NEW PROPAGATION EFFECTS FOR THE INVERTED STRIP DIELECTRIC WAVEGUIDE FOR MILLIMETER WAVES

A. A. Oliner, S. T. Peng and J. P. Hsu*
Microwave Research Institute
Polytechnic Institute of New York
333 Jay Street
Brooklyn, New York 11201

ABSTRACT

The existing theory for the inverted strip dielectric waveguide neglects the presence of additional constituent modes and the coupling between them at the strip sides. An improved theory which accounts for these features reveals interesting unanticipated physical effects, including leakage, resonances, mode coupling and modifications in transverse field distributions.

Summary

Associated with the resurgence in interest during the past few years in millimeter waves, several novel waveguiding structures have been proposed which are suitable for millimeter wave integrated circuits but which avoid the high loss associated with the metallic strip of microstrip line at these high frequencies. One of the most promising of these is the inverted strip dielectric waveguide,[1,2] the cross section of which is shown in Fig. 1. This waveguide, which was

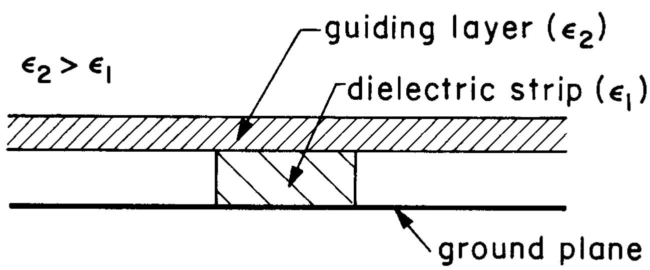

Figure 1: Cross section of the inverted strip dielectric waveguide for millimeter waves.

proposed by Itoh, has the added virtue that the loss due to the metallic ground plane is also minimized, since the dielectric constant values are so chosen that most of the energy resides in the upper dielectric sheet. The dielectric strip serves to confine the guided wave laterally, but the field in the strip region is evanescent vertically, with the result that the field becomes small when it finally reaches the metallic ground plane, and the ground plane current remains low as a consequence.

The published theoretical analysis[1] for the propagation characteristics of this waveguide type is approximate, but it serves well enough to produce reasonable agreement with available experimental results.[1] However, when a more careful examination is made of the comparison between theory and measurements, it is seen that the agreement is poor in some regions and that, in fact, some puzzling discrepancies appear. We have conducted an improved analysis of the behavior of the structure, and we will show in this paper that this improved theory not only produces better agreement with measurement but also reveals a number of very interesting and fundamental propagation effects which the earlier approximate analysis misses entirely.

---

* On leave from Kanagawa University, Japan.

The approximate theoretical analysis[1] mentioned above utilizes the so-called "equivalent dielectric constant" (edc) method, which is essentially a simplified transverse resonance procedure that assumes the presence of only one mode, the lowest TM mode, in each of the constituent transverse regions comprising the guide cross section. Furthermore, in the transverse resonance taken under these conditions in the horizontal direction, the geometrical discontinuities present at the strip sides are completely neglected since each constituent region is viewed as possessing an "equivalent dielectric constant."

The first thing that a more accurate analysis reveals is that in each constituent region in the guide's cross section at least two propagating modes, one TM and the other TE, must be present simultaneously under almost all conditions. In fact, if the dielectric sheet or dielectric strip thickness were increased, then the number of modes present simultaneously would increase to four or to six, etc. When we examine the three structures actually analyzed and measured by Itoh,[1] we find that four simultaneous modes are present in two of them, and that six simultaneous modes are present in part of the third guiding structure.

The second key point that a more accurate analysis indicates is that the TE and TM modes which are present necessarily couple to each other at the geometrical discontinuities corresponding to the sides of the strip. This coupling requirement is readily proven by an examination of the field components that must be present at these strip sides.

As will be shown, the simultaneous presence of these other modes in the constituent regions, and their coupling at the strip sides, produce a number of interesting and sometimes important physical effects not observed earlier. Among these effects are the following:

a) Under appropriate conditions, leakage from the strip sides can occur, changing the dominant bound mode into a leaky mode.

b) Under appropriate conditions, for certain frequencies or strip widths, resonance effects can occur.

c) The transverse field behavior, both vertically and horizontally, can differ significantly from what one expects on the basis of the dominant mode alone.

d) If discrete modes higher than the lowest TE and TM ones are present in the individual constituent regions, the guided modes associated with them will

CH1355-7/78/0000-0408$00.75

almost always be leaky.

These previously unexpected propagation effects could produce unwanted performance difficulties under some circumstances, or else advantage could be taken of them if it is known in advance what the effects are and when they occur. Furthermore, by a proper choice of dimensions or dielectric constants these effects can either be made to appear or be eliminated.

We present in Fig. 2 calculations for the basic surface wave characteristics of the constituent regions

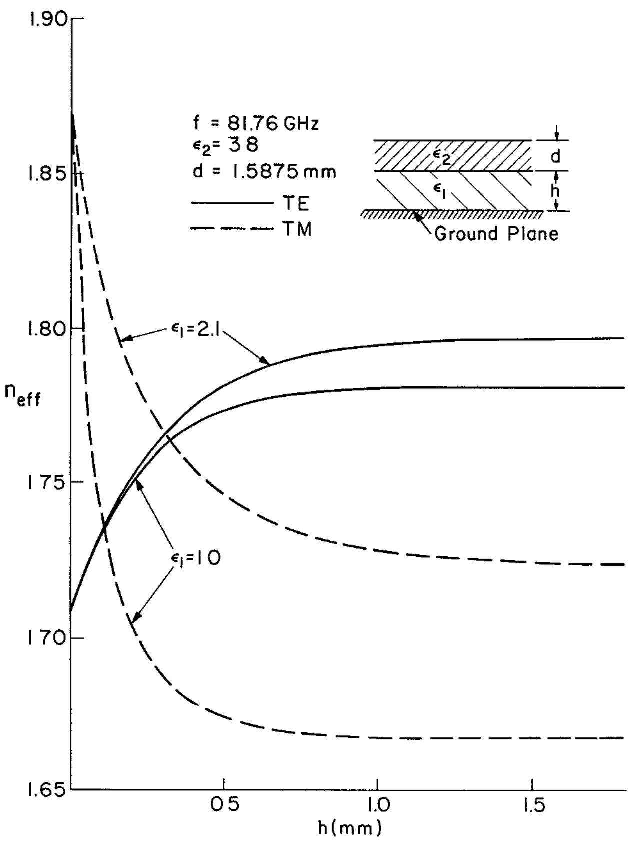

Figure 2: Basic surface wave characteristics for the constituent regions comprising the guide cross section. "Effective dielectric constant" values as a function of strip height for all of the discrete modes existing at that frequency (81.7 GHz).

comprising the inverted strip guide cross section. The calculations are in the form of the "effective dielectric constant," ϵ_{eff}, which is proportional to the propagation constant, as a function of dimensions for the specific parameters chosen by Itoh[1] for his three waveguides. (Actually, the plots are given as $n_{eff} = (\epsilon_{eff})^{1/2}$ vs. h, which is the height of the strip, when d, the height of the upper layer, f, the frequency, and the dielectric constant values in each region are specified.) The two curves labeled $\epsilon_1 = 1.0$ correspond to the constituent portions of the guide cross section which are outside of the strip portion, whereas the two curves labeled $\epsilon_1 = 2.1$ hold for the strip region itself. The three cases examined by Itoh correspond to h = 0.794 mm, 1.588 mm and 3.175 mm. Both inside and outside of the strip region, at least 4 modes are present simultaneously, 2 TE modes and 2 TM modes. In his analysis, Itoh assumed that only the lowest TM mode was present.

Several other interesting features also follow from Fig. 2. Note that the lowest TM mode, which is the mode incident and the one which contains most of the power, is no longer the "dominant" mode in the sense that it is the slowest mode, as it is for a single dielectric layer on a ground plane. As h increases, a cross-over occurs, and the TE mode becomes the "dominant" one. It is the occurrence of this interesting cross-over that makes possible the leakage and resonance effects.

The curves in Fig. 2 are used in a simple way to determine when these leakage and resonance effects will appear. It will be shown in the talk how these curves are used for this purpose, and a simple criterion in this connection will be presented. As mentioned earlier, the leakage and resonance effects arise because of the TE-TM coupling which occurs at the strip sides. The TM wave inside the strip region, which is incident at an angle on the strip side, excites a reflected propagating TM wave inside, an evanescent TM wave outside, and (due to the coupling) TE waves both inside and outside the strip region. If the TE wave excited outside is propagating rather than evanescent, it carries away a small amount of energy at each reflection, resulting in a leaky mode rather than a purely bound mode. If the TE wave inside the strip region is closer to the normal than the TM wave, then resonance effects occur at certain strip widths. (Similar leakage and resonance behaviors have been reported for strip waveguides for integrated optics,[3] but certain differences are present in this millimeter wave structure.)

One or the other of these special effects can be present (or absent) depending on the precise dimensions of the structure. Table I summarizes the resonance and leakage behavior for three sets of dimensions for the inverted strip waveguide, using the dielectric constant values employed by Itoh.

TABLE I

Basic mode: lowest TM
$\epsilon_1 = 2.1, \ \epsilon_2 = 3.8$

Case	d/λ	h/λ	Resonance	Leakage
1	0.10	0.20	no	yes, if $W/\lambda < 0.3$
2	0.20	0.15	yes	yes, if $W/\lambda < 1.5$
3	0.10	0.10	no	no

For case 1, we see that leakage can occur without resonance effects. However, the leakage may be eliminated if the strip width is increased beyond about 0.3λ, which is not difficult to accomplish. On the other hand, in case 2 we observe both resonance and leakage, where the leakage would be present over a rather wide range of values of W/λ. In case 3, neither effect is present, showing that it is certainly possible to design the waveguide without encountering these problems.

A detailed theoretical analysis including all of the constituent modes present and their coupling to each other at the strip sides has been performed for a number of different waveguide parameters. In the talk, comparisons will be shown between the results of these theoretical calculations and the data presented by Itoh[1] for both the longitudinal propagation constant and the transverse field distributions.

References

1. T. Itoh, "Inverted Strip Dielectric Waveguide for Millimeter-Wave Integrated Circuits," IEEE Trans. Microwave Theory Tech., MTT-24, 821-827, November 1976.

2. R. Rudokas and T. Itoh, "Passive Millimeter-Wave IC Components Made of Inverted Strip Dielectric Waveguides," IEEE Trans. Microwave Theory Tech., MTT-24, 978-981, December 1976.

3. S. T. Peng and A. A. Oliner, "Leakage and Resonance Effects on Strip Waveguides for Integrated Optics," International Conference on Integrated Optics and Optical Fiber Communication, Tokyo, Japan, July 18-20, 1977.