CHALLENGE TO 3-D DISCONTINUOUS DIELECTRIC WAVEGUIDE CIRCUIT ANALYSIS

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ABSTRACT

An accurate theoretical approach for discontinuity problems in dielectric 3-D (rectangular) waveguides of open type is presented. This approach takes account of the behavior of both surface wave modes and continuous spectral waves, and is successfully applied to design image-guide grating filters. Experiments proves the effectiveness of our approach.

INTRODUCTION

Dielectric waveguide is a promising candidate for printed-line type millimeter-wave integrated circuits in the shorter millimeter wavelength region. To devise various circuit components, discontinuities play an extremely important role. However, to the authors' knowledge, there is no investigation considering inevitable radiation phenomena in discontinuity problems of 3-D structures of open type without shielding conductor cover. Therefore, we proposed a method[1] for reducing a 3-D discontinuity problem to an equivalent 2-D one from the viewpoint of only the phase constant[1], but the experimental results suggested this method to be an insufficient approximation.

In this paper, the essential propagation mechanism of a mode on the 3-D structures is considered to develop an improved 2-D model, to which a rigorous method proposed by the present authors [2]-[4] can be applied to obtain the radiation characteristics as well as the surface wave transmission ones. It is proved that the numerical results calculated by the present method show an excellent agreement with the experimental results.

THEORETICAL CONSIDERATIONS

We consider here the dielectric image guide (DIG) as a typical example of 3-D structures of open type, and a discontinuity to be expected in such a waveguide is shown in Fig.1; a junction of two kinds of waveguide with different width w_1 and w_2, but the same height h.

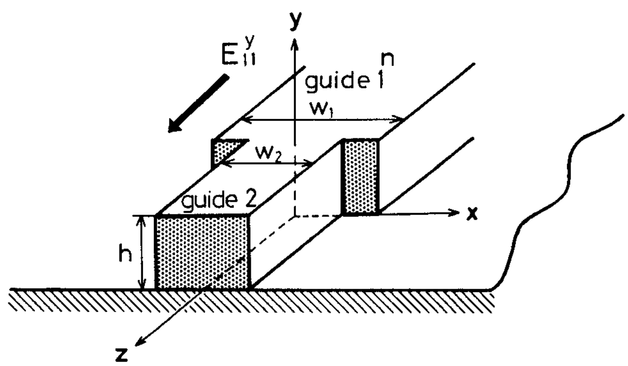

Fig.1. Step discontinuity consisting of two kinds of dielectric image guide.

Here, we assume that each waveguide can support only the fundamental E^y_{11} surface mode (E field is predominantly polarized in the y direction). Since the complete field on each guide is expressed by the sum of the surface mode and the radiation wave with continuous spectrum, the radiation necessarily occurs at the junction plane of Fig.1 for the incidence of E^y_{11} surface mode, together with the transmission and reflection of the surface mode. Moreover, the functional distribution of the resultant field on the transverse plane of each guide is not separable in the orthogonal coordinates, and hence it is almost impossible to analyze directly and accurately such an open 3-D discontinuity problem.

However, if the difference between w_1 and w_2 of Fig.1 is not so large, it is shown[1] that the field distributions of the surface modes on both guides are almost the same each other in the y direction and the significant difference remains in the x direction. Therefore, we may analyze the 3-D discontinuity problem like Fig.1 by considering predominantly the field distributions in the x direction, and have tried to reduce the structure of Fig.1 to an equivalent 2-D structure homogeneous in the y direction as shown in Fig.2. In this model, we followed the waveguide model[5] [6] employed in open microstrip discontinuity problems, and perfectly neglected boundary conditions on both xz

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planes at y=0 and y=h. Although the characteristic impedance of the open dielectric waveguide can not be rigorously defined, the effective refractive index n_{effi} and the effective guide width W_{effi} (i=1,2) are defined so as to make the phase constant and characteristic impedance of this model equal to those of the original structure. However, experiments shown later suggest us that this old 2-D model for dielectric waveguide problem is not so good approximation, so long as the phase constant between the original DIG and the equivalent 2-D structure is kept identical.

Let us here develop an improved new method which satisfies the boundary conditions neglected in the old model by considering the propagation mechanism of the E^y_{11} surface mode. The guiding of the E^y_{11} mode along the axis of the homogeneous DIG is customarily viewed in terms of the TM_0 surface wave on the conductor-baked slab waveguide with thickness h, which bounces back and forth inside the dielectric region at an angle θ to the side dielectric-air interfaces, undergoing total reflection at each bounce, as shown in Fig.3. Such an oblique guidance of TM_0 wave necessarily produces both TE and TM waves with continuous spectrum at the side interfaces [7]. However, these waves are purely reactive in the x direction, and their energy is stored at around such interfaces. Such a stored energy gives an additional phase shift to the total reflection of the TM_0 wave at the side interfaces as shown by a numerical example of Fig.4(a) as a function of the incident angle θ. Then the phase constant of the E^y_{11} mode of a DIG with the width w can be approximately obtained from the transverse resonant condition of the TM_0 wave along a transverse line length of w, by taking account of the additional phase shift. The numerical result is shown in Fig.4(b), where it is

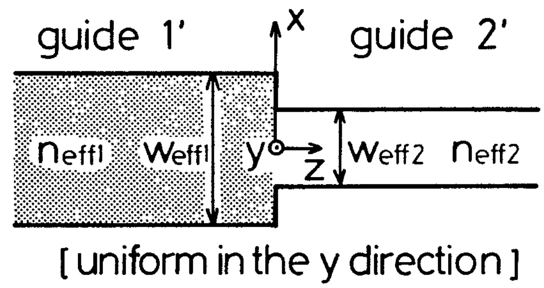


Fig.2. Old equivalent 2-D structure obtained from the viewpoint of the phase constant.

indistinguishably on the rigorous result calculated by Goell's method[8]. As a result, we can assume that the E^y_{11} mode is mainly characterized by the oblique guidance of the TM_0 wave.

Now, when the TM_0 wave is guided on the conductor-baked slab waveguide with the thickness h and the refractive index n_1, it can be approximated by the plane wave which is polarized in the y direction and propagates in the homogeneous medium with the effective refractive index $n^{TM}_{eff} = \beta_{TM}/k_0$ (β_{TM} is the phase constant of the TM_0 wave). Then, the original 3-D structure of Fig.1 can be reduced to the equivalent 2-D structure shown in Fig.5. In this model, the phase shift at the side interface calculated from the total reflection of the plane wave is not accurate as shown by the dotted curve in Fig.6(a), so that the phase constant indicated by the dotted curve in Fig.6(b) is also slightly deviated from the rigorous results indicated by the solid curve. However, this model is reasonable as proved from the experimental results later on for analyzing the discontinuity problem on the x-y plane at z=0. This reason may be that the influence of the phase shift at the

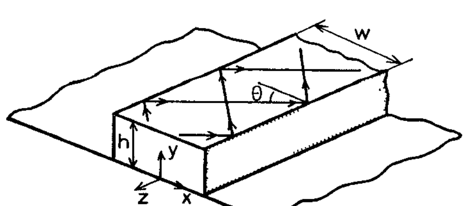
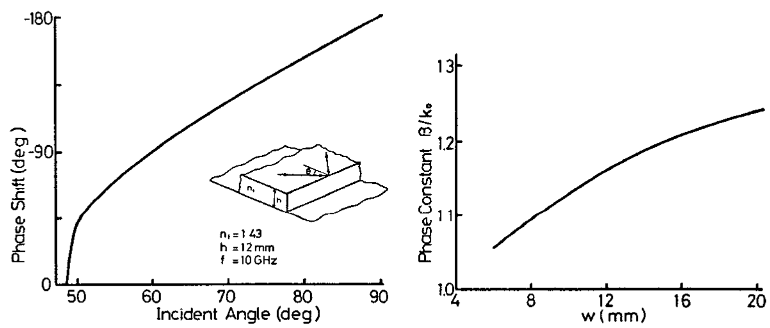


Fig.3. Propagation mechanism of the E^y_{11} mode, in which TM_0 wave bounces back and forth at an angle θ.



(a) (b)

Fig.4. (a) Phase shift of the TM_0 wave suffering from the total reflection at side walls and (b) phase constant of the E^y_{11} mode calculated by the transverse resonance.

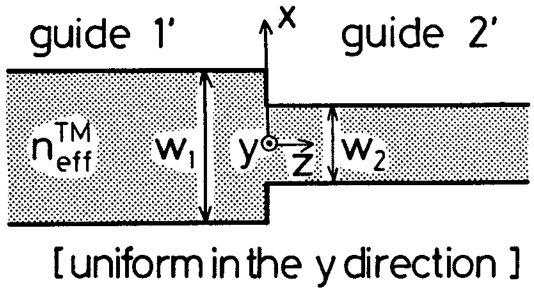
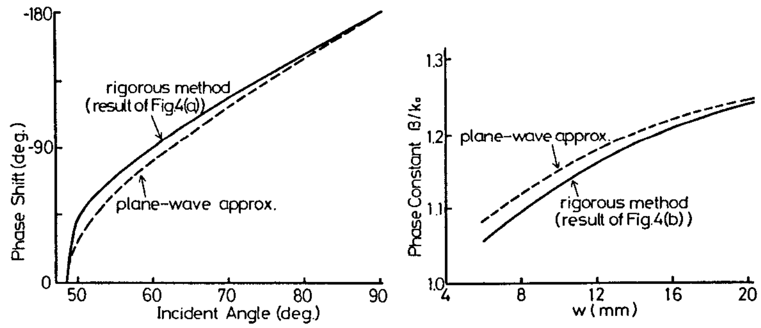


Fig.5. New equivalent 2-D structure obtained from the viewpoint of the propagation mechanism of the TM_0 wave.



(a) Phase shift (b) Phase constant

Fig.6. Comparison between the results for new 2-D model of Fig.5 and the rigorous ones.

side interfaces is not significant on the discontinuity problem at z=0, although it is sensitive to the phase constant. Consequently, when analyzing a DIG consisting of interacting many discontinuities[3], the equivalent network for a discontinuity (see [4] for detail) can be derived from the 2-D model of Fig.5, while the phase constant of the E^y_{11} mode must be calculated as rigorously as possible for obtaining the equivalent network for a homogeneous DIG in between neighboring discontinuities.

Our network approach decomposes the continuous wave into the new discrete modes, each of which can carry a finite magnitude of radiation power. Introduction of such modes makes it possible to solve the wave behavior including the radiation waves by the usual equivalent network approach. At the talk, we will add a more detailed explanation about the network approach which is omitted here.

NUMERICAL AND EXPERIMENTAL CONSIDERATIONS

Numerical examples are considered for the 3-D DIG gratings shown in Fig.7, where they have n_1=1.43 (Teflon), h=12mm, and w_1=20mm, $\beta_1 d_1=\beta_2 d_2=\pi/2$ (β is the phase constant of the E^y_{11} mode at 10 GHz.) , with varying w_2 and N_C (N_C is the number of periodic notches). Fig.8 shows the mid-stopband attenuation A_{MAX} obtained at 10GHz, where the solid curves indicate the numerical results calculated by the present 2-D model of Fig.5 for N_C =22 and N_C=50, and the dashed curves show the result by the old 2-D model of Fig.2. On the other hand, the dots indicate the measured values, and it is confirmed that the present results agree surprisingly well with the measured ones for any w_2.

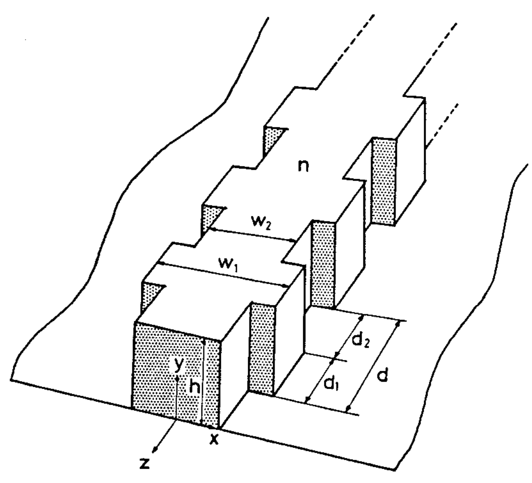


Fig.7. Dielectric image guide gratings with a finite length of periodic notches.

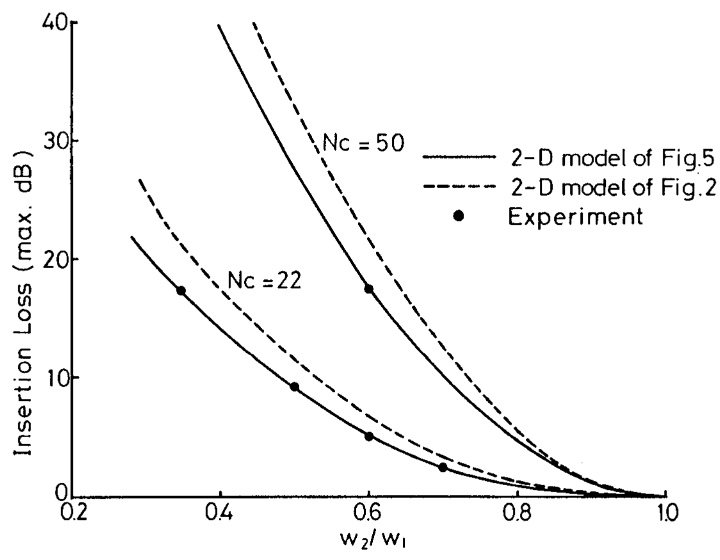
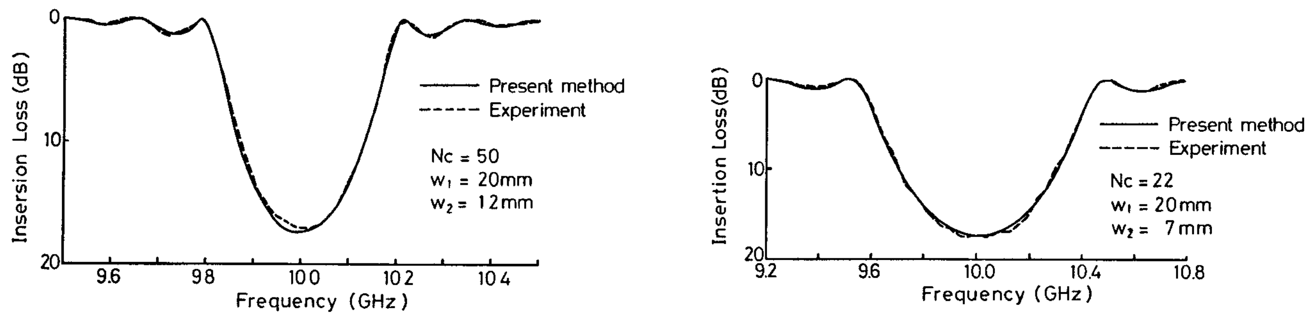
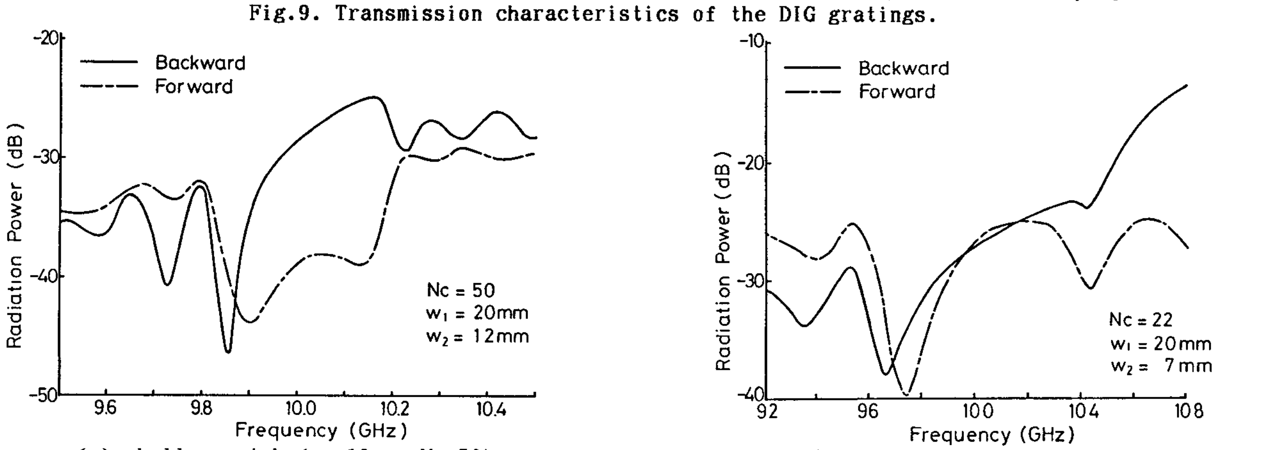


Fig.8. Comparison between numerical and experimetal results of the mid-stopband attenuation.



(a) shallow notch (w_2=12mm, N_c=50) (b) deep notch (w_2=7mm, N_c=22)

Fig.9. Transmission characteristics of the DIG gratings.



(a) shallow notch (w_2=12mm, N_c=50) (b) deep notch (w_2=7mm, N_c=22)

Fig.10. Radiation characteristics of the DIG gratings.

Fig.9(a) and (b) show the frequency characteristics for the gratings with the shallow notch (w_2=12mm, N_c=50) and the deep notch (w_2=7mm, N_c=22). These examples show excellent agreement between the theoretical and the experimental values. Also, this approach can easily calculate the radiation power as shown in Fig.10(a) and (b). It is clear that radiation power of the shallow notch has not so much influence on the insertion loss, but that of the deep notch is never negligible, especially in the higher frequency range corresponding to the leaky wave region of the periodic structure with infinite extent.

In conclusion, we believe that the excellent agreements, seen in Figs.8 and 9, certainly prove the 2-D model proposed here to be effective for analyzing 3-D discontinuous open structures.

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