A Novel Cavity Resonator Measurement Method for Leaky Waveguides

ARTHUR A. OLINER, LIFE FELLOW, IEEE, AND JUNG-SU MYUNG, MEMBER, IEEE

Abstract—In this novel cavity resonator method for measuring the phase and leakage constants of leaky waveguides, power is sent in transversely, in a reversal of the leakage process itself. The cavity therefore requires no coupling holes, and the method is accurate and convenient to use, as shown in an illustrative example.

I. Introduction

A LEAKY waveguide loses energy along its length because of the leakage of power away from the guide; the propagation wavenumber of the leaky waveguide is therefore characterized as $\beta - j\alpha$, where α represents the leakage per unit length (in addition to any metal or dielectric loss that may be present). In order to accurately measure the leakage constant α, it is usually necessary to probe a substantial length of the leaky guide. One therefore needs a long guide (particularly if the leakage per unit length is small), and a movable probe. What is worse is everyone's experience that the power that leaks is easily scattered around, so that the movable probe picks up spurious radiation that interferes with the precision of the measurements. The new cavity resonance measurement procedure presented here eliminates *all* of these problems. With this new method, one works with a short section of the leaky structure, feeds it from the side in the leakage polarization, and varies the frequency through resonance. The measured resonance frequency and the Q of this cavity are related to the β and α sought.

The novel cavity resonator measurement method to be described below was motivated by the frustrations and annoyances produced by the above-mentioned spurious radiation encountered with the direct probing procedure. It was also developed in connection with a specific class of leaky waveguides, the dielectric strip guides for millimeter waves, such as the insular guide and the rib guide, but it is applicable to a much wider class of leaky waveguides. The description of the new method is phrased in the context of a leaky dielectric strip guide, and the specific numerical results are also presented for that type of guide. It should be understood, however, that the waveguide chosen should be viewed as an example and that the method is more widely applicable.

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A. A. Oliner is with the Weber Research Institute, Polytechnic University, Brooklyn, NY 11201.

J.-S. Myung was with the Weber Research Institute, Polytechnic University, Brooklyn, NY. He is now with the ECM Project Management Office, Korea Ministry of National Defense, Seoul, Korea.

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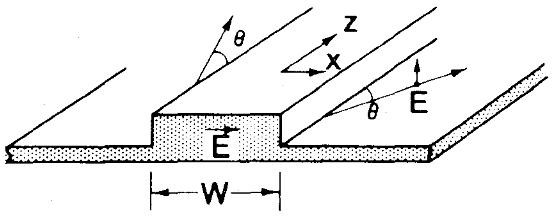

Fig. 1. The dielectric rib waveguide for millimeter waves, an example of a leaky waveguide. This guide can leak when the mode is TE-like, with the primary electric field component shown. Leakage then occurs away from the center rib at an angle θ in the form of a TM surface wave.

II. Description of the New Measurement Method

The *leaky waveguide* chosen for the description of the measurement method is the dielectric rib waveguide for millimeter waves, shown in Fig. 1. When the hybrid mode carried by the waveguide is TE-like, with the primary electric field component oriented as shown in Fig. 1, the mode can be leaky, with the leakage occurring in the form of a TM surface wave supported by the dielectric layers on the sides of the guide [1], [2]. The basic mode propagates in the z direction along the dielectric strip (or rib), and the leaking surface wave propagates away on each side at an angle θ from the z axis. The strip region has width W, and the whole dielectric structure is located on a metal ground plane. These features are summarized in Fig. 1.

To construct the *resonant cavity* on which the new measurement procedure is based, we place a length a of the guide shown in Fig. 1 between parallel vertical metal plates, where the metal plates extend in the x and y directions, as seen in Fig. 2. In that cavity, between the plates, we thus have a strip of dielectric of width a extending along the x direction, with its center portion, of "length" W, having a somewhat greater height, since it corresponds to the strip or rib of the original rib waveguide. If the mode on the original dielectric rib waveguide in Fig. 1 were purely bound, the fields in the x direction away from the rib would be evanescent; if the mode is leaky, and a TE-like mode is present, then a TM surface wave would leak away in the outside region [2]. This TM surface wave propagates at an angle, with both x and z

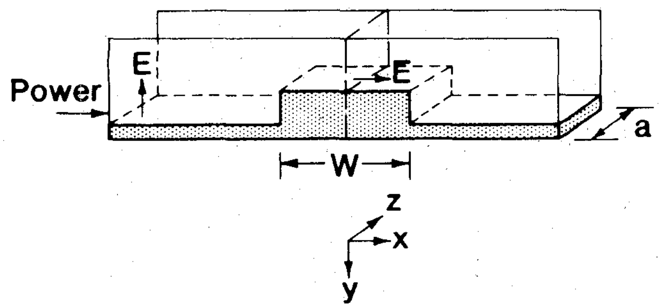

Fig. 2. The resonant cavity measurement arrangement, where a length a of the leaky waveguide in Fig. 1 is placed between parallel metal plates and the structure is excited from one side.

components. When the short-circuiting parallel plates are introduced, this propagating wave, if it could be excited, would thus become a standing wave in the z direction and a propagating wave in the x direction.

The new measurement approach employing the resonant cavity now *reverses* the process. The lowest mode with vertical electric field polarization is sent from one end between the parallel plates, in the x direction, toward the central section of greater dielectric height. This mode is actually the lowest hybrid mode with a vertical electric field only, and is termed an LSM mode in the xz plane or an $E^{(y)}$-type mode; it is also identical with the standard dominant mode in H guide. In the measurement procedure, the frequency is then varied through resonance.

The mode sent into the dielectric-loaded parallel-plate structure in Fig. 2 may equivalently be viewed as a pair of TM surface waves that bounce back and forth between the parallel metal plates. Each wave of this pair of surface waves corresponds, in reverse, to the leaking surface wave shown in Fig. 1. The angle θ_g of these constituent TM waves (in the xz plane) varies as the frequency is changed, in accordance with

$$\cos\theta_g = \frac{k_z}{k_0} = \frac{\lambda_0}{2a}. \tag{1}$$

At an appropriate frequency, the angle θ_g becomes equal to the leakage angle θ, and the incident wave excites a resonance in the central section. The fields in that central section would then increase substantially, particularly for the TE portion of the modal field (the inverse of the leakage situation). Hence, a probe sensitive to that polarization is placed in the midplane of the central region, oriented in the x direction, as seen in Fig. 2, and the power detected is found to peak sharply when the frequency of excitation corresponds to the condition for resonance.

The quantities to be measured are, therefore, the width a of the structure, the frequency f_0 at resonance, and the Q of the resonance. Alternatively, one could directly measure Δf, the frequency separation between half power points, since $Q = f_0/\Delta f$. From these measured values, we may readily obtain β and α for the leaky guided mode on the dielectric rib waveguide.

The relation for β is extremely simple:

$$\beta = k_z = \pi/a. \tag{2}$$

We may alternatively wish to know ϵ_{eff} for the guided mode, where

$$\epsilon_{\text{eff}} = \left(\frac{\beta}{k_0}\right)^2 = \left(\frac{c}{2af_0}\right)^2 \tag{3}$$

using (2), or

$$\epsilon_{\text{eff}} = \left(\frac{15}{af_0}\right)^2 \tag{4}$$

when a is in cm and f_0 is in GHz.

The relation for α can be adapted from the expression [3]

$$Q = \epsilon_r \left[\frac{\lambda_g}{\lambda_0}\right]^2 \frac{\beta}{2\alpha} \tag{5}$$

where all quantities apply to the "inside" of the cavity, i.e., the central region. The cavity is not filled uniformly with a single medium characterized by ϵ_r, however, but it is only partially loaded. It is therefore necessary to replace ϵ_r by ϵ_{eff} in this case, which is given by (3). Relation (5) reduces nicely as a result, and the leakage constant α can be written in terms of the measured cavity Q as

$$\alpha = \frac{\pi}{2aQ} \tag{6}$$

where α is expressed in nepers per cm if a is given in cm. Alternatively, one may wish to express α in terms of nepers per wavelength; then (6) becomes

$$\alpha\lambda_0 = \frac{15\pi}{aQf_0} \tag{7}$$

or

$$\alpha\lambda_0 = \frac{\pi a \Delta f}{15}\epsilon_{\text{eff}} \tag{8}$$

on using (4) and Δf instead of Q, where in both (7) and (8), a is in cm and f_0 and Δf are in GHz.

III. Why This Cavity Resonator Method is Different

The idea of employing a resonant cavity to measure the propagation characteristics of a mode on a waveguide is of course quite old, but such application has generally been to purely bound modes. A resonant cavity has also been proposed for the measurement of the properties of a *leaky* mode [3], where the application was to a rectangular waveguide with its sidewall perforated to permit leakage. That cavity was composed of a length of the leaky waveguide placed between metal plates, but it was excited by coupling holes located in these metal plates at the two ends of the cavity. That method of excitation is the standard one; it yields good results, but the coupling holes introduce an extra contribution to the radiation Q and may therefore reduce the accuracy of the results.

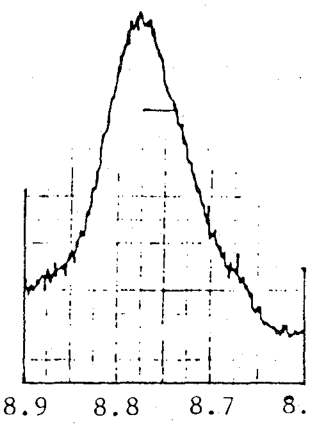

Fig. 3. Typical resonator response, as the frequency is swept through resonance in the cavity arrangement in Fig. 2. This example applies to width $W = 1.10$ cm.

As seen from Fig. 2, the arrangement here is *different*. In the other methods, including that in [3], the guide section is excited *longitudinally*, by coupling holes in the metal planes. Here, the structure is excited *transversely*, by sending in the wave that would have leaked in the reversed situation. No extra coupling holes are needed.

It should be added that the method of transverse excitation used here would not work if the waveguide were not leaky. If the mode were purely bound, with an evanescent transverse field decay, the exciting mode in the resonant cavity arrangement would need to be below cutoff.

IV. Numerical Comparisons with Theory for Specific Rib Waveguides

The measurement method described above was applied to several dielectric rib waveguide structures under conditions of leakage to verify its utility and its accuracy. The basic waveguide was the one shown in Fig. 1 for the field excitation shown; for the different structures, all dimensions remained the same except for the waveguide width W. Six different guide widths were chosen, ranging from $W = 0.80$ cm to $W = 1.50$ cm. The dielectric constant was $\epsilon_r = 2.54$. In the cavity resonator arrangement shown in Fig. 2, dimension a was 1.58 cm, and the probe used was a miniaturized coaxial monopole that came down vertically but had its exposed end bent horizontally in the manner shown in the midplane in Fig. 2. The metal outer conductor of the miniature coaxial line was covered with absorbing material. (Due to the symmetry of the resonance, we could alternatively have placed a short-circuiting plate in that midplane, and had the monopole probe project through it.)

The measurement procedure requires that the frequency be swept through resonance for each of the structures being measured. For the structures chosen, the resonances occurred in the frequency range from about 8.6 GHz to 9.0 GHz. A typical resonator response, in this case for $W = 1.10$ cm, is shown in Fig. 3. The slight asymmetry is due to unsymmetrical detector response, and some jitter is present, but the curves obtained were good enough to yield decent results.

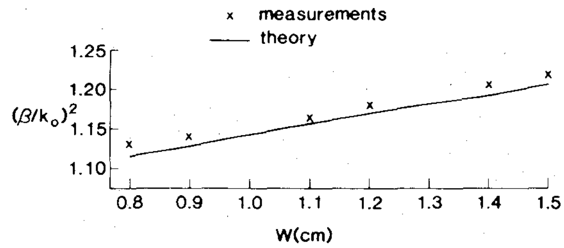

Fig. 4. Comparisons between measured and theoretical values of $\epsilon_{\text{eff}}\,(=(\beta/k_0)^2)$ as a function of guide width W.

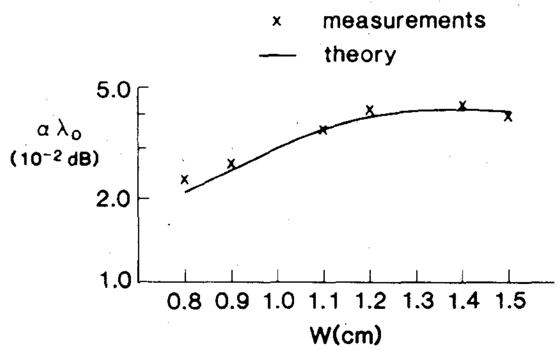

Fig. 5. Comparisons between measured and theoretical values of $\alpha\lambda_0$, the leakage constant per wavelength, as a function of guide width W.

To check the accuracy of the measurements, we also made theoretical calculations of the β and α of the waveguides corresponding to the six different guide widths W. The method used was the mode-matching procedure [1], where ten modes (five TE and five TM) were taken in each region in the guide cross section.

Comparisons between these theoretical calculations and the results of the measurements, on use of relations (4) and (8), are presented in Figs. 4 and 5. The comparisons in Fig. 4 for the effective dielectric constant, or equivalently for $(\beta/k_0)^2$, indicate that the measurements are consistently very slightly higher than the theoretical values. The discrepancy is only of the order of 1 percent, however, and it could be due to a small error in measuring distance a, or in the nominal value of ϵ_r, which could then affect the theoretical values.

The comparisons shown in Fig. 5 for $\alpha\lambda_0$, the leakage attenuation per wavelength, seem to be very good, considering the error sources present, even after taking into account the fact that the plot is on a logarithmic scale. The higher measured values could be accounted for by the presence of small dielectric losses and metal wall losses which are not included in the theoretical results.

We conclude from our experience with this new resonant cavity measurement method that it is convenient to use, and that it yields accurate results when compared with theoretical values. When compared with direct probing procedures, with which we also have experience, the resonant cavity method allows the use of a much simpler setup, and it permits more accurate measurements in general because it eliminates the spurious radiation problems that arise in the direct probing of leaky structures.

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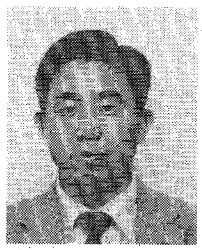
Arthur A. Oliner (M'47–SM'52–F'61–LF'87) was born in Shanghai, China, on March 5, 1921. He received the B.A. degree from Brooklyn College, Brooklyn, NY, and the Ph.D. degree from Cornell University, Ithaca, NY, both in physics, in 1941 and 1946, respectively.

While at Cornell University, he held a Graduate Teaching Assistantship in the Physics Department and also conducted research on a project of the Office of Scientific Research and Development. He joined the Microwave Research Institute of the Polytechnic Institute of Brooklyn, Brooklyn, NY, in 1946, and was made Professor in 1957. From 1966 to 1971, he was Head of the Electrophysics Department; he then became Head of the combined Department of Electrical Engineering and Electrophysics from 1971 through 1974. He was also the Director of the Microwave Research Institute from 1967 to 1981. During the summer of 1964, he was a Walker–Ames Visiting Professor at the University of Washington, Seattle, and during the 1965–1966 academic year he was on sabbatical leave at the Ecole Normale Supérieure, Paris, France, under a Guggenheim Fellowship. During the summer of 1973, he was a Visiting Professor at the Catholic University, Rio de Janeiro, Brazil; in the spring of 1978 he was a Visiting Research Scholar at the Tokyo Institute of Technology, Japan; in the spring of 1980 he was a Visiting Professor at the Huazhong (Central China) Institute of Technology, Wuhan, China; and in the fall of 1982 he was a Visiting Professor at the University of Rome "La Sapienza," Rome, Italy. He has been engaged in research in a wide variety of topics in the microwave field, including network representations of microwave structures, precision measurement methods, guided-wave theory with stress on surface waves and leaky waves, traveling-wave antennas, plasmas, periodic structure theory, and phased arrays. His interests have also included waveguides for surface acoustic waves and integrated optics and, more recently, guiding and radiating structures for the millimeter and near-millimeter wave ranges. He is the author of more than 180 papers, and coauthor or coeditor of three books. He served on the Editorial Boards of the journal *Electronics Letters* (published by the British IEE) and the volume series *Advances in Microwaves* (Academic Press).

Dr. Oliner is a Fellow of the AAAS and the British IEE, and he served as the first MTT National Lecturer in 1967. He has received prizes for two of his papers: the IEEE Microwave Prize in 1967 and the Institution Premium, the highest award of the British IEE, in 1964. He was named an Outstanding Educator of America in 1973, and in 1974 he received a Sigma Xi Citation for Distinguished Research. He was a National Chairman of the IEEE MTT Society, a member of the IEEE Publication Board, and General Chairman of three symposia. In 1977 he was elected an Honorary Life Member of the IEEE MTT Society, and in 1982 he received the IEEE Microwave Career Award. In 1984, he was a recipient of the IEEE Centennial Medal. He is a member of several Commissions of the International Union of Radio Science (URSI), a past Chairman of Commission 1 (now A), and a past USA Chairman of Commission D. He is also a former Chairman of a National Academy of Sciences Advisory Panel to the National Bureau of Standards.



Jung-Su Myung (S'78–M'82) was born in Pyungbook, North Korea, on March 3, 1943. He received the B.S. degree from the Korea Air Force Academy in 1967, the B.S.E.E. degree in electronic engineering from Seoul National University in 1971, the M.S. degree in electrical engineering from the Korea Advanced Institute of Science in 1975, and the M.S. and Ph.D. degrees in electrophysics from the Polytechnic Institute of New York in 1980 and 1982.

From 1967 to 1969, he worked as a radar maintenance officer at the Korea Air Force Communications and Electronics School. In 1971 he joined the faculty of the Korea Air Force Academy as an instructor. There he was involved with the Electronic Countermeasures Research Group of the Faculty Board, later becoming the project manager. After receiving the Ph.D. degree, Dr. Myung returned in 1982 to the Korea Air Force Academy and became the Head of the Engineering Division of the Faculty Board for two years, after which he worked as the Director of the Registrar of the academy for two years, until 1986. During that period he was also an Associate Professor of Electrical Engineering, teaching courses on radar engineering and microwaves. In 1986 he moved from the Air Force Academy to the Ministry of National Defense of Korea to join the Electronic Warfare Project Management Office as Technical Director. Since October 1987, he has been the Manager of the ECM Project Management Office. Dr. Myung is a member of the Korea Institute of Electronics Engineers and is a colonel in the Korea Air Force.