PRINTED-CIRCUIT WAVEGUIDES WITH ANISOTROPIC SUBSTRATES: A NEW LEAKAGE EFFECT

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ABSTRACT

A new class of power leakage effects has been found for the dominant mode on uniform printed-circuit waveguides when anisotropic dielectric materials are used as substrates. We demonstrate both from physical reasoning and by accurate quantitative calculations that above a certain critical frequency the dominant mode on uniform printed-circuit waveguides, such as microstrip line, slot line or coplanar waveguide (whether of finite or infinite width), on suitable anisotropic substrates will leak power into surface waves on the substrate, and that the maximum leakage rate can be rather large. This power leakage is a qualitatively new effect, reported here for the first time, and is entirely distinct from the leakage or radiation into surface waves that occurs at junctions or discontinuities on the line.

1. Introduction

It is well known that many of the materials used as substrates for microwave and millimeter-wave integrated circuits exhibit dielectric anisotropy. Among such materials, monocrystalline sapphire (the principal crystal axis permittivity: $\varepsilon_{\parallel}$ = 11.6, the transverse axis permittivity: $\varepsilon_{\perp}$ = 9.4), monocrystalline magnesium fluoride ($\varepsilon_{\parallel}$ = 4.826, $\varepsilon_{\perp}$ = 5.5), pyrolitic boron nitride ($\varepsilon_{\parallel}$ = 3.4, $\varepsilon_{\perp}$ = 5.12), ceramic-impregnated teflon (*e.g.*, Epsilam 10; $\varepsilon_{\parallel}$ = 10.3, $\varepsilon_{\perp}$ = 13.0) and so on, have been suggested for potential use as a substrate for microwave and millimeter-wave applications[1,2]. Since the effect of anisotropy in substrates becomes significant as the frequency increases, it must be accurately taken into account when complex, high-density circuits based on such anisotropic substrates are developed, especially in the millimeter-wave region.

Various full-wave analyses have appeared so far in the literature (see [1] for an excellent summary), and they reported a significant deviation of the characteristics from the isotropic case for microstrip line, slot line and coplanar waveguide. None of those analyses, however, inquired into new qualitative effects that may be caused by the anisotropic nature of the substrate. One such effect (which we are clarifying here) is a new type of power leakage of the dominant mode on uniform printed-circuit waveguides. The published analyses miss such leakage effects altogether, and they are therefore incomplete in discussing the characteristics of such waveguides. This paper discusses for the first time such possible leakage problems.

2. Power Leakage on Microstrip Line due to the Anisotropic Nature of Dielectric Substrates

Of the various possible printed-circuit waveguides, this paper treats only microstrip line, slot line and coplanar waveguide, where the last two structures may have plates of either finite or infinite width. The same qualitative physical principles apply in a similar fashion to other printed-circuit guides. It turns out, however, that the effect for microstrip line is somewhat different from that for slot line and coplanar waveguide, and we therefore consider them separately.

Let us first consider the microstrip line. For the case of an isotropic substrate, the dominant

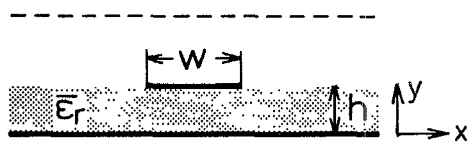

Fig.1. Cross section of microstrip line with an anisotropic substrate. The dashed line represents a possible top cover which the microstrip line may or may not have. The leakage effect discussed here applies to either case.

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microstrip-line mode has its electric field predominantly along the axis perpendicular to the substrate surface. (Hereafter, this axis is referred to as the y-axis, while the lateral direction and the strip axis are referred to as the x-axis and the z-axis, respectively, as shown in Fig.1.) The dashed line in Fig.1 represents a possible conducting top cover, which the microstrip line may or may not have. The leakage effect discussed below can occur in either case. The microstrip line also includes the conductor-backed dielectric slab regions extending semi-infinitely outside the strip, on which the dominant TM_0 surface-wave mode (polarized mainly in the y direction) can propagate at all frequencies and the TE_1 surface-wave mode (polarized mainly in the xz plane) propagates above its cutoff frequency. When the phase velocity relations among the dominant microstrip-line mode, and the TM_0 and TE_1 surface-wave modes on the slab are examined, it is concluded that no power leakage occurs in the dominant mode on microstrip line at any frequency, as is commonly understood.

On the other hand, when the substrate is anisotropic, and when the principal crystal axis coincides with the y-axis, the TE_1 surface-wave mode is affected primarily by $\varepsilon_\perp$, whereas the TM_0 surface-wave mode and the dominant mode on the microstrip line are affected primarily by $\varepsilon_\parallel$. In fact, it is easy to show that at high frequencies the ratio β/k_0, where β is the phase constant in the z (or strip) direction, approaches the asymptotic value $\sqrt{\varepsilon_\parallel}$ or $\sqrt{\varepsilon_\perp}$ for modes that are TM or TE, respectively, in the y direction. For substrates for which $\varepsilon_\perp > \varepsilon_\parallel$, therefore, the curve of β/k_0 vs. frequency for the TE_1 surface-wave mode can be expected to cross the corresponding curve for the microstrip-line dominant mode at some sufficiently high frequency. Above that critical frequency, the dominant mode on microstrip line leaks power at some angle into the TE_1 surface-wave mode on the dielectric layer outside of the strip region. The angle of such surface-wave leakage will be discussed later on, in connection with the phase constant of the dominant microstrip-line mode. The critical crossing mentioned above will occur at a lower frequency when the anisotropic ratio $\varepsilon_\perp/\varepsilon_\parallel$ is larger. Therefore, the new power leakage effect mentioned here can be expected to occur for substrates made of, for example, pyrolitic boron nitride ($\varepsilon_\perp/\varepsilon_\parallel$ = 1.506) or Epsilam 10 ($\varepsilon_\perp/\varepsilon_\parallel$ = 1.263). Calculation results for these materials are shown below.

3. Power Leakage on Slot Line and Coplanar Waveguide

When the substrates is isotropic, the dominant mode on microstrip line never leaks. For slot line and coplanar waveguide, on the other hand, the dominant mode can leak even when the substrate is isotropic and the plates of the basic guide are infinitely wide. This new and initially unexpected result was reported by us [3] at the 1988 MTT Symposium, although the main portion of the discussion dealt with conductor-backed structures. What we reported then was that dominant-mode leakage on these guides would occur above a critical frequency, but that the leakage would be present in the form of the TM_0 surface-wave mode. At some still higher critical frequency, leakage would also occur into the TE_1 surface-wave mode. (For microstrip line on a suitable anisotropic substrate, we showed above that the leakage occurs in the form of the TE_1 surface-wave mode.)

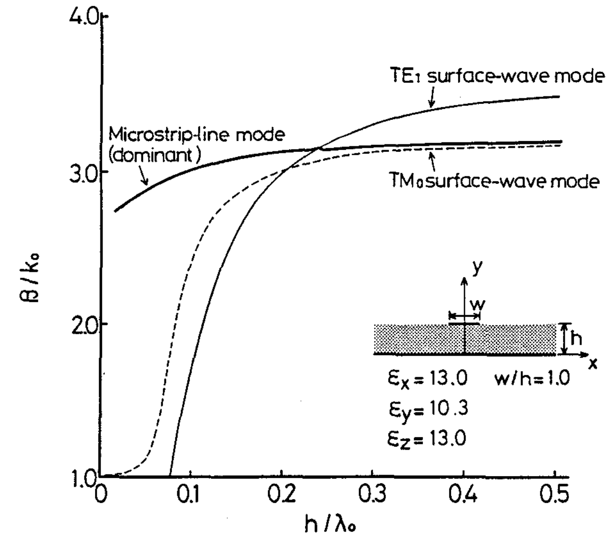
We find in the current study the new result that, when anisotropic substrate is used, the critical frequency relating to the onset of leakage changes significantly, shifting up or down depending on the type of anisotropy. This interesting result can be explained qualitatively by considerations similar to those in Section 2 above. It should be noted here that the dominant mode on these guides, unlike that on microstrip line, is polarized primarily in the direction parallel to the substrate surface (*i.e.*, the x-axis), while the surface-wave mode which is important for the onset of leakage is the dominant TM_0 mode on the dielectric slab with a metal plate on its top surface. This latter mode, of course, is polarized mainly in the y-axis. As a result, when the principal crystal axis again coincides with the y-axis and when $\varepsilon_\perp > \varepsilon_\parallel$, the anisotropy of the substrate tends to lower the β/k_0 curve for the TM_0 mode and raise that for the dominant mode on slot line or coplanar waveguide. That anisotropy ratio therefore serves to raise the critical frequency for leakage. Alternatively, when $\varepsilon_\perp < \varepsilon_\parallel$ the critical frequency will be lowered, making the leakage problem worse.

From these considerations, we see that to avoid dominant-mode leakage altogether on microstrip line, the substrate should have $\varepsilon_\perp/\varepsilon_\parallel < 1$, but for slot line or coplanar waveguide, in order to move the leakage effect to higher frequencies, we require that $\varepsilon_\perp/\varepsilon_\parallel > 1$.

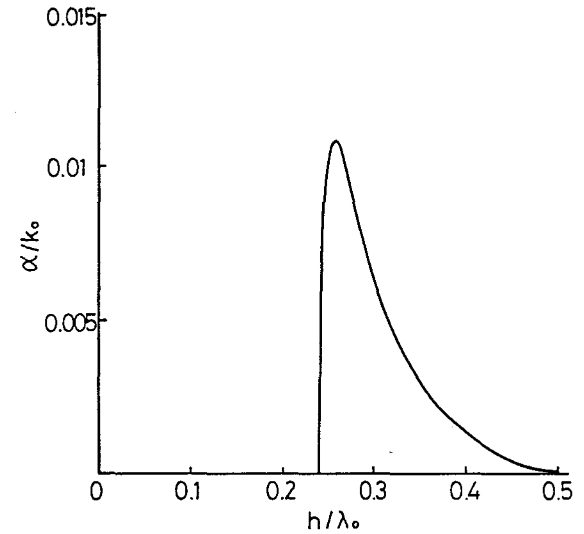
4. Quantitative Result:Full-Wave Theoretical Approach

We have developed a full-wave theoretical approach for this class of problems. It is the mode-matching method, which is purely numerical in nature, but is capable of yielding accurate results when a sufficient number of modes is employed in each elementary region. For the calculations, convergence in the mean square sense is imposed, and the procedure is reliable and asymptotically rigorous.

In this section, we apply this method to micro-



(a)



(b)

Fig.2. (a) Curves of normalized phase constant β/k_0 as a function of frequency (since h is kept constant) for the dominant mode on microstrip line, and for the TM_0 and TE_1 surface-wave modes on the dielectric layer outside of the strip region. Since $\varepsilon_{\|}$ ($=\varepsilon_y$) is smaller than $\varepsilon_{\perp}$ ($=\varepsilon_x=\varepsilon_z$), the curve for the TE_1 mode is seen to cross the curve for the microstrip-line dominant mode.
(b) Curve for normalized leakage constant α/k_0 for the dominant mode on microstrip line as a function of frequency (since h is kept constant). We note that leakage occurs for frequencies greater than the critical crossing frequency shown in Fig.2(a).

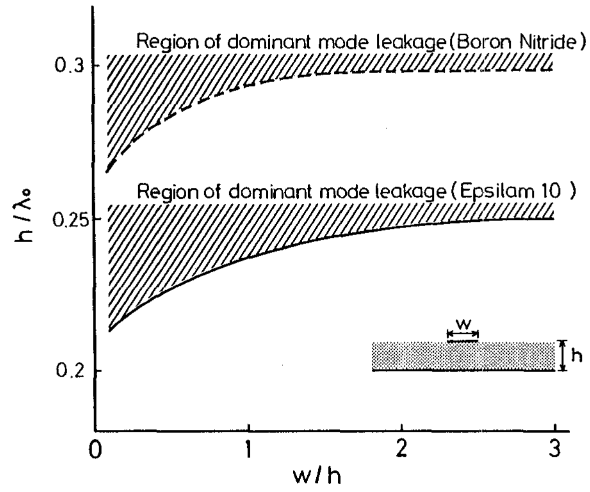


Fig.3. Curves of normalized critical crossing frequency, or thickness h/λ_0 of the substrate, as a function of w/h. For the hatched region above the solid curve (Epsilam 10) or the dashed curve (pyrolitic boron nitride), the dominant mode on the microstrip line becomes leaky and power radiates in surface-wave form.

strip line with anisotropic substrates made of pyrolitic boron nitride and Epsilam 10. For the sake of convenience in numerical calculations, a conducting cover plate or shield is put above the microstrip line. Its height is changed over a wide range, and the convergence of solutions is confirmed when only very small differences occur as the height is changed. In the calculations, we fixed both the thickness h of the substrate and the height H of the cover plate, and we varied the frequency while keeping constant the width w of the strip.

Fig.2 shows the result for the normalized phase constant β/k_0 (where $\beta = 2\pi/\lambda_g$) and normalized leakage constant α/k_0 when Epsilam 10 is used as a substrate. As expected from our physical considerations, we see that leakage indeed occurs for the dominant mode on microstrip line and that it occurs suddenly at a critical frequency. The maximum value of α/k_0 is about 0.01, corresponding to a leakage rate of about 0.55 dB per wavelength, which is a rather large value. It is also found that the behaviors of β/k_0 and α/k_0 for the microstrip line with pyrolitic boron nitride as a substrate are similar to those in Fig.2.

In these calculations, we can recognize that a mode-coupling region exists near the critical crossing frequency. This region is unusual because it involves spectral real solutions on one side and nonspectral complex solutions on the other side. We are now examining such mode-coupling effects in detail.

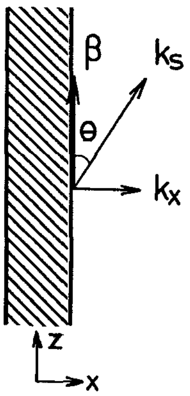


Fig.4. Top view of microstrip line, showing the angle θ of leakage into the surface surface wave of wavenumber k_S.

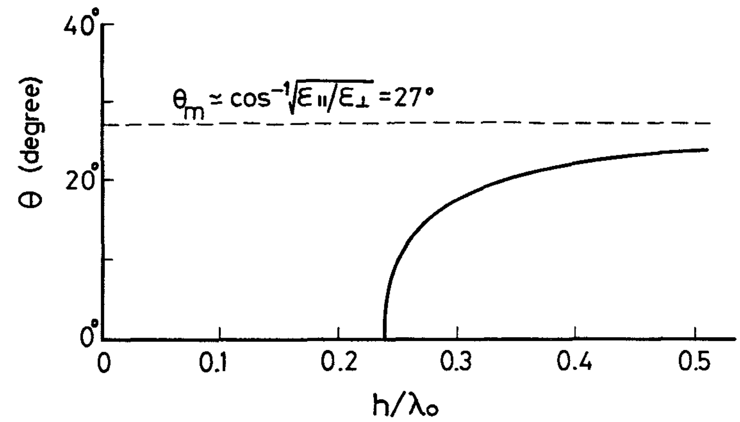


Fig.5. Variation of surface-wave leakage angle θ as a function of frequency (since h is kept constant). The direction of the leakage is seen to swing away from the strip axis by only a moderate amount in this example.

The critical frequency mentioned above depends, of course, on both the strip width w and the substrate thickness h. The solid curve of Fig.3 shows such a relation for Epsilam 10, while the dashed curve shows corresponding results for pyrolitic boron nitride. It is seen that the curves cover a very wide range of characteristic impedance values for the microstrip line. For the regions above these curves, power leaks from the dominant microstrip-line mode into the surface-wave mode on the outside. Again, it should be noted that the polarization of this leaky surface-wave mode is different from that of the dominant microstrip-line mode.

Let us next consider the angle of the leakage. Fig.4 shows a top view of the microstrip line. The angle θ of the leakage is related to the phase constant β of the dominant microstrip-line mode by $\cos\theta = \beta/k_S = (\beta/k_0)/(k_S/k_0)$, where k_S is the wavenumber of the TE_1 surface-wave mode. Leakage occurs above the critical frequency f_C corresponding to the crossing where $\beta = k_S$. At first, when $f = f_C$, the leakage angle θ is zero, with the leakage parallel to the strip. Since k_S/k_0 increases more rapidly than β/k_0 does as frequency increases, angle θ increases, and the leakage direction swings away from the strip direction. Fig.5 shows the result for the leakage angle θ as a function of the normalized frequency calculated for Epsilam 10. The maximum angle, which is reached monotonically, is seen to correspond roughly to $\cos\theta = \sqrt{\varepsilon_{\parallel}/\varepsilon_{\perp}}$, so that $\theta \cong 27°$. Thus, the leakage direction for the present case does not swing very far away from the strip axis.

Only a few numerical examples are given here because of limited available space, but it is obvious that the analytical approach mentioned above is applicable, with appropriate modification, to slot line and coplanar waveguide with anisotropic substrates.

The new leakage effect reported here can evidently be very important for millimeter-wave integrated circuits, where such leakage can cause serious performance difficulties.

Acknowledgments

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