G-2

CONDUCTOR-BACKED SLOT LINE AND COPLANAR WAVEGUIDE: DANGERS AND FULL-WAVE ANALYSES

H. Shigesawa and M. Tsuji
Doshisha University, Kyoto, Japan
and
A. A. Oliner
Polytechnic University, Brooklyn, New York

ABSTRACT

Despite the many attractive features of conductor-backed slot line and coplanar waveguide, there are dangers or potential surprises in their use. We have developed two theoretical approaches, one purely numerical and the other in network form and analytical in nature, that agree well with each other and with measurements in a special case. They provide, for the first time, a quantitative description of these potential surprises when the line conductors are either infinite or finite in width.

1. Introduction

It is very tempting in microwave integrated circuits, including MMICs, to introduce a conductor backing for slot line or coplanar waveguide because such conductor backing has many *advantages*. Among these advantages, as quoted in the literature [e.g., 1,2], are: lowers Z_o , lessens dispersion, improves mechanical strength, allows easier implementation of mixed coplanar waveguide-microstrip or slot line-microstrip circuits, helps in grounding floating regions, convenient for dc biasing, and provides a convenient heat sink. There are also certain important *dangers*, or serious potential problems, that are introduced by the use of conductor backing. These potential problems include leakage of power into surface waves or into the dielectric region between the plates, unexpected cross talk, significant alteration of the guide wavelength, and unexpected or unwanted coupling to neighboring lines.

These possible unpleasant consequences seem *not* to have been discussed in the literature, except for a recent paper [3] which observed correctly that in conductor-backed coplanar waveguides leakage of power occurs into the dielectric-filled parallel-plate regions on the sides. No quantitative information was provided, however, on the rate of that leakage. In this paper, we present *both theoretical and measured* results for such leakage rates; the theoretical values are computed using two different methods that provide full-wave analyses, and these theoretical results agree well with each other and with the measurements.

The type of potential problem outlined above depends on the *lateral extent*, or *width*, of either the conductor backing or the plates comprising the slot line or the coplanar waveguide. Several examples of conductor-backed slot line, with various conductors of infinite and finite lateral extent, are presented in Fig. 1; the upper shielding plate or cover, which is customarily there but plays a minor role, is omitted from Fig. 1 for simplicity (and clarity). Studies have been conducted for both slot line and coplanar waveguide, but we present here only the results for slot line because of space limitations and the fact that the slot line structure is a bit simpler.

Structure (a), and its equivalent in coplanar waveguide, will *always* leak power into the dielectric-filled parallel-plate regions, and the leakage rate is *rather high*, as we show later. Structure (b) represents the other extreme, a conductor-backed two-strip line; however, it is also a pair of coupled microstrip lines in its odd mode. That structure and those in (c), (d), (e) and (h) will not leak at lower frequencies but may leak into a surface wave in the outer regions *at higher frequencies*. All structures with finite metal lengths that are not short, such as (c), (e), (f) and (h), face the danger that when no leakage occurs the guide wavelength can be seriously altered from its expected value by the loading produced by the finite transverse line lengths. Structure (d), which involves only a short conductor back, and which is utilized in the de Ronde coupler [4], will not face this danger. Finally, we show in (g) and (h) that *coupling* (desired or not) can occur between parallel slot lines *not near each other* on the same side or on opposite sides. These examples are meant to be indicative of the sort of structure that can encounter unexpected difficulties, but they are not intended to be exhaustive. Although these considerations are made above for slot line, they apply equally well to coplanar waveguide.

The only full-wave analyses that appear in the literature apply to the infinitely wide structure in (a) [1] and the other extreme in (b). The analysis that applies to (a) was actually performed for coplanar waveguide, but it was done several years ago, before it was recognized that leakage could occur; that analysis is therefore incomplete since it misses the leakage effect altogether. Many full-wave analyses for the structure in (b) appear in the literature (see [5] for a very good summary), in the context of the odd mode of a pair of coupled microstrip lines. None of those treatments, however, inquired as to whether or not leakage into a surface wave could occur at the higher frequencies. On the other hand, an approximate analysis [6] was performed for the two coplanar strips *without* conductor backing which does ask this question, and indeed answers it in the affirmative, with measurements to back up the conclusion. To our knowledge, there are no full-wave

0149-645X/88/0000-0199$01.00 © 1988 IEEE

analyses for any of the other situations, for either slot line or coplanar waveguide.

In this paper we present two methods of analysis that are applicable to all of the structures in Fig. 1, thereby providing for the first time a systematic full-wave analytical procedure for determining the effect of finite plate widths on the modal propagation characteristics. In Sec. 2, the two full-wave theoretical methods are outlined. One method is based on mode matching and the other employs a new transverse equivalent network where the elements are expressed in simple closed form. In Sec. 3, these methods are applied to the infinitely wide structure in Fig. 1(a). It is shown that results from the two methods agree rather well with each other for that structure. Measurements were also made for both the guidance and the leakage properties; some measurement features are described and the agreement with theory is shown. In addition to demonstrating that the conductor backing leads to a high leakage rate, the comparisons with measurement and those between the theories show that the theoretical methods are reliable.

Some of the unexpected dangers that can arise when the plates are *finite* in lateral extent are discussed in Sec. 4. Only one numerical example is given because of limited available space, but additional ones will be presented during the talk for both slot line and coplanar waveguide.

2. Full-Wave Theoretical Approaches

We have developed two full-wave theoretical approaches for this class of problems. One is the *mode matching* method, applied in the x direction shown in Fig. 2; it is purely numerical in nature, but is capable of yielding accurate results when a sufficient number of modes is employed. For the calculations described in Sec. 3, 50 TE modes and 50 TM modes in each region were included, and convergence in the mean square sense was imposed. The procedure is reliable and asymptotically rigorous, but requires some computer time.

The second theoretical method is based on a *new transverse equivalent network* applicable to the slot that couples two parallel plate guides, as shown in Fig. 2, where one of the two guides is dielectric filled. The new network is an adaptation of the tee junction network used as a constituent in the network characterizing a scanning array [7]. The network is shown in the upper portion of Fig. 3; when the full guide cross section is symmetrical (with respect to the yz plane), the network reduces to the simplified form in the lower part of Fig. 3. The dispersion relation for the propagation characteristics of the conductor-backed slot line mode is obtained by simply taking a resonance of this transverse equivalent network. The expressions for the elements of this network are all in simple closed form, so that the dispersion relation is likewise in closed form, and numerical calculations may be made quickly and cheaply. The lateral terminations on the transmission lines in the network must be appropriate to the structure under analysis. For the structure in Fig. 1(a), for example, the terminations would simply be the respective characteristic admittances of each line.

This network is easily extended in order to apply to coplanar waveguide, which may be viewed as two closely spaced slot lines operated in their even mode. Simple modifications in the mode-matching procedure also permit it to be applied directly to coplanar waveguide.

3. Application to Conductor-Backed Slot Lines of Infinite Width

In this section, we apply each of the two theoretical methods to the structure in Fig. 1(a), obtain the performance characteristics, and then compare the numerical results with each other and with some *measurements* that we took.

For the first set of calculations, we fixed the height b of the dielectric layer and the height t of the metal shield above, and we varied the width d of the slot while keeping the frequency constant. The mode-matching procedure is valid over a wide range of d/λ_o, whereas the network method is valid until the slot width d becomes slightly greater than the dielectric height b. Over their respective ranges of validity, a comparison is presented in Fig. 4 for the two theories for the normalized phase constant β/k_o (where $\beta = 2\pi/\lambda_g$) and normalized leakage constant α/k_o of the slot line mode, as a function of d/λ_o. The agreement is seen to be quite good, especially in the range for which d/λ_o is about 0.1 or 0.2, which corresponds to most practical situations.

The new information relates to the fact that there is leakage, and to the high values of α/k_o. We see that a typical value is $\alpha/k_o = 0.1$, and that it occurs at $d/\lambda_o \approx 0.1$; the axial leakage rate in dB per slot width is thus about 0.5, which is a very large value. The leakage occurs as a TEM wave in the dielectric-filled parallel-plate regions, and proceeds at an angle θ from the slot axis equal to $\cos^{-1}(\beta/k_o\sqrt{\varepsilon_r})$, which for $d/\lambda_o = 0.1$ is 31°.

We next made similar computations for different values of t/λ_o, the height of the cover plate or shield. In particular, detailed calculations were made for $t/\lambda_o = 0.667$ and 3.33, and it was found that only small differences occur when t/λ_o is changed. The height of the cover plate thus plays a minor role only.

Armed with that information, we performed a set of *measurements* on a conductor-backed slot line at a frequency of 10.0 GHz. The dielectric was polyethylene, with $\varepsilon_r = 2.25$, the dielectric height b was 8.0 mm, there was no top cover plate, and the slot width was varied. The slot was excited by a metal loop that curved over the slot, and was fed by a miniature coax line at one end and short-circuited at the other end. The conductors forming the conductor-backed slot line were about 40 cm wide and about 20 cm long for the high-leakage cases, and about 60 cm long for the lower-leakage cases; absorbing material was placed around all the edges to simulate a structure of infinite width. In addition to measurements of λ_g and α, the field in one case was probed across the far end parallel to the x direction to determine the leaky-wave field distribution. A sketch of the measurement set-up, and a plot of the cut in the x direction of the leaky-wave field, are shown in Fig. 5.

Comparisons between the theoretical results for β/k_o and α/k_o and the measured values over a wide range of slot widths are presented in Fig. 6. It is seen that the agreement is fairly good, but could be better, particularly for low d/λ_o. However, the slots were narrow there and difficult to excite cleanly; furthermore, the leakage loss rate was so high that it was difficult to measure λ_g accurately. Overall, the agreement is deemed sufficiently good that we may have confidence in the validity of the theory.

4. Effects for Plates of Finite Width

We have established above that for conductor-backed slot lines of infinite width, or infinite lateral extent, power leaks into the dielectric-filled parallel-plate region and the mode becomes a leaky mode characterized by a complex propagation constant. When either the top or the bottom plates are finite, as in structures (c), (e) or (f) in Fig. 1, the parallel plates can no longer support a TEM wave to infinity transversely, and the TEM wave (which travels out at an angle) becomes totally reflected from the sides. The propagation wavenumber is then purely real, but we are not then safe from nasty surprises. Let us examine some possibilities.

First, we recognize that the field fully fills the parallel-plate regions that remain. That means that the field exists at the outer sides and then decays exponentially from there. Thus, another slot line, such as those shown in Figs. 1(g) or (h), can *couple* strongly to the original slot line either intentionally or inadvertently.

A second phenomenon can become important when the widths c_1 or c_2 in Figs. 1(e) or (f), say, are not short. Such a situation can arise when the plates extend to the edges of the supporting board and are then terminated in some fashion. If the termination on the side does not permit leakage, the outward-traveling TEM wave will be totally reflected and a transverse standing wave will be created. That standing wave can place an admittance termination at reference plane T in the network shown in Fig. 3 in such a way as to very strongly load that network and thus significantly influence the value of β (or λ_g) of the slot line mode. The network can be employed directly to determine quantitatively the effect on β for various cases. Examples will be presented in the talk.

The third important potential surprise can occur at *higher frequencies* for structures like (b), (c) or (e) in Fig. 1. What is required is a region beyond the finite plate width that can support a surface wave. At higher frequencies the value of β for the slot line can become *lower* than the value of β for the surface wave. For frequencies *above* that cross-over point, power will leak from the slot line mode into the surface wave on the outside, and the propagation wavenumber for the slot line mode will become complex. Such leakage could produce unexpected cross talk with neighboring circuits. An example is given in Fig. 7.

Although the discussion above concentrated on slot line due to space limitations, these considerations apply to coplanar waveguide as well, and numerical examples for both slot line and coplanar waveguide will be presented at the symposium talk.

References

1. Y. C. Shih and T. Itoh, "Analysis of Conductor-Backed Coplanar Waveguide," Electronics Letters, Vol. 18, No. 12, pp. 538-540, 10 June 1982.

2. G. Ghione and C. U. Naldi, "Coplanar Waveguides for MMIC Applications: Effect of Upper Shielding, Conductor Backing, Finite-Extent Ground Planes, and Line-to-Line Coupling," IEEE Trans. Microwave Theory Tech., Vol. MTT-35, pp. 260-267, March 1987.

3. R. W. Jackson, "Considerations in the Use of Coplanar Waveguide for Millimeter-Wave Integrated Circuits," IEEE Trans. on Microwave Theory Tech., Vol. MTT-34, pp. 1450-1456, December 1986.

4. F. C. de Ronde, "A New Class of Microstrip Directional Couplers," Digest IEEE International Microwave Symposium, pp. 184-189, 1970.

5. K. C. Gupta, R. Garg and I. J. Bahl, Microstrip Lines and Slotlines, Chap. 8, Artech House, Dedham, MA, 1979.

6. D. B. Rutledge, D. P. Neikirk and D. P. Kasilingam, Chapter, "Integrated Circuit Antennas," Infrared and Millimeter Waves, Vol. 10, K. J. Button, Ed., pp. 1-90, 1983.

7. P. Lampariello and A. A. Oliner, "A Novel Phased Array of Printed-Circuit Leaky-Wave Line Sources," Proc. 17th European Microwave Conference, pp. 555-560, Rome, Italy, September 7-11, 1987.

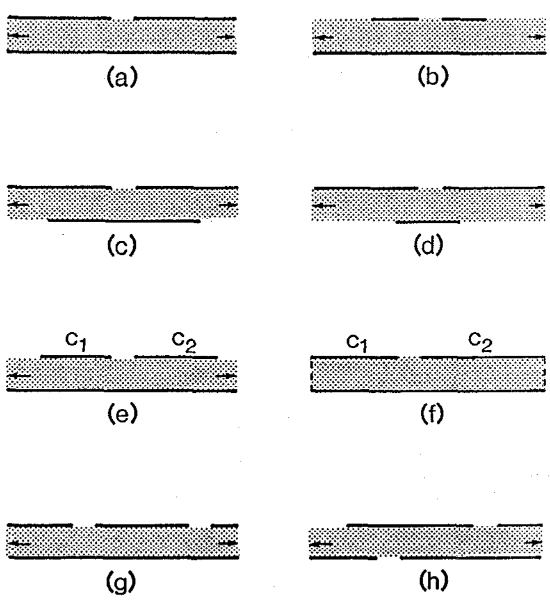

Fig. 1 Several examples of conductor-backed slot line, where either the slot line conductors or the backing conductor can be of infinite or finite lateral extent. The upper shielding plate or cover is omitted for clarity.

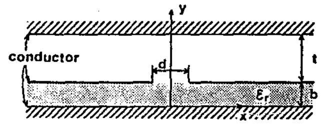

Fig. 2 Cross section of a slot line of infinite width that is conductor backed.

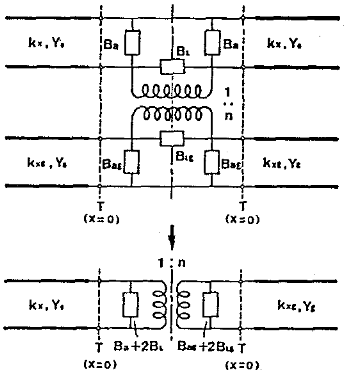

Fig. 3 Transverse equivalent network for a slot line with a top cover and with conductor backing. The reference plane T is located at the slot midplane. The terminations on the connecting transmission lines depend on the details of the structure in the lateral (x) direction. When the slot line structure is symmetrical, the upper network reduces to the simpler lower one.

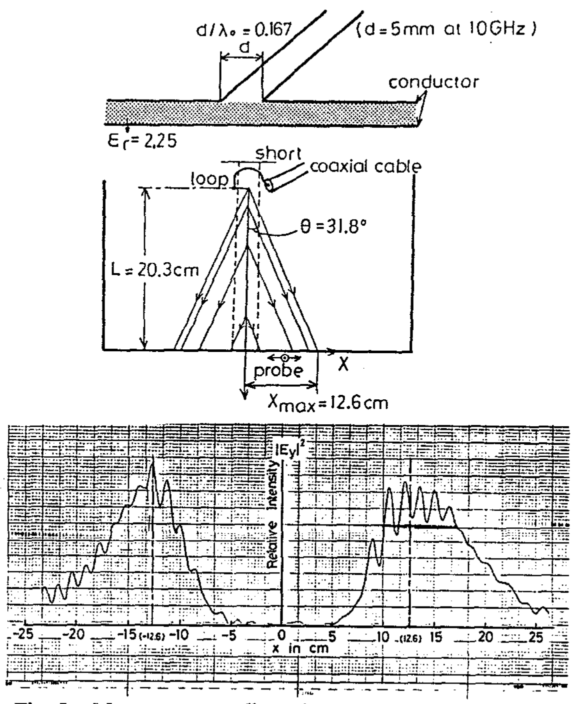

Fig. 5 Measurements: dimensions of slot line structure, method of excitation, angle of leakage, and sample of measured leakage pattern obtained by probing transversely (across, in the x direction).

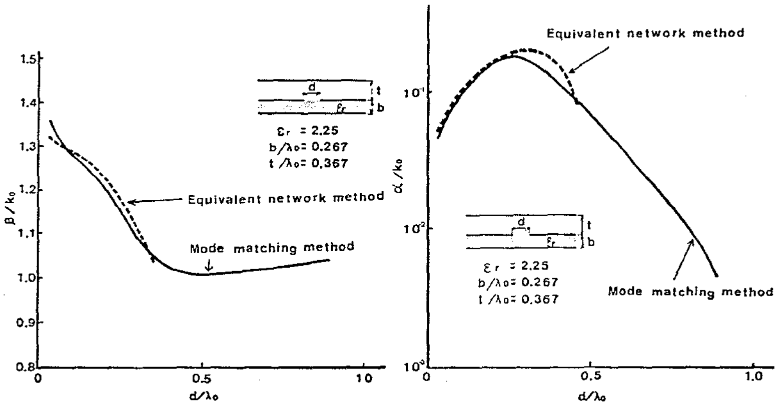

Fig. 4 Comparisons between the two theoretical methods for the normalized phase and leakage constants as a function of normalized slot width, for a conductor-backed slot line of finite width. Most slot lines have values of d/λ_0 between 0.1 and 0.2, where the agreement between the methods is very good.

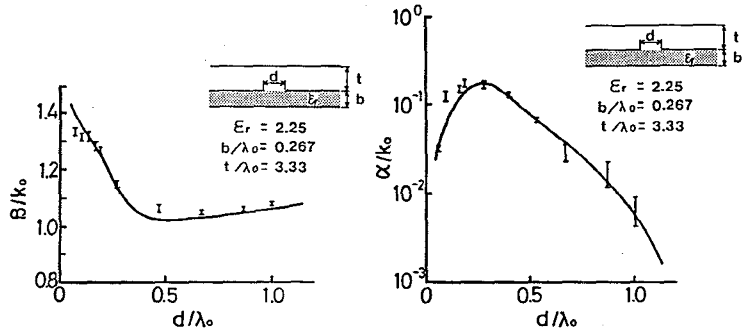

Fig. 6 Comparisons between measured points and theoretical curves for the normalized phase and leakage constants as a function of normalized slot width, for a conductor-backed slot line of infinite width.

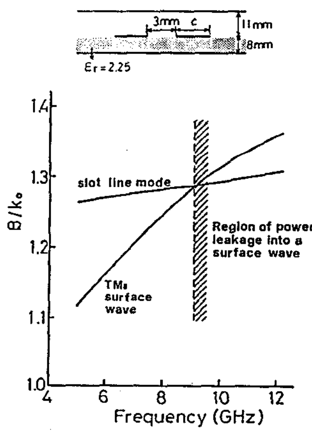

Fig. 7 Curves of the normalized phase constant β/k_0 vs. frequency for the lowest TM surface wave and for the slot line mode. We note that for frequencies greater than about 9 GHz in this plot the wavenumber for the slot line mode is less than that for the surface wave, so that the slot line mode becomes *leaky* and power radiates in surface wave form.