MICROSTRIP LINE 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 microstrip line 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 microstrip line will leak power into surface waves on the substrate. 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. The same qualitative physical principles apply in a similar fashion to other printed-circuit guides, such as slot line or coplanar waveguide, though omitting their discussions here.

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: $\varepsilon_\perp$ = 11.6, the transverse axis permittivity:$\varepsilon_\parallel$ = 9.4), monocrystalline magnesium fluoride ($\varepsilon_\perp$ = 4.826, $\varepsilon_\parallel$ = 5.5), pyrolitic boron nitride ($\varepsilon_\perp$ = 3.4, $\varepsilon_\parallel$ = 5.12), ceramic-impregnated teflon (*e.g.*, Epsilam 10; $\varepsilon_\perp$ = 10.3, $\varepsilon_\parallel$ = 13.0) and so on, have been suggested for potential use as a substrate for microwave and millimeter-wave applications[1,2].

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. None of those analyses, however, inquired into 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 due to the Anisotropic Nature of Dielectric Substrates

For the case of an isotropic substrate, the dominant microstrip-line mode has its electric field predominantly along the axis perpendicular to the substrate surface or the y axis in Fig.1. The dashed line 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 was discussed elsewhere[4]. 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 ($\varepsilon_\perp/\varepsilon_\parallel = 1.263$).

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 from the considerations 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].

4. Quantitative Result:Full-Wave Theoretical Approach

We apply a full-wave theoretical approach based on the mode-matching method to microstrip line with anisotropic substrates made of pyrolitic boron nitride and Epsilam 10. Fig.2 shows the result for the normalized phase constant β/k_0 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.

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.

In the calculations of Fig.2(a), 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. Below the crossing frequency, the β value is real, and the spectral domaion method is also applicable to calculate it. On the other hand, the β value is complex above the crossing frequency. However, the leakage loss α/k_0 is negligible as the

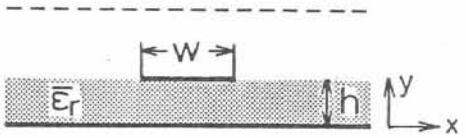


Fig.1. Cross section of microstrip line with an anisotropic substrate. The dashed line represents a possible top cover which the microstrip line may or may not have. The leakage effect discussed here applies to either case.

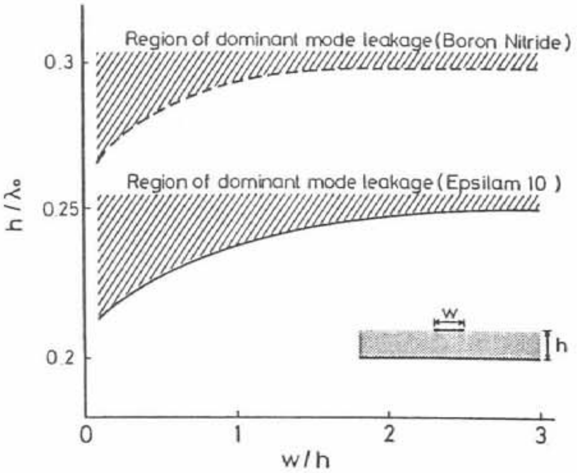
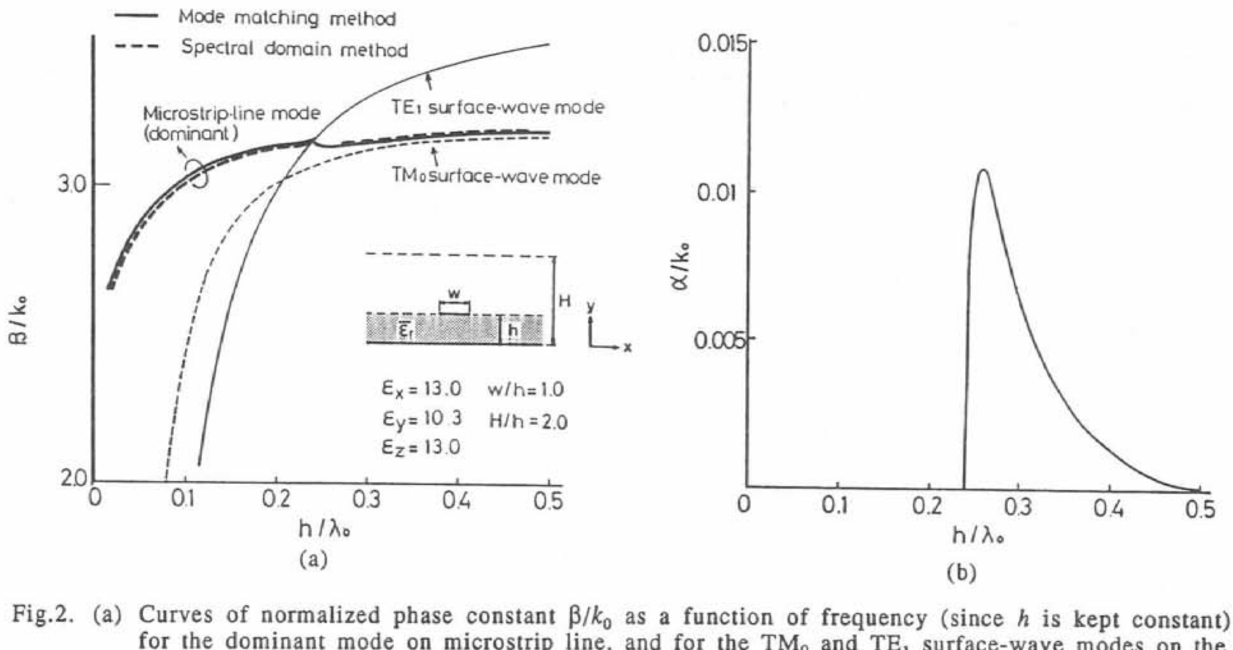


Fig.3. Curves of normalized critical crossing frequency, or thickness h/λ_0 of the substrate, as a function of w/h. For the hatched region above the solid curve (Epsilam 10) or the dashed curve (pyrolitic boron nitride), the dominant mode on the microstrip line becomes leaky and power radiates in surface-wave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



(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 $\varepsilon_{\parallel}$ $(=\varepsilon_y)$ 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).

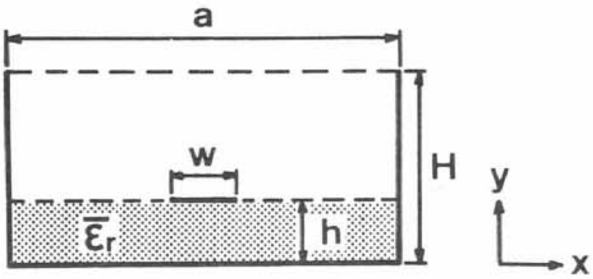


Fig.4. Microstrip line with conducting side walls.

frequency increases. Therefore, for the portion of β/k_0 curve except near the critical crossing frequency, the β values can be approximated by the real values obtained in an easy way which places conducting side walls spaced *a* apart as shown in Fig.4. There is then no leakage loss, but box modes are present, which can be viewed as a pair of surface waves bouncing between the sides. In the higher frequency region, the box modes then couple with the microstrip-line mode in a box. Therefore, if avoiding the calculations on such coupling points, the real phase constant β_b/k_0 of the microstrip-line mode in a box becomes a good approximation to that of the microstrip-line mode without side walls. For this calculation, the spectral domain method is again effectivelly used, and the obtained result is shown by the the dashed curve, which shows a good agreement with the accurate mode-matching result(the solid curve).

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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