A New Method for the Characterization of Groove-Guide Leaky-Wave Antenna with an Asymmetrically Located Metal Strip

Zhewang Ma and Eikichi Yamashita, *Fellow, IEEE*

Abstract— **A full-wave characterization of the groove-guide leaky-wave antenna is described based on the mode-matching procedure. All higher order modes are taken into account, and the radiating open end is treated in a concise and accurate way by using the generalized scattering matrix technique. The formulation is versatile and rigorous. Numerical results are compared with previous data.**

I. Introduction

The LEAKY-WAVE ANTENNA based on the groove guide for millimeter-wave use was first proposed by P. Lampariello and A. A. Oliner in [1], [2], where a metal strip was added to the groove guide in an asymmetrical fashion, as shown in Fig. 1. This type of antenna is particularly suitable for the use at millimeter-wave frequencies because of its simplicity in the structure permitting easier fabrication at higher millimeter-wave frequencies where conventional antenna dimensions become very small; and because of the low-loss property of the groove guide at high millimeter-wave frequencies where the waveguide material losses may otherwise be so great as to compete with the leakage loss, thereby degrading the antenna performance and reducing antenna efficiency.

The properties of the leaky-wave antenna was analyzed in [1], [2] based on the transverse equivalent network. First the correct transverse modes were identified, then the equivalent circuit representations were deduced for all discontinuities, including step junctions, an asymmetrical coupling strip, and a radiating open end. All the expressions of the network constituents were given in closed form and were easily used for numerical calculations, although their mathematical derivation was not an easy task. However, approximations were introduced in the treatment of the asymmetric coupling strip and the step junction, and higher order mode coupling between discontinuities was also neglected. The theoretical equivalent circuit representation for the coupling strip was obtained by employing the *small obstacle theory,* so that it was valid only for small values of the strip width. In practical applications, one may wish to obtain greater leakage per unit length which requires wider strip widths. Therefore, a more versatile and accurate theory is desirable.

Manuscript received August 13, 1992.
The authors are with the Department of Electronic Engineering, University of Electro-Communications, 1-5-1 Chofugaoka, Chofu-shi, Tokyo 182, Japan.
IEEE Log Number 9205313.

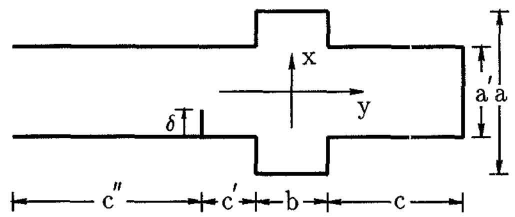

Fig. 1. Cross-section of the groove-guide leaky-wave antenna with an asymmetrically located metal strip.

In this letter, a full-wave analysis of the groove-guide leaky-wave antenna is described based on the mode-matching procedure. The coupling of higher order modes between discontinuities formed by the coupling strip and the step junction is taken into account by using the generalized scattering matrix technique. The radiating open end is simply represented by a matrix $\boldsymbol{R}^{(L)}$ whose elements are all zeros except $R^{(L)}_{1,1}$, whose expression has been available in [1] and in the *Waveguide Handbook* [3]. Numerical results by this method are compared with those of [2], and brief discussions are given.

II. Theory

The analysis process is similar to that of a previous paper [4], where dispersion characteristics of arbitrarily profiled groove-guides were given. Details can also be referred to Refs. [5], [6].

The principal new feature in the final eigenvalue matrix of this letter is attributed to the treatment of the radiating open end. Hybrid fields in the guide are expressed as a superposition of the LSE and LSM modes with respect to the z-direction, that is, the TE and TM modes with respect to the y-direction, as shown in Fig. 1. All the TE and TM modes are in the state below cut-off frequencies (along the y-direction) in the narrow parallel plate region of the width a', except the TE_0 mode (a mode akin to the TEM mode between parallel plates), which propagates all the way to the end of the waveguide and leaks away. The length c'' is assumed to be so long that the fields of all the evanescent modes have decayed to negligible magnitudes as they reach the open end. This means that all the evanescent modes can hardly see the effect of the open end, and the effect of the open end on the evanescent modes can be approximately represented by zero reflection and coupling coefficients $R^{(L)}_{m,n} = 0, (m, n = 1, 2, \cdots, m = n \neq 1)$.On the other hand, the propagating leaky TE_0 mode fields are reflected

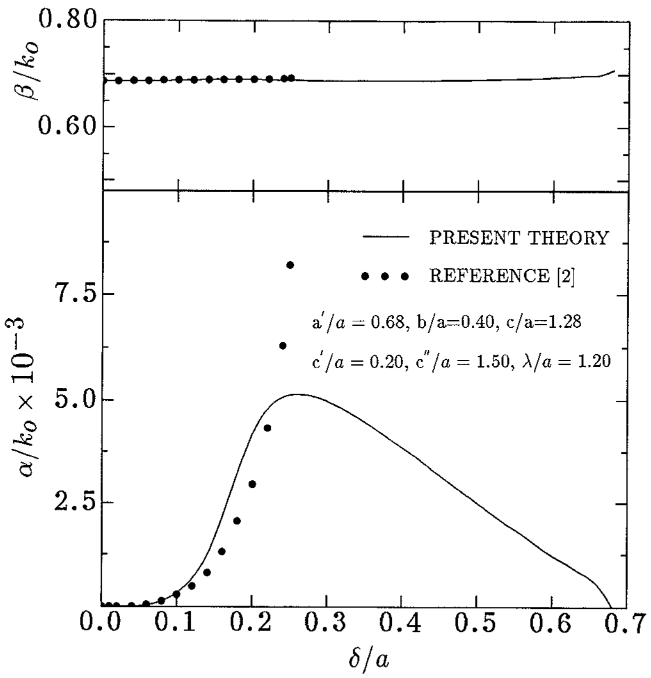

Fig. 2. Variations of the normalized phase constant β/k_0 and leakage constant α/k_0 with the normalized strip width $\delta/a (a = 5.0mm)$.

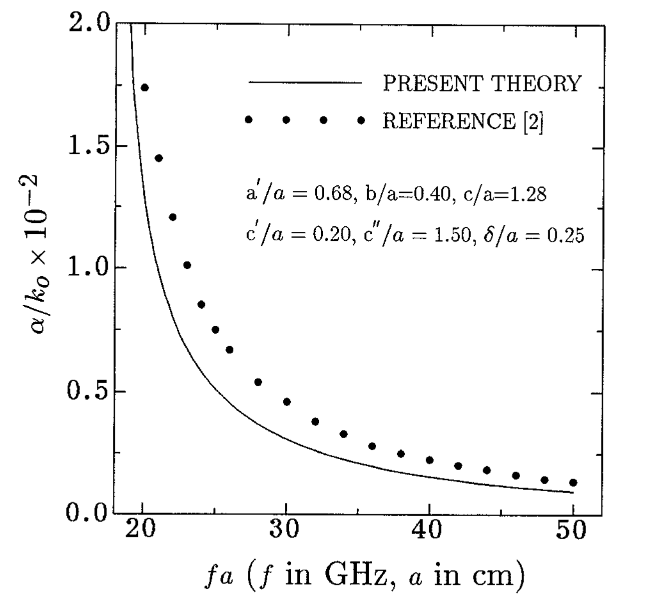

Fig. 3. Variation of the normalized leakage constant α/k_0 with the frequency-width product $fa (a = 5.0mm)$.

at the open end with the reflection coefficient given by

$$R_{1,1}^{(L)} = (1.0 - G_R - jB_R)/(1.0 + G_R + jB_R) \quad (1)$$

where $G_R + jB_R$ is the normalized equivalent admittance of the open end for the propagating TE_0 mode. This expression is directly available in the *Waveguide Handbook* [p. 179] and in [1]. The right end of the guide is closed by a perfect conductor to prevent radiation from it, where the reflection coefficients of all the modes are $R_{n,n}^{(R)} = -1, (n = 1, 2, \cdots)$, and the coupling coefficients $R_{m,n}^{(R)} = 0, (m, n = 1, 2, \cdots, m \neq n)$. The final eigenvalue equation and eigenvalue matrix are given by

$$\det \boldsymbol{G} = 0 \quad (2)$$

$$\boldsymbol{G} = \boldsymbol{I} - \left(\boldsymbol{S}_{21}^{(L)}\boldsymbol{E}^{(L)}\boldsymbol{S}_{12}^{(L)} + \boldsymbol{S}_{22}^{(L)}\right)\boldsymbol{D}^{(M)} \cdot \left(\boldsymbol{S}_{21}^{(R)}\boldsymbol{E}^{(R)}\boldsymbol{S}_{12}^{(R)} + \boldsymbol{S}_{22}^{(R)}\right)\boldsymbol{D}^{(M)}, \quad (3)$$

where

$$\boldsymbol{E}^{(L)} = \boldsymbol{R}^{(L)}\boldsymbol{D}^{(L)}\boldsymbol{D}^{(L)}\left(\boldsymbol{I} - \boldsymbol{S}_{11}^{(L)}\boldsymbol{R}^{(L)}\boldsymbol{D}^{(L)}\boldsymbol{D}^{(L)}\right)^{-1} \quad (4)$$

$$\boldsymbol{E}^{(R)} = \boldsymbol{R}^{(R)}\boldsymbol{D}^{(R)}\boldsymbol{D}^{(R)}\left(\boldsymbol{I} - \boldsymbol{S}_{11}^{(R)}\boldsymbol{R}^{(R)}\boldsymbol{D}^{(R)}\boldsymbol{D}^{(R)}\right)^{-1} \quad (5)$$

and $\boldsymbol{D}^{(L)}, \boldsymbol{D}^{(R)}$, and $\boldsymbol{D}^{(M)}$ are diagonal matrices with diagonal elements $D_{nn} = e^{-jk_{yin}l}$. The eigenvalue matrix $\boldsymbol{G}$ keeps the diagonal dominant property [4], [5] so that the root searching process is quite stable and fast converging.

III. Numerical Results

Fig. 2 shows the dependence of the normalized phase constant β/k_0 and the leakage constant α/k_0 on the normalized width δ/a of the asymmetric coupling strip. The results for β from the two theories agree well, and the results for α are also in good agreement for small values of δ/a. As δ/a is increased, our result becomes greater than that of [2]. It has been emphasized in [1] and [2] that the coupling network representing the additional asymmetrical strip was derived using the small obstacle theory which originally assumed that the obstacle was far from the plates, and was only valid for small values of the strip width δ. For wider strip widths, it was expected in [1], [2] that the leakage rates are actually greater than computed values using the small obstacle approach. Our result confirms their expectations.

With the further increase of δ/a, however, our numerical values of α/k_0 are gradually decreased. This observation can be explained in such a way that when the strip width is small the increase of δ reinforces the coupling between the leaky TE_0 mode and evanescent higher order modes so that the leakage rate is increased; when the strip width is further increased, however, the height of the radiating window becomes smaller, and more power is confined in the inner region of the guide, so that the leakage rate is decreased. When $\delta/a = 0.68 (\delta/a' = 1.0)$, the guide is completely closed and no radiation occurs. The numerical values of α/k_0 based on the small obstacle theory [2], however, is increased monotonously with the increase of δ/a. This result is not accurate for large values of δ/a.

Fig. 3 shows the variation of α/k_0 as a function of the frequency-width product fa. It is seen that α varies over a wide range with particular sensitivity to frequencies near cutoff. Since α/k_0 has been computed for a large strip width $\delta/a = 0.25$, the result of [2] is larger than that of the present theory as expected from Fig. 2.

IV. Conclusion

The groove-guide leaky-wave antenna with an asymmetrically located metal strip was, for the first time, characterized with our rigorous method. The numerical computation based on this method clearly showed a new result of the leakage constant for large values of the metal strip width. This method is versatile and accurate, and can also be applied to the analysis of other types of groove-guide leaky-wave antennas.

ACKNOWLEDGMENT

The authors would like to thank Mr. L. Zhu and Mr. Y. Qian for their helpful discussions.

REFERENCES

[1] P. Lampariello and A. A. Oliner, "A new leaky wave antenna for millimeter waves using an asymmetric strip in groove guide, Part I: Theory," *IEEE Trans. Antennas Propagat.*, vol. AP-33, pp. 1285–1294, Dec. 1985.

[2] ——, "A new leaky wave antenna for millimeter waves using an asymmetric strip in groove guide, Part II: Design consideration," *IEEE Trans. Antennas Propagat.*, vol. AP-33, pp. 1295–1303, Dec. 1985.

[3] N. Marcuvitz, *Waveguide Handbook*, vol. 10, Radiation Laboratory Series. New York: McGraw-Hill, 1951.

[4] Z. Ma, E. Yamashita, and S. Xu, "Modal analysis of open groove guide with arbitrary groove profile,"*IEEE Microwave Guided Wave Lett.*, vol. 2, pp. 364–366, Sept. 1992.

[5] ——, "Hybrid-mode analysis of planar transmission lines with arbitrary metallization cross sections," *IEEE Trans. Microwave Theory Tech.*, accepted for publication, Mar. 1993.

[6] J. Bornemann, "A scattering-type transverse resonance technique for the calculation of (M) MIC transmission line characteristics," *IEEE Trans. Microwave Theory Tech.*, vol. 39, pp. 2083–2088, Dec. 1991.