AN APPROXIMATE ANALYSIS OF RIB WAVEGUIDES

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The transmission characteristics of dielectric rib waveguides are analyzed by the approximate mode matching method and their experiments with newly developed techniques confirm the validity of our analysis. Moreover, a more advanced method in consideration of the coupling between TE and TM modes is discussed.

Introduction

Typical waveguides for practical application of integrated circuits in the millimeter and submillimeter wave regions are usually rectangular strips of dielectric material that are placed on or embedded in an another dielectric substrate. A basic structure of such waveguides is a rib waveguide shown in Fig.1. This waveguide has indeed practical applications, but its open structure having irregular and unbounded boundaries makes it difficult to perform its precise analysis. In a rough approximation, however, there may be TE and TM waves with respect to the y direction, and the approximate analyses[1,2] assume often the presence of only one type of these waves as a characteristic mode, i.e., TEy or TMy mode. Under this assumption, we can calculate the propagation characteristics by introducing a new approximation for eigen functions and by considering the boundary conditions in the least-squares sense.[3]

First, this paper will discuss such an approximation by comparison with many results obtained by the careful and precise experiments in the 50 GHz region. Afterwards, a more advanced approximation will be discussed by considering the coupling between both mode types which composes a new class of leaky modes predicted by Peng and Oliner.[4]

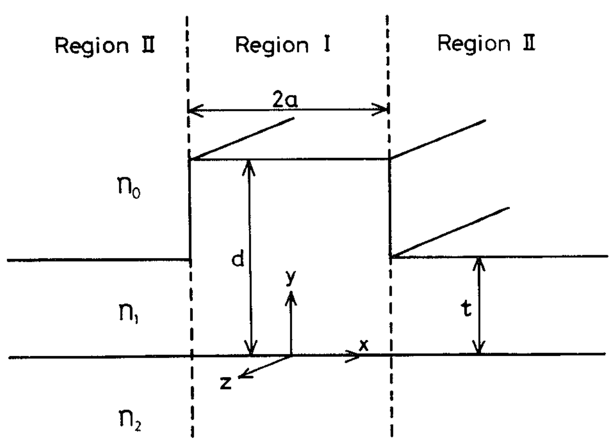

Figure 1. Schematic diagram of a rib waveguide.

Analytical Considerations

Now, let us subdivide this guide cross-section into two constituent regions, i.e., regions I and II, and consider separately each of those regions as if the region I is a rectangular dielectric waveguide and also the region II is semi-infinite slab waveguides. Then we assume that all the field components can be expanded only into the propagating eigen-modes with unknown modal amplitudes Am and Bm in each region.[5] For this assumption, the wavenumbers in the y direction can be easily found independently of those in the x direction from the well-known eigen-value equations of asymmetric slab waveguide.

We must next impose the continuity condition of the fields through the infinite y-z plane at $x = a$. However, in our approximation, it is impossible to match analytically the fields of both regions in the whole regions of $|y| < \infty$, so that let us fit the fields to this boundary condition in the sense of least-squares.

For this purpose, we introduce the mean-squares error F in the continuity condition of approximated fields as Eq.(3) in [5]. Thus the eigen-values of a rib waveguide will be obtained by minimizing F with respect to both amplitude coefficients Am, Bm and the propagation constant h.

Experiments

In order to confirm the accuracy of the present approximation, experiments are performed carefully and precisely in the 50 GHz region. The experimental set-up is shown in Fig.2, where the rib waveguide consists of the polyethylene ($n_1 = 1.461$) and the air ($n_0 = n_2 = 1.0$), and two kinds of the movable grating couplers proposed for the loss measurement of a dielectric slab waveguide in the submillimeter-wave region[6] are used effectively. One of these couplers is constructed by the steel wires of 1.4 mm in diameter arranged with the period of 3.2 mm on the rigid frame and used in the measurement of the TMy mode.
The other constructed by the dielectric lines of 1.0 mm in diameter with the period of 3.0 mm is used in the measurement of the TEy mode. These couplers are movable along the propagating direction on a rib waveguide. The reception of the wave as well as its launching is performed by a pyramidal horn, and one of horn is mounted on the rotatable arm so as to measure the direction θout of a radiated wave from the grating coupler peculiar to each guided mode. The distance between the receiving horn and the coupler is 40 cm.

First, the phase constants for the TMyo and TEyo modes are measured from the radiation angle θout for various values of 2a/t. The results of the TMyo mode for $d/t = 1.5$ and 2.0 are plotted in Fig.3(a) and (b), respectively and also the result of the TEyo mode for $d/t = 2.0$ is plotted in Fig.4 as a function of t/λ_0. Moreover, Fig.5 shows the result of the next higher order TEy_1 mode which has antisymmetry with respect to the y axis in Fig.1. In these figures, the solid and dashed curves indicate the theoretical values calculated by our analytical method in consideration of the only lowest slab mode at each region I, II. As seen from them, the experimental results show the satisfactory agreement with the calculated ones, in spite of a poor approximation for the eigen functions. Furthermore, the careful comparisons between our analytical method and others have been done, and those results conclude that it is difficult to judge the quality of each method as far as the dispersion characteristics are concerned.

On the other hand, the attenuation constant of each mode can be easily found by measuring the radiation power from the coupler as a function of the transmission length between the launching horn and the grating coupler. Fig.6(a) and (b) show the results of the attenuation constants for the TMyo mode in the waveguides with $d/t = 2.0$ and $2a/t = 3.0$, and for the TEyo mode with $d/t = 2.0$ and $2a/t = 2.0$, respectively. The inset in Fig.6(a) indicates an example of the relative output power as a function of the guide length, from which we may confirm the suficient accuracy and reliability of our loss measurement. The solid curves denote the theoretical values of our method, assuming that the loss tangent $\tan\delta$ is 1×10^{-4} or 2×10^{-4} for a polyethylene. Considering the fact that the $\tan\delta$ of 2×10^{-4} is overestimated[7], the measured values may be slightly greater than the theoretical one. This discrepancy is significant in some cases, even if there are some experimental errors, and we should examine the loss characteristics (i.e., the field expressions) more carefully at least by considering the coupling between fundamental TEy and TMy modes.

Discussions

For such an advanced approximation, the field expressions for a mode may be expanded into both TEy and TMy wave components as follows;

$$e^{I} = A\,E^{I}(\mathrm{TEy}) + B\,\tilde{E}^{I}(\mathrm{TMy}),\quad h^{I} = A\,H^{I}(\mathrm{TEy}) + B\,\tilde{H}^{I}(\mathrm{TMy})$$

for region I

$$e^{II} = C\,E^{II}(\mathrm{TEy}) + D\,\tilde{E}^{II}(\mathrm{TMy}),\quad h^{II} = C\,H^{II}(\mathrm{TEy}) + D\,\tilde{H}^{II}(\mathrm{TMy})$$

for region II.

Thus, for the mode which may exist when the y-z plane at $x = 0$ is replaced with an electric (a magnetic) wall, the predominant component in the total field (e,h) will be the TEy (TMy) wave at least for the lowest mode, and the minor TMy (TEy) wave produced by the coupling with the TEy (TMy) wave will become leaky because of its cutoff nature in the x direction when the rib width 2a is narrow. In such a case, the rib waveguide supports a leaky mode , and its leakage loss has to add to the theoretical attenuation constants of Fig.6.

Such s leakage effect will disappear as the width 2a becomes wide, and after that we have to calculate the attenuation constant as a surface mode of which fields should be expressed by using not (E,H) or ($\tilde{E},\tilde{H}$) but (e,h) . We are now performing such calculations for the attenuation constant, and these results will be presented during the talk.

References

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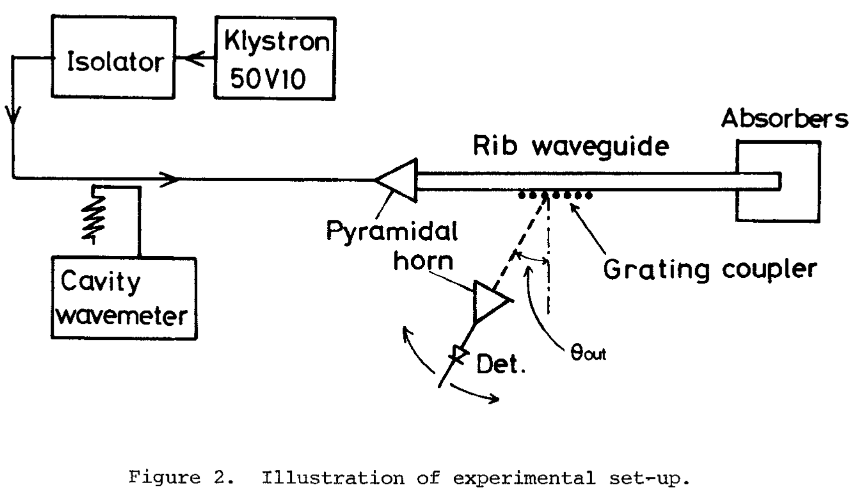
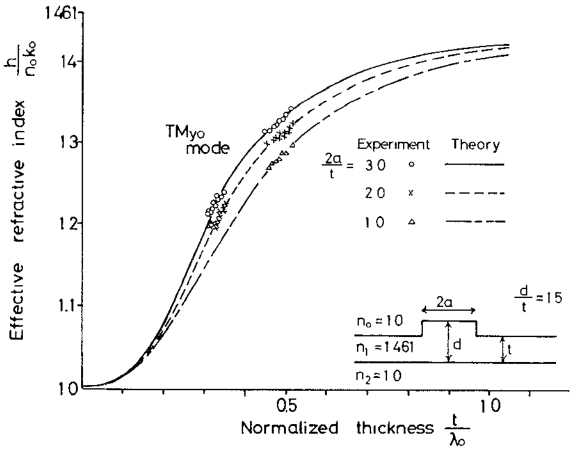
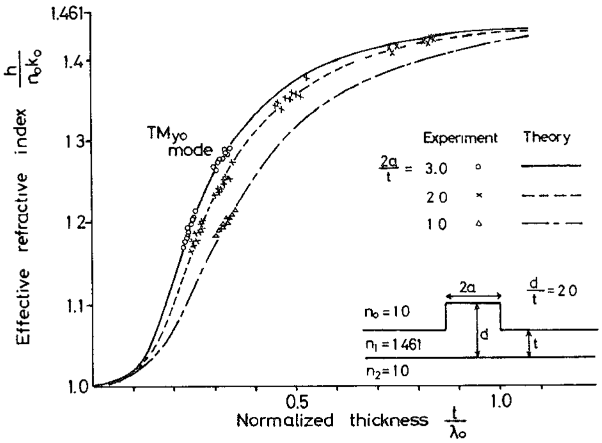


Figure 2. Illustration of experimental set-up.



(a) d/t = 1.5



(b) d/t = 2.0

Figure 3. Measurements of the phase constant for the TMyo mode.

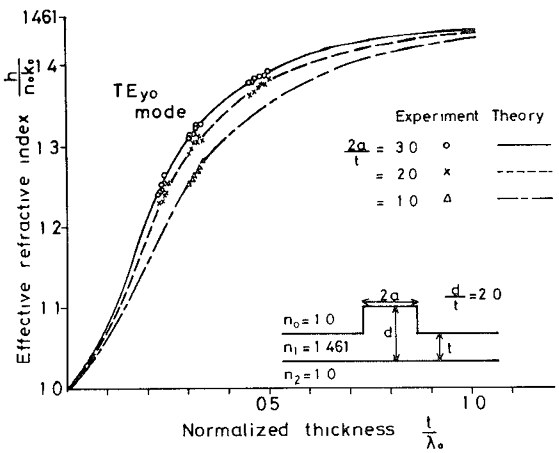


Figure 4. Measurements of the phase constant for the TEyo mode with d/t = 2.0.

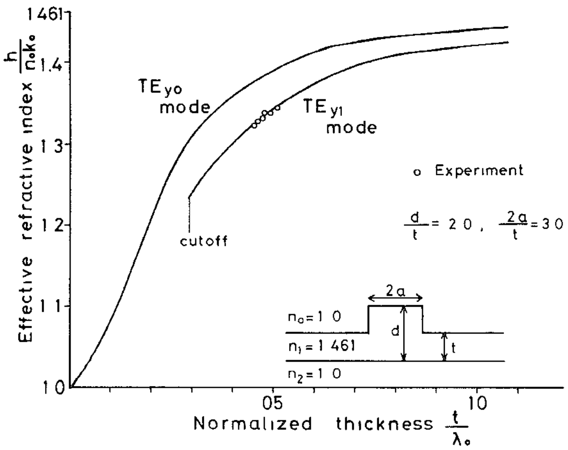
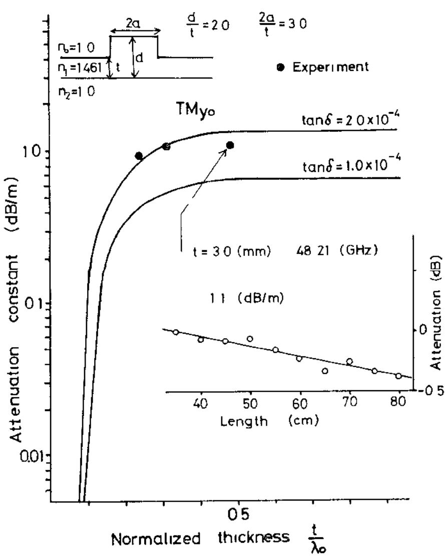
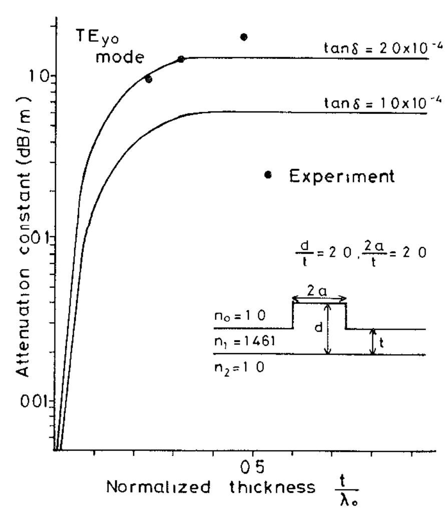


Figure 5. Measurements of the phase constant for the TEy_1 mode with d/t = 2.0.



(a) TMyo mode



(b) TEyo mode

Figure 6. Loss measurements.