THE NATURE OF THE LEAKAGE FROM HIGHER MODES ON MICROSTRIP LINE

A. A. Oliner and K. S. Lee

Polytechnic University
Brooklyn, New York 11201

ABSTRACT

Some confusion in the literature is clarified regarding the properties of microstrip line higher modes in the neighborhood of cutoff. It is shown that those modes become leaky in that range, and that the leakage occurs in two forms, a surface wave and a space wave. Numerical values obtained from an accurate analysis are presented that illustrate the nature of the leakage for microstrip lines with either open or covered tops.

1. Introduction and Summary

During the late 1970's, a paper presented by H. Ermert at the European Microwave Conference stimulated instant controversy. That paper and a subsequent publication [1] presented a thorough mode-matching analysis of modes on microstrip line, treating numerically the dominant mode and the first two higher modes. A principal conclusion was that a "radiation" region exists close to the cutoff of those modes. Because the description of this region, made in that talk and in published papers [1,2], was incomplete and therefore unclear to many, confusion persisted and certain practical consequences remained hidden.

Also in this general period, a paper by W. Menzel [3] presented a new traveling-wave antenna on microstrip line fed in its first higher mode and operated near to the cutoff of that mode. Menzel assumed that the propagation wavenumber of the first higher mode was real in the very region where Ermert said no such solutions exist; since his guided wave, with a real wavenumber, was fast in that frequency range, Menzel presumed that it should radiate. His approximate analysis and his physical reasoning were therefore also incomplete, but his proposed antenna was valid and his measurements demonstrated reasonably successful performance.

The first feature of the present paper involves the clarification of the confusion or contradictions implicit in the paragraphs above. These apparent contradictions are resolved when it is realized that leaky modes are present in this "radiation" region, and particularly so if the region can be characterized by only a single leaky mode. Not all leaky modes are physically significant, and more than one leaky mode may be present at the same time; each case must be examined separately for the physical significance of the role of leaky waves in any given "radiation" region. We have conducted such an examination, making use of the steepest descent plane, and we found that Ermert's "radiation" region is characterized in a highly convergent manner by essentially a single leaky mode.

Once we recognize the relevance of leaky modes to the "radiation" region of microstrip line higher modes, the application to leaky wave antennas becomes evident. In particular, it is clear that Menzel's antenna is a leaky wave antenna in principle, even though he did not recognize this fact and did not discuss the antenna's design or behavior in those terms. A leaky wave analysis explains quantitatively the performance features and the limitations of his antenna, and it also tells us how to improve the antenna performance in a controlled way. We will not be discussing any application to antennas here, however, but we will confine our attention to other interesting features of these modes, such as the nature of the leakage, and the need to modify our concepts of "cutoff" for higher modes on microstrip line.

It is shown that the power in any of these leaky modes is contained in only a surface wave in part of the frequency range and in a combination of a space wave and a surface wave in the remainder of the range. Simple conditions define the relevant portions of the range.

When the microstrip line is open above as well as on the sides, the space wave corresponds to radiation in a specified pattern. When the microstrip line is open on the sides but has a top cover, the "space wave" consists of a number of non-surface-wave modes that propagate away in the outside waveguide, composed of the dielectric layer between parallel plates. If the plate spacing is made larger (relative to wavelength), the number of propagating modes will increase. From a mode-matching analysis, we have found that, when the surface wave and the "space wave" are both present, the portion of power in the surface wave decreases substantially as the plate spacing is increased. Results as a function of top cover spacing will be presented.

We have derived an accurate transverse resonance formulation for the propagation characteristics of the higher modes, both in the purely bound range (real wavenumbers) and the "radiation" range (complex wavenumbers). Using this solution, we present numerical comparisons with special cases in the literature, showing the differences between the values for an open top and a covered top. In this derivation, we employed a rigorous (Wiener-Hopf) solution derived by D. C. Chang and E. F. Kuester [4] for the reflection from one side of that microstrip line. We made a parametric dependence study of the leakage and phase constants of the first three higher modes in the "radiation" range; we found that the leakage rate α grows rapidly as the mode approaches "cutoff," as expected, but that the phase constant β behaved unexpectedly. After approaching zero, it slowly increased again and continued to increase as the frequency was lowered further, requiring us to alter our earlier understandings of the nature of "cutoff" for higher microstrip line modes in open regions.

2. The "Radiation" Region and Leaky Modes

One of the figures presented by Ermert [1,2] is reproduced here, with modifications, as Fig. 1. His curves are the solid ones shown, for the lowest mode and the first two higher modes of microstrip line. All of his wavenumber values are real, meaning that the modes are purely bound in those ranges. He states, however, that in the region shown lined no real solutions exist, and he called this region the "radiation region." We have added the dashed lines appearing in this region in Fig. 1, which corresponds to complex solutions, and where, of course, only the real part is plotted. Physically, these complex solutions signify that this mode has become leaky in this region.

Ermert selects a spectral description for the modes of microstrip, and in his second paper [2] he rejects any inclusion of leaky modes since they are nonspectral (true). He then concludes that these leaky modes are "no longer of importance" in his analysis (false). His rejection of leaky modes not only caused much initial confusion, but it prevents one from understanding certain practical consequences. Not all leaky modes are physically significant, but we have shown by employing the steepest descent plane that for this problem the continuous spectrum in Ermert's radiation region is characterized in a highly convergent manner by essentially a single leaky mode. The physical importance of leaky modes despite their nonspectral nature is quite an old story, but it must be shown in each case that a particular leaky mode is physically valid; in this case, we have shown that it is, in agreement with obvious physical intuition.

3. The Two Forms of Leakage

It is shown next that leakage can occur in two forms: a surface wave and a space wave. Furthermore, the onset of leakage for each form is given by simple conditions.

A top view of the strip and the dielectric region around it is shown in Fig. 2. With this figure, we examine the case of leakage away from the strip in the form of a surface wave on the dielectric layer outside of the strip region. When there is leakage into the surface wave, the modal field propagates axially (in the z direction) with phase constant β, and the surface wave propagates away (on both sides) at some angle with phase constant k_s, as shown in Fig. 2. The surface wave wavenumber k_s has components k_z and k_x in the z and x directions, respectively, where k_z must be equal to β, since all field constituents are part of the same leaky modal field. We may therefore write:

$$k_x^2 = k_s^2 - \beta^2 \quad (1)$$

For actual leakage, k_x must be real, so that the condition for leakage is $k_x^2 > 0$. (When there is no leakage, i.e., the mode is purely bound, the modal field decays transversely and k_x is imaginary.) Applying this condition to (1), we find that, for leakage,

$$\beta < k_s \quad (2)$$

Relation (2) defines the lined region in Fig. 1; the upper boundary of that region is actually the dispersion curve for the surface wave, of wavenumber k_s, that can be supported by the dielectric layer on a ground plane, if the microstrip line is open above, or by the dielectric layer between parallel plates, if there is a metal top cover. At the onset of the surface wave, it emerges essentially parallel to the strip axis, consistent with the condition $\beta = k_s$.

As β (and therefore the frequency) is decreased below the value k_s, power leaks away in the form of a surface wave, as discussed above. As β is decreased further, power is then also leaked away in another form, the space wave. If the microstrip line is open above, this space wave actually corresponds to radiation at some angle, the value of this angle changing with the frequency. At the onset of this space wave, the wave emerges essentially parallel to the strip axis, so that $\beta = k_o$ then, where $k_o = (2\pi/\lambda_o)$ is the free space wavenumber. This boundary corresponds to the horizontal line $\beta/k_o = 1$ in Fig. 1. For values of $\beta/k_o<1$, or

$$\beta < k_o \quad (3)$$

power will leak into a space wave in addition to the surface wave.

What happens when the microstrip line has a top cover, of height h? If $h<\lambda_o/2$, approximately, such that only the surface wave can propagate in the dielectric-loaded parallel plate region, then all the other modes are below cutoff, and power can leak away only in surface wave form. If the plate spacing is increased, then some of the non-surface-wave modes are above cutoff, and these modes can also carry away power. The "space wave" then corresponds to the sum of those modes.

At what value of β do these "space wave" modes begin to contribute to the leakage? The value depends on the height h of the top cover. Space does not permit us to present the appropriate relations, but, as examples, we find that for h/λ_0 = 5, 2, and 1, β/k_0 = 0.995, 0.97, and 0.87, respectively.

4. Numerical Values for the Leakage and Phase Constants

We have derived an accurate expression for the propagation characteristics of the first higher microstrip mode, both in its purely bound range (real wavenumbers) and in its leakage range (complex wavenumbers). Our analysis involves a horizontal transverse resonance in which we employed as a key constituent a solution for the strip sides given by Chang and Kuester [4].

We compared our numerical values for open tops with special cases appearing in the literature for covered tops, to determine where they differ. First, we compared our results in the real wavenumber range with those of Ermert [1]; the curves will be presented in the talk. Then, in the complex wavenumber range, the only available numbers for a special case (a top cover with small height) are given by J. Boukamp and R. H. Jansen as part of a larger paper [5]. Our comparison with their numbers is presented in Fig. 3. It is interesting to note that entirely different theoretical approaches were used in these three cases; Ermert employed a horizontal mode-matching procedure, and Boukamp and Jansen used a vertical spectral domain approach.

In Fig. 3, we plot the leakage constant α/k_0 and the phase constant β/k_0 as a function of frequency. The solid line curves represents our solution, which is valid for an open microstrip line, and the dashed curves are the numbers presented by Boukamp and Jansen for a line with a top cover of small height. The dimensional parameters, which are identical for the two cases except for the top cover, are given in the figure caption.

It is seen that in the plots in Fig. 3(a) for the leakage constant the two curves are roughly parallel to each other, with the covered case leaking more strongly, even though the leakage for each begins at about the same frequency. We should also note that the forms of leakage are different for each. For the solid line, the leakage is mostly in the form of a space wave, whereas the dashed line, for the covered top case, has all the leakage in surface wave form. Another important feature evident from Fig. 3(a) is that the values of α/k_0 are quite high, meaning that a substantial amount of power can leak per unit length if the frequency is made somewhat lower than the one corresponding to the onset of leakage. For example, for a frequency of 12.8 GHz for this case, for the structure with a top cover, the value of α/k_0 is about 0.20, corresponding to a leakage attenuation rate of about 4.6 dB/cm! For the open structure, the leakage rate is lower but still high, being about 2.4 dB/cm.

5. References

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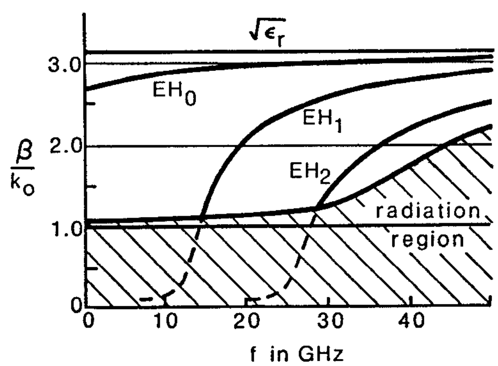

Fig. 1 Dispersion curves for the lowest mode and the first two higher modes in microstrip line with a top cover. The normalized phase constant β/k_0 is plotted against frequency. The solid lines (given by Ermert [1,2]) represent real wavenumbers, whereas the dashed lines correspond to the real parts of the leaky mode (complex) solutions in the "radiation region." The microstrip line dimensions are: strip width = 3.00 mm; dielectric layer thickness = 0.635 mm, ϵ_r = 9.80, and the height of the top cover is five times the dielectric layer thickness.

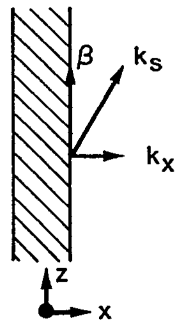

Fig. 2 Top view of the strip of microstrip line and the dielectric region around it. Wavenumbers β and k_s correspond, respectively, to the phase constant of the leaky mode guided by the strip and the wavenumber of the surface wave that propagates away at some angle during the leakage process.

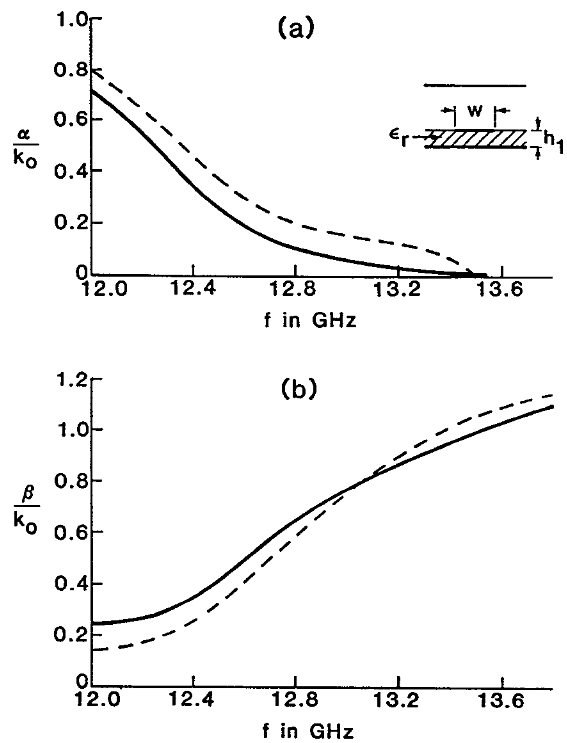

Fig. 3 Variation of leakage constant α/k_o (figure (a)) and phase constant β/k_o (figure (b)) with frequency for the first higher microstrip mode in its leakage range. The solid lines in both (a) and (b) represent our solution for an open microstrip line, and the dashed lines are the numbers presented by Boukamp and Jansen [5] for a line with a top cover of small height. The microstrip line dimensions are those given in reference [5]: dielectric layer thickness h_1 , ε_r = 9.7, and, for the covered case, the height of the top cover = 10 h_1 .