DIRECT EXPERIMENTAL CONFIRMATION OF NEW LEAKAGE EFFECTS ON OPEN DIELECTRIC STRIP WAVEGUIDES

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Abstract

Certain open dielectric strip waveguides for millimeter waves and for integrated optics leak under appropriate circumstances. This leakage was predicted theoretically and indicated experimentally in indirect fashion. Here, direct measurements are presented which verify not only the leakage but also the resonance effect associated with it.

Introduction

Two of the present co-authors were the first to predict that the propagation characteristics of a class of open dielectric waveguides could, under appropriate circumstances, involve the leakage of guided energy and leakage-related resonance effects.[1-3] This class of waveguides includes some of the dielectric strip waveguides which are currently being considered for application to millimeter-wave integrated circuits at the shorter millimeter wavelengths. Among these are the insular guide[4] and the inverted strip guide.[5] If unexpected leakage occurs, the resulting cross talk between neighboring elements of the integrated circuit could deteriorate the performance properties of the circuit. On the other hand, the leakage could possibly be exploited to produce novel components. In either case, it is important to know when leakage can occur and how to control it.

The early theories which described the propagation behavior of these dielectric strip waveguides were approximate, and they missed entirely these interesting leakage effects. References 1 to 3 predicted them theoretically. Measurements were also taken[6] which indicated in indirect fashion that such leakage effects were present. There remains the need for direct experimental confirmation, and that need is satisfied by the present contribution, which demonstrates not only the nature of the leakage in general but also the presence of the resonance effect associated with it.

Background

The leakage behavior is described in detail in Reference 3, but a very brief summary is in order here. The basic dielectric image guide does not leak but any modification of it that includes some form of dielectric layer can permit the lateral leakage of a surface wave. The dielectric rib or ridge guide, which is a variant of the insular guide, is an example of such a modified waveguide, and is shown in Fig. 1. On such dielectric strip waveguides, the dominant mode does not leak, but the lowest mode of the other polarization, and all higher modes, can leak. Since it is impossible to excite the dominant (hybrid) mode with perfect efficiency, some portion of the power on the guide will almost always be present in a mode which can leak. On some waveguides, such as the inverted strip guide, the mode with E vertical may not be the dominant mode, depending on the geometrical parameters, so that the major part of the power can then leak. When leakage occurs, the power escapes in the form of a surface wave that propagates away at some angle to the dielectric strip; however, the leakage power has a polarization opposite to that which dominates in the strip region itself. For example, if the hybrid mode on the strip is predominantly E horizontal, the leakage power will have E vertical.

Consistent with customary leaky wave behavior, if the field is probed transversely away from the strip, it increases until it reaches a maximum and then it drops off rapidly. References 1 and 3 also predict that the power that leaks drops to almost zero when the condition $k_x W = 2n\pi$ is satisfied, where n is an integer, W is the strip width, and k_x is the component of the transverse wavenumber, in the direction across the strip, of the mode corresponding to the leakage power. This drop in leakage power corresponds to a resonance effect and manifests itself quite dramatically. Both the leakage itself and the resonance property of the leakage are due to mode conversion between TE and TM surface waves at the dielectric step junctions corresponding to the sides of the dielectric strip waveguide. These phenomena can be explained directly in terms of a simple diagram, and such a brief explanation will be included in the talk.

The leakage may alternatively be expressed in terms of its contribution to the attenuation constant of the guided hybrid mode. At the resonances, this contribution to the attenuation constant goes almost to zero. Thus, an indirect proof of the existence of leakage effects can be obtained by measuring the attenuation constant of a length of dielectric strip waveguide as a function of guide width W, and comparing the result to the theoretically calculated values. Such a comparison was first made in Reference 6, but we have repeated our own version of it here in Fig. 2 because of its usefulness in the direct measurements to be described later.

The leaky mode under examination is the lowest hybrid TM-like mode on the rib waveguide in Fig. 1. The measured values, shown as individuals circles, are obtained from insertion loss measurements on a length of leaky dielectric strip guide. Such loss measurements include contributions from the leakage, from the intrinsic dielectric loss of the guide material, and from coupling losses at the input and output ends of the strip guide. An estimate is made of the material loss, assuming $\tan\delta = 3\times10^{-4}$ on the basis of other measurements, and the resulting curve is the fine almost-solid line in Fig. 2. The leakage loss is computed from the theory in Reference 2, and the sum of the material loss and the theoretical leakage loss is plotted as the solid line in Fig. 2. The difference between this curve and the measured points (averaged by the dashed curve) is due to coupling losses, which are difficult to estimate independently. Despite the quantitative discrepancy, the shapes of the solid and dashed curves are the same, with the maxima and the minima occurring at the same values of W.

We pay particular attention to the measured points indicated as ① and ② . The leakage is certainly strong at point ① , so that leakage power should be easy to measure directly at that value of W. On the other hand, at point ② the leakage is nearly zero and corresponds to a resonance, according to the theory. The direct measurements of the fields described below are made at widths W corresponding to points ① and ② .

The New Direct Measurements of Leakage

The direct probe measurements of the leakage fields are made using the experimental set-up shown schematically in Fig. 3. The thin dielectric portion, of thickness t_2, of the dielectric rib waveguide shown in Fig. 1 has the area $1.0 \times 1.0\,m^2$, and the side edges are terminated by electromagnetic wave absorbers. The lowest guided mode on this waveguide is the hybrid TE-like mode,[3] and that mode, being the dominant mode, will not leak. However, if we excite the lowest hybrid TM-like mode on the strip when the waveguide dimensions are those given in Fig. 2, the mode will be leaky, and the leakage will produce a leaky TE surface wave on the dielectric layer of thickness t_2.

The hybrid mode on the rib (or strip) portion of the structure contains both TE and TM content, but mainly TM; on the other hand, the leaky surface wave outside, on the thin layer, has only TE content. To detect the presence of both types of wave, the transverse field intensity distributions are measured by scanning a polarization-sensitive detector along the transverse (x) direction at the output end of the waveguide, as shown in Fig. 3.

As seen from Fig. 2, the maximum leakage, and therefore the maximum mode conversion into the leaking TE surface wave, occurs at $W/\lambda_o = 0.77$ (W = 4.55 mm), while the resonance effect appears at $W/\lambda_o = 1.92$ (W = 11.35 mm). Points ① and ② on Fig. 2 do not occur exactly at these values but they are close enough to them to represent, respectively, a strong leakage case and a case for which the leakage is negligible. The measurements taken at 50 GHz for guide widths corresponding to these two cases are described separately below.

(a) Strong Leakage Case

We first describe the measurements taken at $W/\lambda_o = 0.85$ (W = 5.00 mm), corresponding to point ① on Fig. 2. Measurements of the field distributions obtained by the polarization-sensitive detectors placed at the waveguide end, as shown in Fig. 3, are presented in Fig. 4. We first note that the detector sensitive to TM-wave properties (vertical electric field) shows that the field of that type exists only in the neighborhood of the rib (or strip), and that such a field constituent is purely bound to the rib region. Furthermore, the vertical electric field is maximum at the rib center, as theory predicts. On the other hand, for TE-wave polarization (horizontal electric field), the field detected has a null at x = 0, the rib center, then grows in its average intensity along the x direction, and finally decays rapidly beyong $x \cong 31$ cm. Such behavior is exactly that expected of the leaky wave. The decay beyond $x \cong 31$ cm is due to the finite length of the waveguide. Since the waveguide length L is 83 cm, the growing feature of the leaky wave field in the x direction can be observed only within the wedge-shaped region delimited by $|x| \leq x_{max} = L \tan\theta_{out}$ at the waveguide end, where the definition of the exit angle θ_{out} is the same as that in Fig. 8 of Reference 3. In our case, x_{max} = 30.9 cm, which agrees well with the observed value of 31 cm in Fig. 4. The strong standing-wave-like pattern appearing in Fig. 4 is due to interference with spurious radiation from the source and reflections from the sides, but it is inessential in the considerations and does not affect the conclusions given above.

(b) Resonance Case

The rib waveguide dimensions for this case correspond to those for point ② in Fig. 2. The waveguide should now be subject to the resonance effect mentioned above, so that the cancellation of the leakage energy occurs, and the total mode remains essentially bound to the region of the rib. The measurements presented in Fig. 5 clearly verify this situation. The TM-wave portion of the TM-like hybrid mode is bound to the rib region, as before, but the TE-wave response is now entirely different from that appearing in Fig. 4. The leaky TE surface wave has now dramatically disappeared, thus fully verifying the leakage-related resonance effect.

The TE-wave field is seen to be limited to the vicinity of the rib region, and the TE-wave portion of the TM-like hybrid mode there exhibits a null in E_x at the center, exactly as predicted by theory.[2,3]

Although additional interesting experimental data will be shown at the oral presentation, the direct measurements presented here of the bound and leaky wave portions of the hybrid mode fields are sufficient to clearly verify both the nature of the leakage and the existence of the resonance effect and its associated cancellation of the leakage.

Acknowledgment

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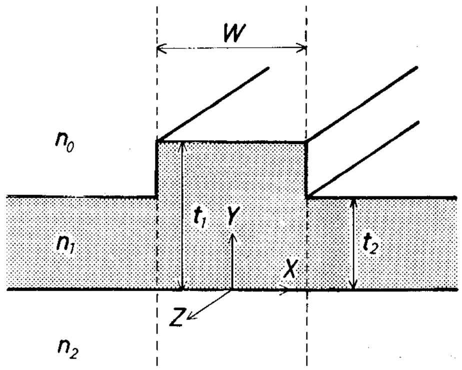

Fig. 1 The dielectric rib waveguide, an example of dielectric strip waveguides for which leakage can occur.

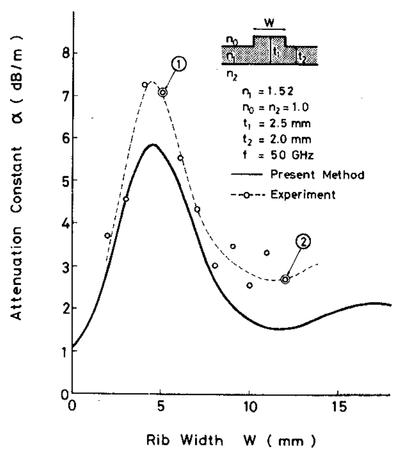

Fig. 2 Measured and theoretical values of the attenuation constant of the lowest hybrid TM-like mode of dielectric rib waveguide as a function of width W. The fine almost-solid line is the estimated dielectric material loss, the heavier solid line is the theoretical leakage loss, added to the material loss, and the individual circles (averaged by the dashed line) represent the measured values obtained by insertion loss measurements. The discrepancy between the dashed and solid curves is due to coupling losses in the measurements which are not accounted for. The individual points ① and ②, which represent strong leakage and no leakage, respectively, correspond to measurements in Figs. 4 and 5, respectively.

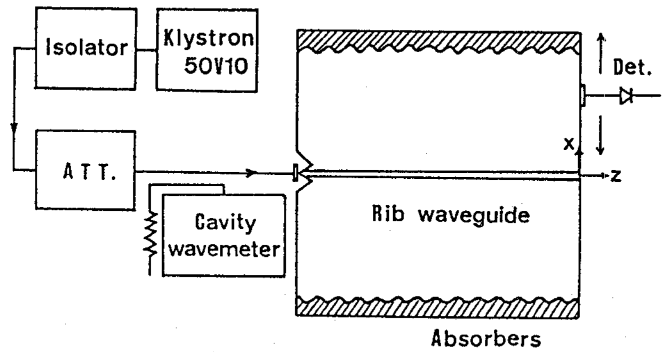

Fig. 3 Schematic diagram of the experimental setup that permits direct probing of the leaky surface wave fields.

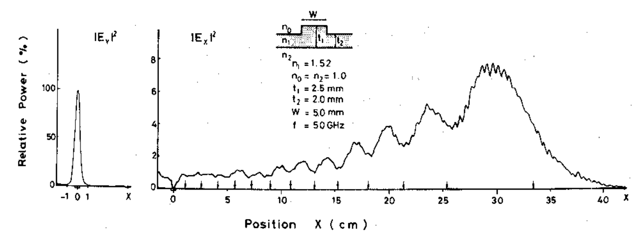

Fig. 4 Measured field intensity distributions in the transverse direction at the waveguide end. These results are obtained for the structural dimensions corresponding to point ① of Fig. 2, representing a strong leakage case.

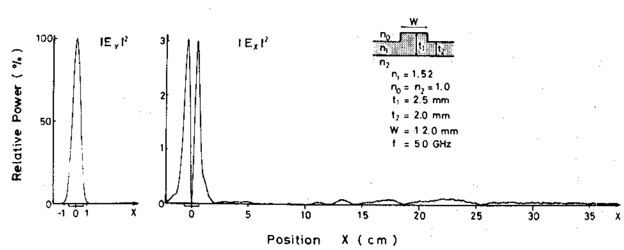

Fig. 5 Measured field intensity distributions in the transverse direction at the waveguide end, for the structural dimensions corresponding to point ② of Fig. 2, representing the resonance case, for which the leakage almost disappears.