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MICROWAVE NETWORK ANALYSIS OF A LEAKY-WAVE STRUCTURE IN NON-RADIATIVE DIELECTRIC WAVEGUIDE

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Abstract

An accurate microwave network analysis is presented for a new leaky-wave structure based on a recent nonradiative (and practical) modification of H guide. The structure can serve as the basis for a new millimeter wave antenna of simple configuration. The analysis employs a transverse equivalent network, with some subtle features, that yields a dispersion relation in closed form; numerical values are presented for the phase and leakage constants, including experimental confirmation.

1. INTRODUCTION

Two recent papers [1,2] proposed a new type of waveguide for millimeter waves, and showed that various components based on it can be readily designed and fabricated. By a seemingly trivial modification, the authors, T. Yoneyama and S. Nishida, transformed the old well-known H guide, which had languished for the past decade and appeared to have no future, into a potentially practical waveguide with attractive features. The old H guide stressed its potential for low-loss long runs of waveguide by making the spacing between the metal plates large, certainly greater than half a wavelength; as a result, the waveguide had lower loss, but any discontinuities or bends in it would produce leakage of power away from the guide. Yoneyama and Nishida observed simply that when the spacing is reduced to less than half a wavelength all the bends and discontinuities become purely reactive; they therefore call their guide "nonradiative dielectric waveguide" (or NRD guide). As a result of this modification, many components can be constructed easily, and in an integrated circuit fashion, and these authors proceeded to demonstrate how to fabricate some of them, such as feeds, terminations, ring resonators and filters.

These papers treat only reactive components in NRD guide, however. The present paper considers a leaky-wave structure in this guide, which can serve as the basis for a new leaky-wave antenna, and can be directly connected to the abovementioned circuits in integrated circuit fashion.

We present a very accurate theory for the leakage and phase constants of this leaky-wave structure, employing a microwave network approach. A key feature of this theory involves an almost-rigorous transverse equivalent network, which requires two coupled transmission lines. Some subtle features are involved in the derivation of the elements of this equivalent network, including the best choice of constituent transverse modes, an analytic continuation into the below cutoff domain, and mode coupling at an air-dielectric interface. The resulting expression for the leakage and phase constants is in closed form.

2. THE CAUSE OF THE LEAKAGE

The new NRD guide, shown in Fig. 1, looks like the old H guide except that the spacing between the plates is less than a half wavelength to assure the nonradiative feature. In the vertical (y) direction, the field is of standing wave form in the dielectric region and is exponentially decaying in the air regions above and below. The guided wave propagates in the z direction.

The leaky-wave structure based on this waveguide is shown in Fig. 2, where we see that the leakage is created simply by decreasing the distance d between the dielectric strip and the top of the metal plates. When distance d is small, the fields have not yet decayed to negligible values at the upper open end, and therefore some power leaks away if the guided wave is fast ($\beta<k_0$).

3. ALMOST-RIGOROUS TRANSVERSE EQUIVALENT NETWORK

The structure in Fig. 2 is analyzed as a leaky waveguide which possesses a complex propagation constant $\beta-j\alpha$, where β is the phase constant and α is the attenuation or leakage constant. We therefore establish a transverse equivalent network for the cross section of the structure, and from the resonance of this network we obtain the dispersion relation for the β and α values. An almost-rigorous equivalent network is presented in Fig. 3, where it is seen that two coupled transmission lines are required in the representation. The reason for two lines is that the waveguide modes are hybrid, and possess all six field components in the presence of the radiating open end.

If we employ the usual TE and TM modes in these transmission lines which represent the constituent transverse modes, the lines will remain uncoupled at the air-dielectric interface but will be coupled together at the radiating open end. On the other hand, the open end is uniform longitudinally, and this geometrical arrangement suggests the use of $E^{(z)}$-type and $H^{(z)}$-type modes (alternatively called LSM and LSE modes, respectively, with respect to the xy plane). Transmission lines representing such modes will not couple at the radiating open end, but do become coupled at the air-dielectric interface. These two valid but alternative representations were considered, and we chose the second of these as the simpler approach for our structure.

The transverse equivalent network in Fig. 3 thus corresponds to the $E^{(z)}$-type and $H^{(z)}$-type transverse modes mentioned above. The coupling network at the air-dielectric interface was obtained from an adaptation of a network presented earlier by P.J.B. Clarricoats and A.A. Oliner [3] for cylindrical air-dielectric interfaces; that network was suitably transformed here for planar interfaces.

The principal new feature in the transverse equivalent network in Fig. 3 relates to the terminal admittances representing the $E^{(z)}$-type and $H^{(z)}$-type modes incident on the radiating open end. Those admittances were not available in the literature but were derived by analytic continuation of expressions for reflection coefficient given by L.A. Weinstein [4]. Those reflection coefficients applied to normal incidence of ordinary parallel plate modes; modifications were made to account for a longitudinal wavenumber variation (corresponding to oblique incidence) and then for modes below cutoff, the latter step producing results which appear totally different since the phases and the amplitudes of the reflection coefficients then become exchanged.

The terminal admittances in Fig. 3 assume that all the higher modes in the transmission lines decay exponentially to infinity. In principle, they "see" the air-dielectric interface distance d away. In practice, that distance is large for the higher modes; for example, for the first higher mode in a specific case the field at the air-dielectric interface was about 30 dB lower than its value at the radiating open end. Because of this feature, however, we have referred to this analysis as almost rigorous.

4. TYPICAL NUMERICAL RESULTS

The dispersion relation for α and β found from a resonance of the transverse equivalent network in Fig. 3 contains elements all of which are in closed form, thus permitting easy calculation. We have examined the various parametric dependences of α and β on the dimensions a, b and d, and on the dielectric constant ε. Here we present only a single typical case, corresponding to certain geometrical parameters given in [2]. The theoretical values of β and α are shown as the solid lines in Figs. 4 and 5 for this case as a function of distance d (see Fig. 2). For distance d>2mm, one sees from Fig. 4 that the value of β remains essentially unchanged. It is seen in Fig. 5 that α increases as d is shortened, as expected since the field decays exponentially away from the dielectric region. Thus, the value of α that one can achieve spans a very large range.

Also shown on Fig. 5 are some measured points, kindly taken at our request by T. Yoneyama [5]. Although these measurements were made at a frequency of 50 GHz and the calculations correspond to 48 GHz, the frequencies are sufficiently similar to permit comparison. It is seen that the agreement is certainly quite good.

This leaky-wave structure may be used as the basis for a new leaky-wave antenna, but such considerations will not be discussed here.

REFERENCES

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5. T. Yoneyama, private communication, July 4, 1983.

ACKNOWLEDGMENT

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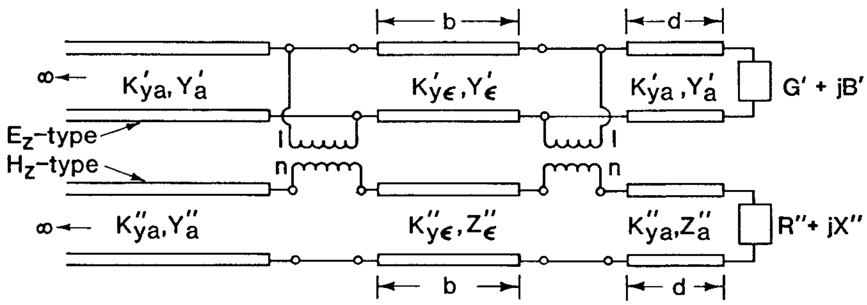

Fig. 3. Rigorous transverse equivalent network for the structure shown in Fig. 2. The network is placed on its side for clarity.

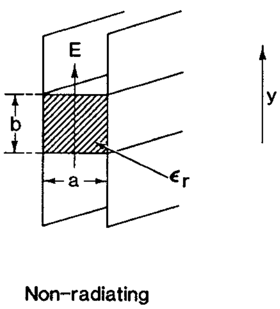

Fig. 1. Cross section view of non-radiative dielectric waveguide, where $a<\lambda_0/2$.

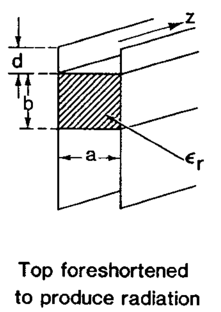

Fig. 2. Cross section view of leaky-wave structure where leakage is controlled by distance d.

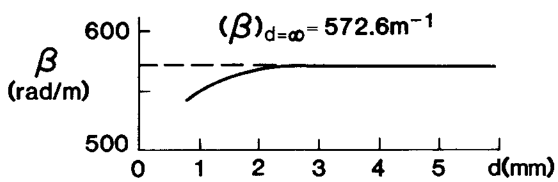

Fig. 4. Phase constant β in radians/meter of the leaky-wave structure in Fig. 2 as a function of d in mm, showing that β is independent of a d beyond some minimum value of d.

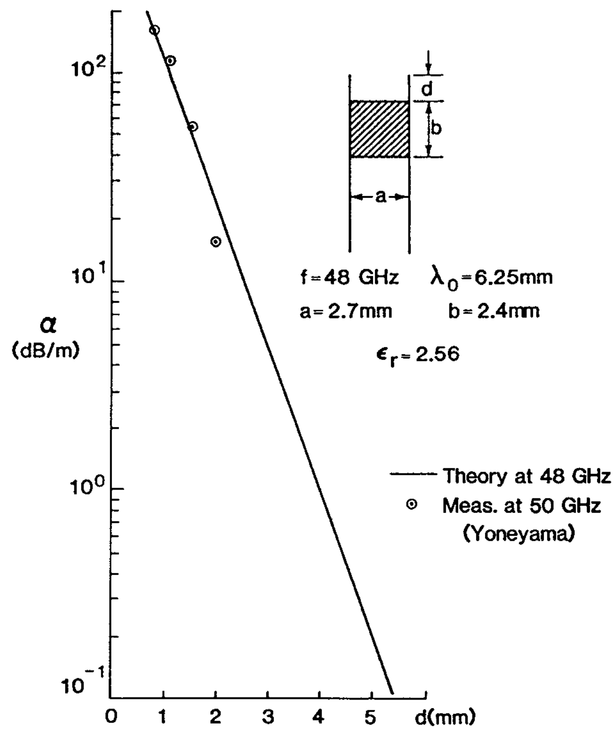

Fig. 5. Leakage constant α in dB/meter of the leaky-wave structure in Fig. 2 as a function of the distance d in mm between the dielectric strip and the radiating open end.