beta < k_{\mathrm{TM}_0}$ over a range of air-gap thicknesses, and is thus physically meaningful.

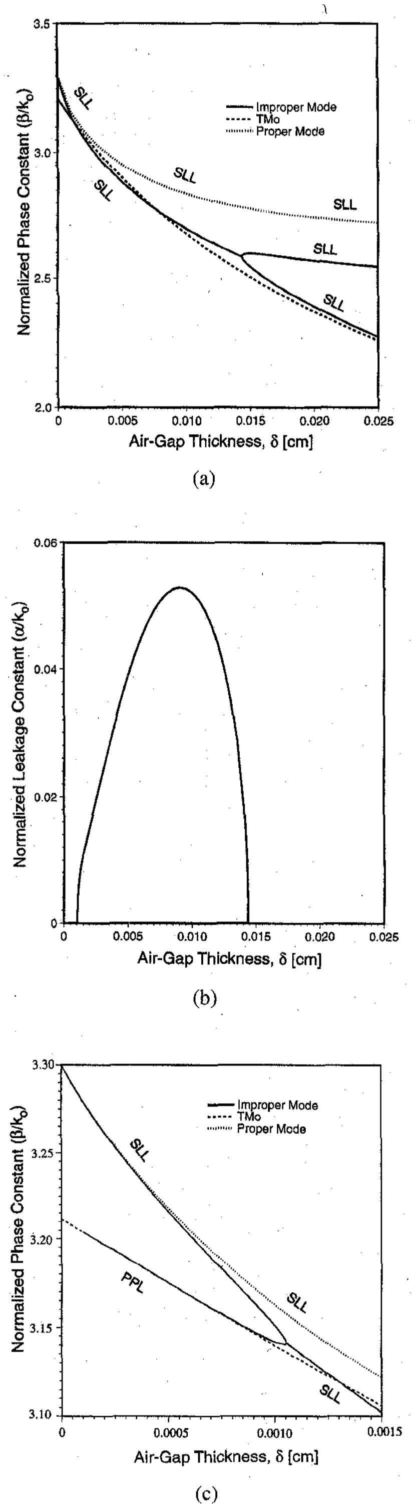


Fig. 6. (a) Normalized phase constant β/k_0 for the proper and improper modes, and k_{TM_0}/k_0, versus the air-gap thickness δ for the stripline structure of Fig. 1 with a *negative uniaxial* (Epsilam-10) substrate, having $w = h = 0.1$ cm and $\epsilon_{ry} = 10.3 < \epsilon_{rt} = 13.0$, at 3.0 GHz. Two separate splitting points are now present, the new one at a very small value of δ. The labels PPL and SLL indicate when the solution has a parallel-plate-like field or a stripline-like field. (b) The normalized leakage constant α/k_0 for the leaky mode in part (a). (c) A magnified plot showing the dispersion curves in the new spectral-gap region (very small air gaps) for the plot in part (a).

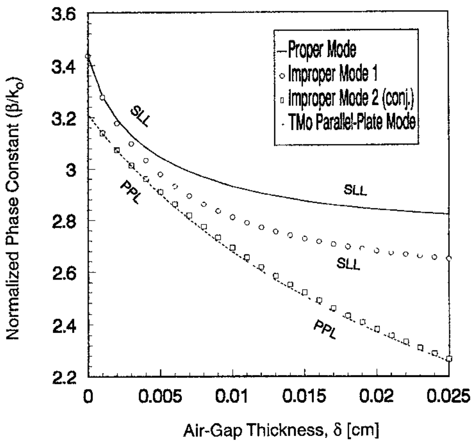


Fig. 7. Normalized phase constant β/k_0 for the proper and improper modes, and k_{TM_0}/k_0, versus the air-gap thickness δ for the stripline structure of Fig. 1 with a *very strongly* negative uniaxial substrate, having $w = h = 0.1$ cm and $\epsilon_{ry} = 10.3 < \epsilon_{rt} = 18.0$, at 3.0 GHz. The two separate splitting points shown in Fig. 6(a) have now joined together, so that no leakage occurs for any air-gap thickness. The labels PPL and SLL indicate when the solution has a parallel-plate-like field or a stripline-like field.

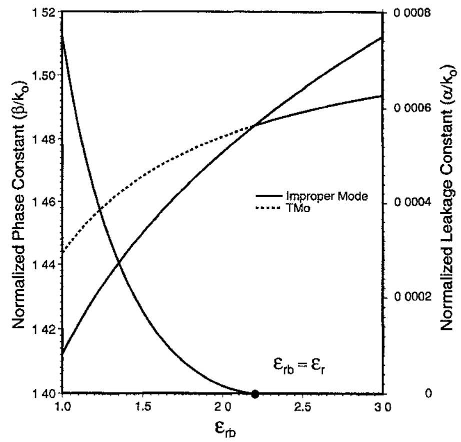


Fig. 8. Normalized phase constant β/k_0 for the proper and improper modes, and k_{TM_0}/k_0, versus the relative permittivity ϵ_{rb} of the *bonding-film* layer for the structure of Fig. 1, when the air gap is replaced with an isotropic bonding film. The substrate is *isotropic* with a relative permittivity $\epsilon_r = 2.2$, $w = h = 0.1$ cm, and $\delta = 0.01$ cm, at 3.0 GHz.

The bound mode retains a stripline-like field in this region, and it is therefore expected that *both* the leaky mode and the bound mode would be excited by a practical stripline feed in this region. As the air-gap thickness increases still further, the leaky mode enters the other (second) spectral-gap region and becomes nonphysical, and it is then the bound mode that would be predominantly excited, as in the isotropic case. The plot of leakage constant in Fig. 6(b) shows that the maximum value of the leakage constant is less than that for the isotropic case of Fig. 3(b).

As the degree of negative anisotropy increases ($\nu = \epsilon_t/\epsilon_y$ becomes larger), the two splitting points in Fig. 6(a) approach each other, so that the region of leakage between them becomes smaller. Eventually, as the substrate is made sufficiently negative uniaxial, the two splitting points come together. For any value of ν beyond this value, there is no leakage for *any* air-gap thickness, since there is no leaky mode. Only the proper mode and a pair of nonphysical improper real solution exits in this case. This is illustrated in Fig. 7, which shows the dispersion plot for a negative uniaxial substrate which has a larger value of ν than for Fig. 6. The normal component of permittivity is kept the same as in Fig. 6, but the transverse component is increased to a value of 18.0. For this degree of anisotropy the two splitting points have already merged together. The bound mode solution is stripline-like throughout the entire range of air-gap thickness, and is the only mode that would be excited by a practical stripline feed throughout this entire range.

Figs. 6 and 7 demonstrate that a negative uniaxial anisotropy tends to suppress the leakage. Furthermore, if the degree of anisotropy is sufficiently large, there will never be any leakage regardless of the air-gap thickness.

D. Suppression of Leakage

The existence of a dominant leaky mode on a printed-circuit transmission line is undesirable, since the excitation of this mode will result in crosstalk and spurious coupling with adjacent circuit elements. This is especially important when the mode that is predominantly excited by a practical feed is such a leaky mode. As discussed in the sections above, this will be the case for the stripline structure with a small air gap above the conducting strip, unless the substrate is negative uniaxial and the air gap is *very small*. Therefore, it is important to investigate methods for *suppressing* the leakage. Perhaps the simplest method is to replace the air gap in Fig. 1 with a region of bonding film. For simplicity, the bonding film will be assumed to be isotropic (which is usually the case in practice).

In Fig. 8, a plot is shown of the normalized phase constant β/k_0 for the proper and improper modes, and k_{TM_0}/k_0, versus the relative permittivity of the bonding film ϵ_{rb} for the case of an *isotropic* substrate with $\epsilon_r = 2.2$, for a stripline with a small air gap. When $\epsilon_{rb} < \epsilon_r$, the leaky mode is a stripline-like mode with $\beta < k_{\mathrm{TM}_0}$, while the proper mode is a parallel-plate-like mode. The dispersion curves of the proper mode and the TM_0 parallel-plate mode are almost coincident in this region. At the point $\epsilon_{rb} = \epsilon_r$ all the solutions converge, and for $\epsilon_{rb} > \epsilon_r$ three modal solutions exist, none of which are leaky: the proper mode, and two improper real modes that do not have physical meaning (the same type of modes seen in Fig. 3(a) beyond the splitting point). In the region $\epsilon_{rb} > \epsilon_r$, the bound mode curve is almost coincident with the upper improper real solution, while the TM_0 curve is almost coincident with the lower improper real solution. The upper two curves have a stripline-like field, while the lower improper real curve has a parallel-plate-like field. The bound mode therefore suddenly changes character from a parallel-plate-like mode for $\epsilon_{rb} < \epsilon_r$ to a stripline-like mode for $\epsilon_{rb} > \epsilon_r$. Hence, when $\epsilon_{rb} > \epsilon_r$, the stripline mode that is excited by a practical feed is a *bound* mode, not a leaky mode.

Fig. 9 next shows the dispersion plot for a stripline with a small air gap having a substrate that is *positive uniaxial* (sapphire). The normalized leakage constant α is also included in this figure. The bound mode is not shown in this figure for clarity, although it is almost coincident with the TM_0 curve

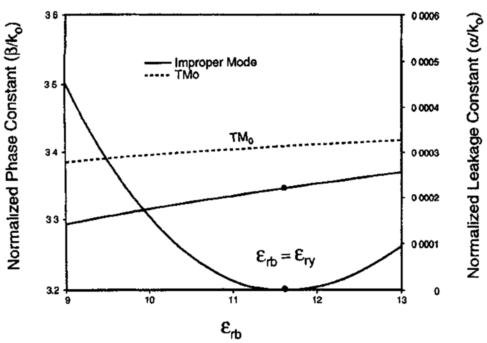


Fig. 9. Normalized phase constant β/k_0 and leakage constant α/k_0 for the leaky mode, and k_{TM_0}/k_0, versus the relative permittivity ϵ_{rb} of the bonding film layer for the structure of Fig. 1, when the air gap is replaced with an isotropic bonding film. The substrate is *positive uniaxial* (sapphire) with $\epsilon_{ry} = 11.6 > \epsilon_{rt} = 9.6$, $w = h = 0.1$ cm, and $\delta = 0.01$ cm, at 3.0 GHz.

throughout the entire range. The introduction of a bonding film with moderate permittivity ϵ_{rb} does not change the leaky mode into two improper real modes, as in the isotopic case (a larger value of ϵ_{rb} would, but such a value is off the scale of this plot). The figure shows that an interesting effect occurs at the point $\epsilon_{rb} = \epsilon_{ry}$, namely that the leakage goes to zero. This occurs because the permittivity component ϵ_{ry} is now continuous throughout the stripline structure, and the TM_0 parallel-plate mode consequently becomes a TEM parallel-plate mode that does not couple to the strip current, and is therefore not launched by the stripline mode. At this one particular value, $\epsilon_{rb} = \epsilon_{ry}$, the leaky mode becomes a bound mode (totally distinct from the bound mode that is almost coincident with the TM_0 curve, but is not shown). Hence, to eliminate leakage when using a positive uniaxial substrate, the condition $\epsilon_{rb} = \epsilon_{ry}$ is necessary (unless a bonding film with a very large permittivity is used, in which case the suppression effect is similar to that for the isotropic case).

Fig. 10 shows the dispersion plot and the leakage behavior for a *negative uniaxial* substrate (Epsilam-10). Again, for clarity, the bound mode has not been shown in this plot. Qualitatively, this case is similar to the isotropic case in that a sufficiently large value of ϵ_{rb} eliminates leakage by causing the leaky mode to split into two nonphysical improper real modes. In this case, however, the required value of ϵ_{rb} needed to achieve this splitting is less than both ϵ_{ry} and ϵ_{rt}. Above the splitting point, the bound mode (which is almost coincident with the upper improper real curve, but is not shown) is stripline-like, as in the isotropic case. Hence, a practical stripline feed would excite the *bound* in this region, not the leaky mode.

IV. Conclusion

The properties of a dominant leaky mode that exists on stripline with an air gap above the conducting strip have been examined for the case of uniaxial substrates. When the substrate is *isotropic*, the leaky mode exists whenever the air gap is small. The leaky mode has a stripline-like field, and is in fact the continuation of the usual TEM stripline mode that exists when there is no air gap. The air gap introduces

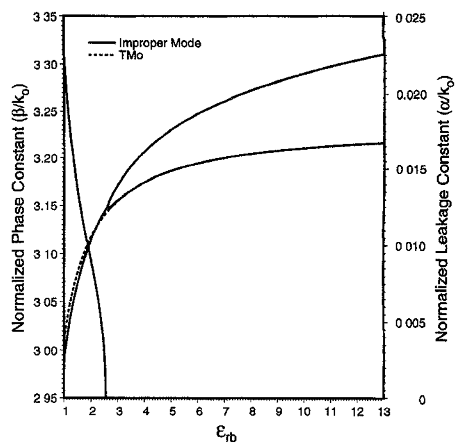


Fig. 10. Normalized phase constant β/k_0 and leakage constant α/k_0 for the improper (leaky) mode, and k_{TM_0}/k_0, versus the relative permittivity ϵ_{rb} of the bonding film layer for the structure of Fig. 1, when the air gap is replaced with an isotropic bonding film. The substrate is *negative uniaxial* (Epsilam-10) with $\epsilon_{ry} = 10.3 < \epsilon_{rt} = 13.0$, $w = h = 0.1$ cm, and $\delta = 0.003$ cm, at 3.0 GHz.

an asymmetry that couples the field of the TM_0 parallel-plate mode of the background structure to the current on the strip, resulting in leakage into the TM_0 mode. This leaky mode is present in addition to a bound mode, which has a parallel-plate-like field and is the continuation of the TEM parallel-plate mode that exists when there is no air gap. Because of the stripline-like nature of the leaky mode, it is the *leaky* mode that is excited by a practical stripline feed when a small air gap exists above the conducting strip. As the air gap becomes larger, the character of the bound mode changes into a stripline-like field, while the leaky mode splits into two improper real solutions that have no physical meaning. Hence, for larger air gaps it is only the *bound* mode that would be excited by a practical stripline feed.

When the substrate is *positive uniaxial* (the normal component of permittivity is greater than the transverse component), the dispersion curves remain qualitatively similar to those of the isotropic case over most of the range of air-gap thicknesses. However, the leakage tends to become *more pronounced* relative to the isotropic case. Also, as the air-gap thickness approaches zero, an interesting effect is observed, namely, that the leaky mode remains a fast wave with respect to the TM_0 parallel-plate mode, even though the leakage tends to zero. This effect is due to the fact that the stripline mode "sees" an effective permittivity that is less than that seen by the TM_0 mode (which becomes a TEM mode in the limit of zero air-gap thickness) and thus remains a fast wave. Because the TM_0 mode becomes a TEM parallel-plate mode in the limit of zero air-gap thickness, however, it does not couple to the strip current, and hence there is no leakage.

A different physical behavior occurs when the substrate is *negative uniaxial* (the normal component of permittivity is less than the transverse component). Below a certain *very small* value of air-gap thickness the leaky mode splits into two improper real solutions that are nonphysical. In this region the bound-mode solution has a stripline-like field and is the only mode that would be excited by a practical stripline feed. Hence, there is *no leakage* provided the air gap is *very small*. When the thickness of the air gap increases beyond the splitting point, a leaky mode and a bound mode exist simultaneously, and both of them have a stripline-like field. Hence, *both* modes would be excited by a practical stripline feed. For still larger air-gap thicknesses the leaky mode again splits into two nonphysical improper real solutions, while the bound mode retains a stripline-like field. In this region it is once again only the *bound* mode that would be excited by a practical stripline seed.

REFERENCES

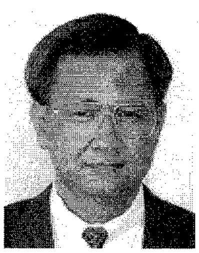
[1] D. Nghiem, J. T. Williams, D. R. Jackson, and A. A. Oliner, "Proper and improper modal solutions for inhomogeneous stripline," in *IEEE Int. Microwave Symp. Dig.*, June 1991, pp. 567–570.

[2] ——, "Leakage of the dominant mode on stripline with a small air gap," *IEEE Trans. Microwave Theory Tech.*,vol. 43, no. 11, Nov. 1995, pp. 2549–2556.

[3] A. A. Oliner and K. S. Lee, "The nature of leakage from higher-order modes on microstrip lines," in *IEEE Int. Microwave Symp. Dig.*, Baltimore, MD, June 1986, pp. 57–60.

[4] T. Itoh, "Spectral domain immitance approach for dispersion characteristics of the generalized printed transmission lines," *IEEE Trans. Microwave Theory Tech.*, vol. 28, pp. 733–736, July 1980.

[5] H. Shigesawa, M. Tsuji, and A. A. Oliner, "The nature of the spectral gap between bound and leaky solutions when dielectric loss is present in printed circuit lines," *Radio Sci.*, vol. 28, no. 6, pp. 1235–1243, 1993.



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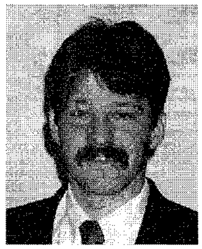

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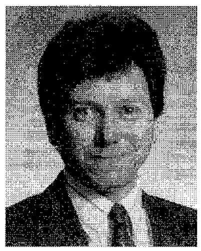

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Arthur A. Oliner (M'47-SM'52-F'61-LF'87) , for a photograph and biography, see p. 1560 of the August 1994 issue of this TRANSACTIONS.