MICROWAVE NETWORK REPRESENTATION OF DISCONTINUITY IN OPEN DIELECTRIC WAVEGUIDES AND ITS APPLICATIONS TO PERIODIC STRUCTURES

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ABSTRACT

A network approach is proposed for analyzing the interaction of discontinuities in open dielectric waveguides by taking account of the continuous spectrum accurately. This approach develops an unprecedented method to investigate the effect of finite length of periodic structures on their transmission characteristics. This paper discusses this effect on the radiation patterns when a finite periodic structure is operated in the leaky wave region, while in a different regime of operation, we present a new and completely theoretical accurate procedure for the design of grating filters on a dielectric image waveguide, demonstrating successful experiments.

INTRODUCTION

The step in an open planar dielectric waveguide is a basic discontinuity in various optical and millimeter wave components. However, because of its open nature, unwanted radiation always occurs at the step. To minimize such a radiation, components such as filters and resonators based on periodic structures have been proposed, since large reflection combined with negligible radiation can be expected in their stop bands, corresponding to Bragg reflection. On the other hand, in a different regime of operation, such periodic structures can be positively applied to leaky wave antennas.

If such a structure has a finite extent in its length, one must accurately analyze the interaction of the step discontinuities taking account of the continuous spectrum, as Rozzi et. al.[1] did. Their approach is attractive, but can not be available because of ineffective treatment of the continuous spectrum.

We present here an effective method analyzing the interaction of the step discontinuities by means of a Legendre transform of the continuous spectrum. Our approach is applied to discuss the finite periodic structure as both leaky wave antennas and filters.

GENERAL ANALYSIS

We first analyze a step discontinuity problem. In order to minimize the details, even type TE-mode excitation of a symmetric step is considered as shown in Fig.1. In the analysis of open waveguides, one always encounters a big difficulty, how to discretize the continuous spectrum which usually does not extend in the whole range of spectrum, but in a limited narrow range of it. The well-known Laguerre transform is always not effective to circumvent this difficulty. Our effective approach already discussed [2] divides the continuous spectrum into three ranges; one corresponds to the radiation part, the second is an optimally scaled extent of the reactive part and the third, disregarded here, is the rest of the reactive part. Then, we have only to discretize independently the spectrum in each range by means of the Legendre transform to which the normalized Legendre functions provide the complete set of basis functions. This approach is quite adaptive to arbitrary distribution of the continuous spectrum and such a discretization makes it possible to derive the equivalent network including radiation phenomena for a junction plane of both guides as shown in Fig.2. In this network, we have the terminal ports corresponding to the radiation part and to the reactive part of the continuous spectrum, along with the ports corresponding to the surface waves. Emphasis is on that the definition of terminal ports of the continuous spectrum is perfectly different from that of surface-wave ports: a port of the continuous spectrum does not correspond to a field distribution given by a single eigenvalue like a surface-wave mode, but corresponds to that having the continuous spectrum characterized by one of Legendre functions.

It is important to note that the functional form of the continuous spectrum part changes as a wave propagates (or radiates) along the uniform guide. This results in the continuous change in the amplitude of each Legendre function along the uniform guide. This change in functional form means that a wave group characterized by a Legendre function continuously couples with other wave groups with different Legendre functions. As a result, it is necessary

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to introduce the equivalent circuits R_1 and R_2 for the continuous spectrum ports to express a uniform guide section as shown in Fig.3. In contrast, the discrete surface-wave mode can propagate without coupling each other, and the guide can be equivalently expressed by a finite number of uncoupled transmission lines. It is easy to obtain the circuit parameters of R_i by calculating the complex amplitude of each Legendre function at the right (the left) terminal plane of R_i when a wave group with kth Legendre function is inputted from the left (the right) side of R_i. The model shown in Fig.3 is amenable to ordinary microwave network approach, and the periodic structures with a finite length can be easily analyzed by the cascaded connection of such networks.

NUMERICAL RESULTS

Fig.4 shows an example of the calculated results of the periodic structure with a finite length. Each guide in the uniform sections can support only the dominant surface-wave mode. This figure shows the reflection power of the dominant TE surface-wave mode and also the radiation power (backward) for 10 and 20 corrugations as a function of the normalized period d/λ_0 (λ_0 is the wavelength in the free space). It is found that in the first Bragg reflection region at around $d/\lambda_0 = 0.42$, strong reflection occurs with negligible radiation, but in the higher frequency region at around $d/\lambda_0 = 0.45$ the influence of radiation is not negligible because of the effect of the finite length. It is believed that the discussions on such an influence are unprecedented to the best knowledge of the authors. The peak of radiation power at around $d/\lambda_0 = 0.84$ corresponds to the second Bragg reflection region.

GRATINGS AS A LEAKY WAVE ANTENNA

Fig.4 shows that the leaky wave region starts from about $d/\lambda_0 = 0.45$. Fig.5 shows the radiation patterns in cases of 10 and 20 corrugations, calculated at $d/\lambda_0 = 0.48$ by the steepest descent method. The effect of the finite length of the structure is, of course, significant in that the main lobe becomes narrow as the number of corrugations increases. Further discussions will be presented elsewhere.

GRATINGS AS A FILTER

The general analysis mentioned above can be available for developing a new and completely theoretical design procedure of dielectric image guide (DIG) gratings, instead of a method of Matthaei et al.[3] which uses a combination of approximate theory and experiments on a trial grating.

The DIG gratings investigated here propagate the lowest-order E^y_{11} mode of which E-field is predominantly vertically polarized to the ground plane and it is assumed, by referring Fig.4, that in so far as the first Bragg reflection region is used, the energy carried away by the continuous waves is almost negligible,and we may consider only surface-wave ports in Fig.3.

The design of DIG gratings needs to have accurate data for the effective ratio (r) of the wave impedance of the notched regions to that of the unnotched regions, and also data for the wave velocity in each region. To this end, we first expand the electromagnetic fields of the E^y_{11} mode in both regions into a series of circular harmonics, as Goell [4] did. These fields are then matched at the discontinuity plane by means of the least squares boundary residual method [2], and finally the transmission matrix for the equivalent circuit of discontinuity is obtained. In our filter design, the length of each transmission line is chosen as a quarter-wavelength long at a given mid-stopband frequency f_0. For this purpose, we set up a routine to calculate the phase constant based on a procedure due to Goell [4]. Our procedure, however, differs from his in that the field continuity on DIG surface is solved by the least squares boundary residual method. Using such routines, we can calculate the mid-stopband attenuation L_{max} by the cascaded connection of finite number of such discontinuities connected by the uniform transmission lines. Fig.7 shows the dependence of L_{max} on the guide width w_2, assuming DIG gratings operated in X-band. The solid curves indicate the results obtained by our theory, while the dashed curves show the results obtained by the method suggested by Matthaei et al.[3]. The black circles indicate the measured values, and our results surprisingly agree well with the measured ones even for the deep notch range with large w_2.

Now, for a grating design, the desired L_{max} is first given, and it is necessary to solve the possible sets of structural parameters of DIG gratings to realize it. Fig.8 shows an example of the design charts of DIG gratings. All the structural parameters are normalized by the wavelength λ_0 at f_0. The solid curves show the relation between w_1/λ_0 and w_2/w_1 which produces an indicated L_{max}, while the dashed curves show the fractional 3 dB bandwidth Δf. Thus, specifying the point corresponding to the given Lmax with the desired bandwidth, one can find the necessary structural parameters, that is, h, w_1, w_2, d_1 and d_2.

EXPERIMENTS

A design example of DIG gratings is considered in X band by employing $n_r = 1.52$ with $h/w_1 = 0.6$. $L_{max} = 30$ dB and 1.92 % bandwidth are specified at the center frequency $f_0 = 10.0$ GHz. This specification is indicated by the circle on Fig.8. Fig.9 shows the measured result of the DIG grating designed, and experiment shows excellent agreement with the designed characteristic.

Network approach presented here may be used as the basis for designing antennas and circuit components, but more practical considerations will not be discussed here.

Acknowledgement

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References

[1] T.E.Rozzi et al., " Field and Network Analysis of Interacting Step Discontinuities in Planar Dielectric Waveguides," IEEE Trans. MTT, vol.MTT-27, pp.303-309, Apr. 1979.

[2] H.Shigesawa et al., " Mode Propagation through a Step Discontinuity in Dielectric Planar Waveguide," 1984 IEEE/MTT-S Inter'l Microwave Symposium Digest, 5-3, pp.121-123, May 1984.

[3] G.L.Matthaei et al., " A Study of the Filter Properties of Single and Parallel-Coupled Dielectric-Waveguide Gratings," IEEE Trans. MTT, vol.MTT-31, pp.825-835, Oct. 1983.

[4] J.E.Goell, " A Circular-Harmonic Computer Analysis of Rectangular Dielectric Waveguides," Bell Syst. Tech. J., vol.48, pp.2132-2160, Sept. 1969.

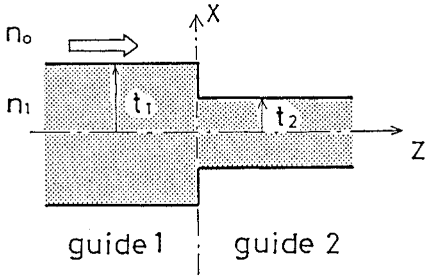

Fig.1. Planar dielectric step discontinuity, where even TE-mode incidence is considered.

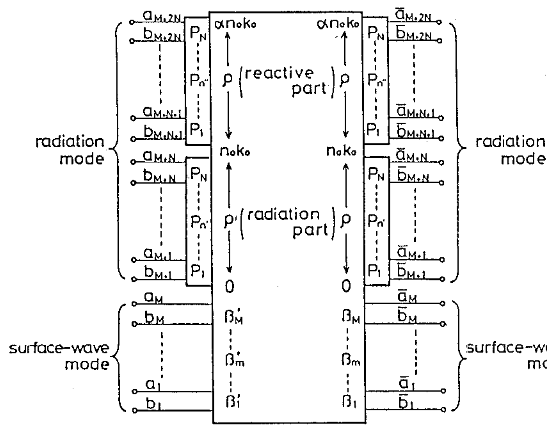

Fig.2. Equivalent network representation for the discontinuity shown in Fig.1, where the wave with continuous spectrum is regrouped discretely in terms of Legendre functions.

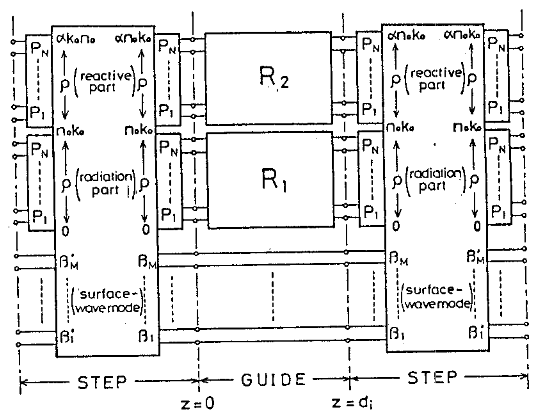

Fig.3. Equivalent network representation for an unit cell, consisting of two steps connected with a uniform guide.

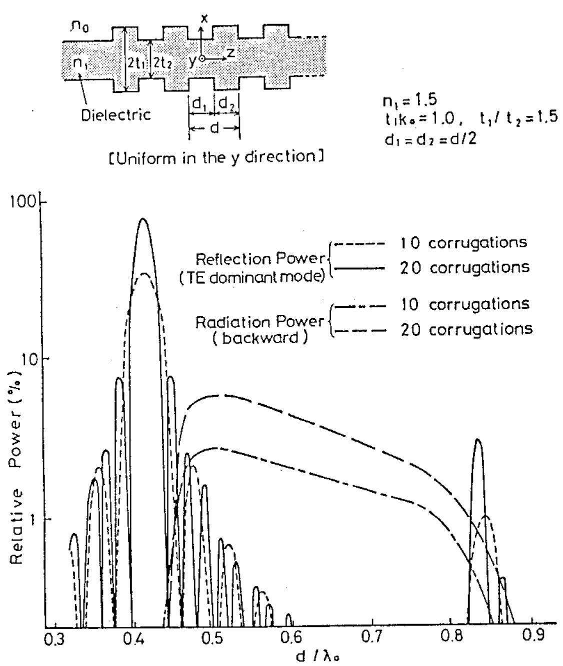

Fig.4. Example of calculated reflection and radiation powers for a periodic structure with a finite length.

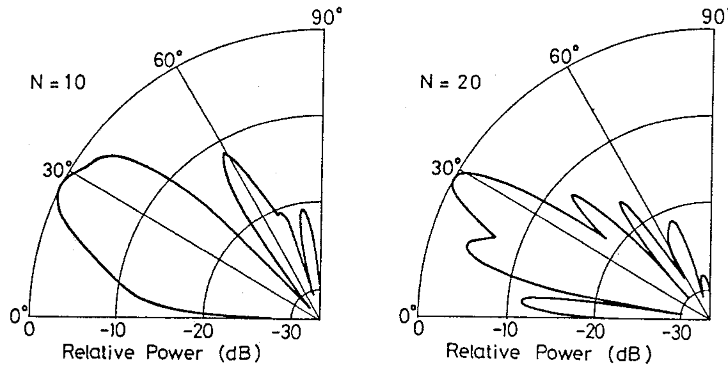

Fig.5. Example of calculated radiation patterns in case of 10 and 20 corrugations.

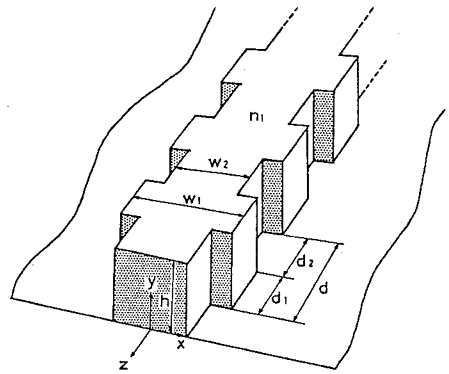

Fig.6. Dielectric image guide with partial periodic corrugation.

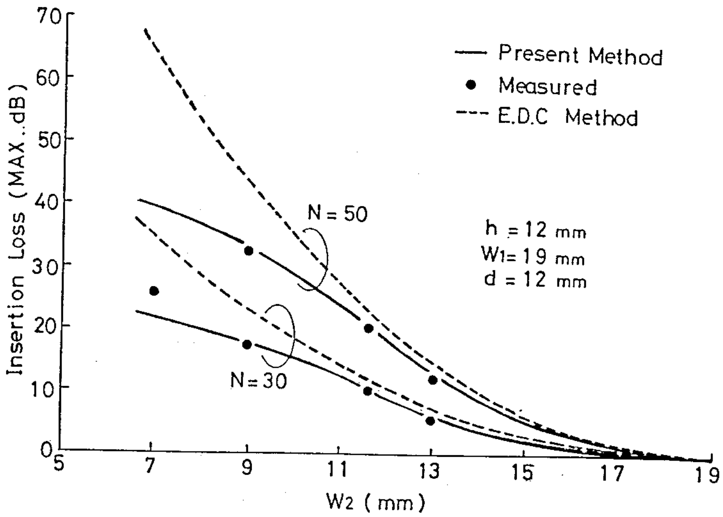

Fig.7. A design chart of dielectric image guide gratings. The circle indicate a design specification.

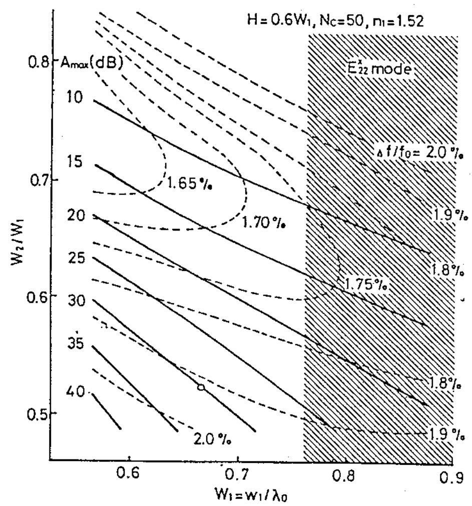

Fig.8. Dependence of maximum insertion loss on the guide width w_2.

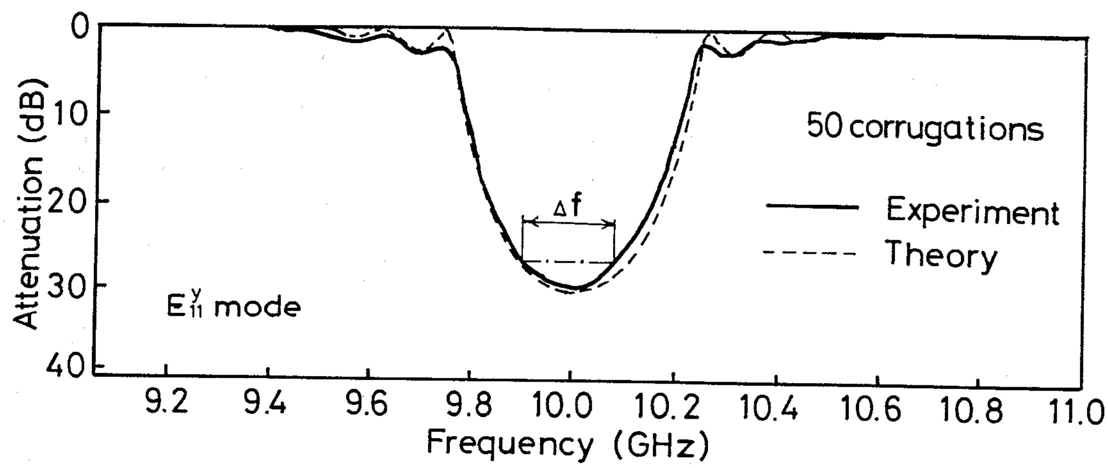

Fig.9. Measured and theoretical attenuations for a designed grating with h=12.0 mm, w_1=20.0 mm, w_2=10.5 mm, d=12.0mm, d_1/d_2=1.0, and n_1=1.52, for f/f_0=1.92 % and Amax=30dB.