A New Leaky Waveguide for Millimeter Waves Using Nonradiative Dielectric (NRD) Waveguide—Part II: Comparison with Experiments

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Abstract—**Accurate measurements were taken of the leakage constant of a leaky-wave structure based on nonradiative dielectric (NRD) waveguide in order to verify the theory derived in the companion paper, part I. Although the structure is intended for millimeter-wave use, measurements were made on a model scaled to X band ($\lambda \simeq 3$ cm) to improve the accuracy of the experimental results.**

The measurements were taken by probing the electric near field strength along the longitudinal direction. Comparisons with accurate theoretical data are presented for different frequencies and geometrical parameters, and very good agreement is found between the measurements and the theory.

I. INTRODUCTION

IN THE COMPANION paper, part I, Sanchez and Oliner [1] present an accurate theory for the leakage and phase constants of a new leaky waveguide based on the recently introduced nonradiative dielectric (NRD) waveguide. This new waveguide is similar to the earlier H dielectric waveguide except that the spacing between the two parallel plates is made less than half of a free-space wavelength to ensure that all discontinuities become reactive. By cutting short one end of the metal plates of the NRD guide shown in Fig. 1(a), the new leaky waveguide shown in Fig. 1(b) is produced. The companion paper, part I, describes the principle of operation of this leaky waveguide, outlines its properties as an antenna, derives the elements of the transverse equivalent network from which the accurate theoretical results were obtained, and presents numerical values for the variation of the leakage constant α and phase constant β as a function of all the geometrical parameters.

The present paper, part II, contains a systematic series of measurements of the leakage constant α for the various frequencies and geometrical parameters, and compares those measurements with corresponding theoretical data.

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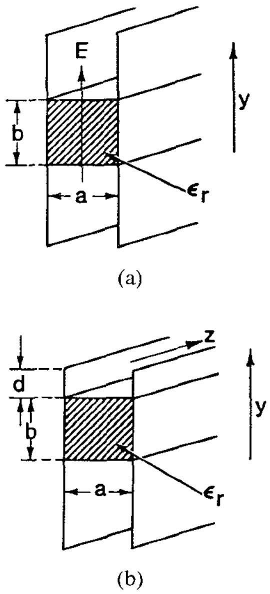

Fig. 1 (a) Cross-sectional view of nonradiative dielectric waveguide where $a < \lambda_0/2$. (b) Cross-sectional view of leaky-wave structure where leakage is controlled by distance d.

The purpose of the experimental study described here was to obtain experimental confirmation of the theory discussed in part I for the leakage constant of this new leaky waveguide. With that goal in mind, we designed, built, and made careful measurements on a X-band ($\lambda \simeq 3$ cm) model of the leaky structure that is actually intended for use at millimeter wavelengths. Some of the important features of the design of the leaky waveguide and of the measurement procedure are summarized in Section II. The reason for employing an X-band model was, of course, to permit increased measurement accuracy. In addition, a few experimental points were taken on a smaller structure at a frequency of 50 GHz at our request and privately reported to us by T. Yoneyama. His measurements were taken before the systematic series of measurements made by us at X-band, and we are grateful to him for verifying the validity of our theory early on.

The measurements taken by Yoneyama at a wavelength of 6.0 mm and those taken by us on a larger scaled structure at wavelengths around 3 cm are all compared in

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Section III with our accurate theoretical results. As is seen, the agreements are very good.

II. Leaky Waveguide Design and Measurement Procedure

A. Dimensional Features of the Leaky Waveguide Structure

Although the leaky waveguide structure is intended for use at millimeter wavelengths, the structure to be measured was scaled to a wavelength of 3 cm so that it could be made larger in size, in order to improve the accuracy of the measured results. The measurements would then be taken in the range 10–11 GHz.

Before the structure is built corresponding to this frequency range, we must know which modes can propagate and what their cutoff wavenumbers are. The axially propagating modes of the NRD guide, before the leakage mechanism is introduced, are hybrid in the longitudinal (z) direction but are TE or TM in the y direction, where the (transverse) y direction is shown in Fig. 1. The standard mode in the NRD guide is the lowest of the modes that are TM in the y direction; this mode has a half sine wave variation in the x direction. The two lowest modes that are TE in the y direction are one that has no variation with x(and is actually not hybrid but TE in the z direction) and one that has a half sine wave variation in the x direction. It turns out that for guide dimensions $a = 0.500$ in, $b = 0.378$ in, and $\epsilon_r = 2.56$, only these three modes can propagate; their cutoff frequencies are, respectively, 9.67 GHz, 0 GHz, and 8.74 GHz. We therefore see that it is essential in the waveguide design to maintain strict symmetry in the construction of the guide and in the excitation of the desired mode, so that the modes of the other polarization are never excited.

The manner in which the leaky waveguide structure was constructed is indicated in Fig. 2, where three orthogonal views are shown.

A 2-m-long structure was made out of two architectural aluminum right angles of equal legs for extra rigidity. The dielectric strip was cut out of polystyrene rod (Stycast 0005: $\epsilon_r = 2.56$ and $\tan\delta = 0.0005$). The separation between plates was chosen to be $a = 0.500$ in to cause the basic guide to be nonradiative ($a/\lambda < 1/2$) in the frequency range of our measurements, and yet to have low metallic losses. The dielectric strip thickness was taken to be $b = 0.378$ in so that only the lowest H-guide mode can propagate.

Spacers were run across the plates well below the dielectric strip and along the nonradiative aperture side to keep the separation between plates constant and hold the strip tightly. The location of these spacers is far enough below the strip so that waveguidance remains unperturbed on this side of the leaky structure. We may also see from the side view in Fig. 2(a) that the structure allows one to change the relative position and the curvature of the dielectric strip between the parallel metal plates.

Fig. 2(c) also shows the transition sections associated with the feed and the termination; these sections are tapered to improve their bandwidth. The transition section was designed to provide a smooth field pattern transformation and to prevent the excitation of other modes. It was made by copper electroplating techniques, having a tapered end (in scissors-like form) which can be put inside the parallel plates. The other end has a standard rectangular waveguide cross section, and the middle portion is a tapered rectangular waveguide. The end of the dielectric strip is also tapered.

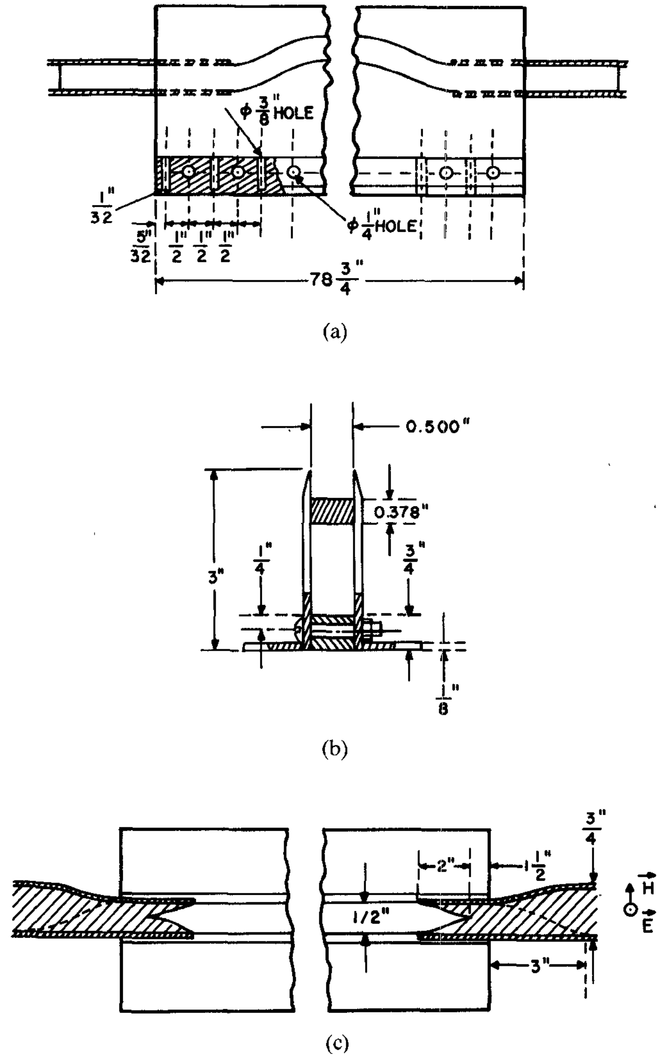

Fig. 2. Three views of the experimental leaky-wave structure showing all relevant dimensions and details of the feed and termination structures. (a) Side view. (b) Cross-sectional view of the middle part of the leaky-wave structure. (c) Top view.

B. The Experimental Method and the Measurement Setup

The block diagram is shown in Fig. 3.

The experimental setup consists of the following items: a detachable leaky waveguide section, two transition waveguide sections, a movable electric-field probe detector, and a conventional 3-cm band measurement setup.

The experimental method proceeds by moving the probe detector parallel to the z direction above the central line on the surface of the dielectric strip, and obtaining the field distribution along the z direction. The average slope

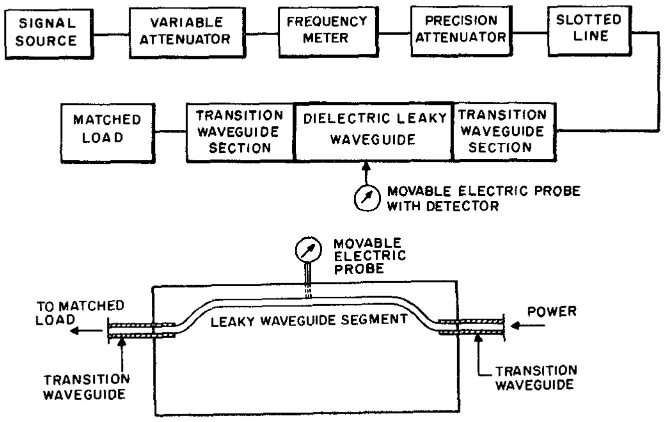

Fig. 3. Block diagram of the experimental setup.

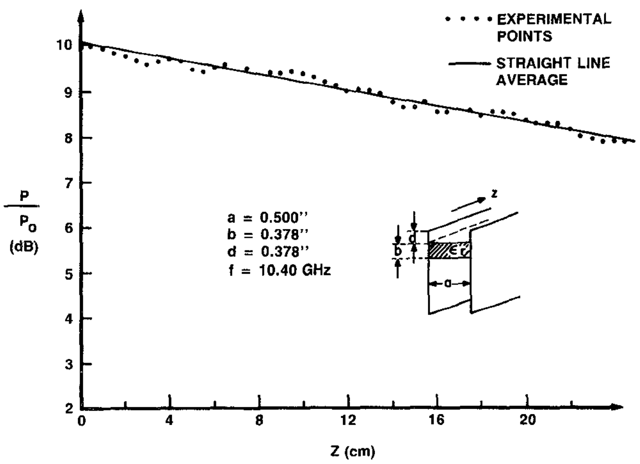

Fig. 4. Typical semilog plot of the measured probe pickup as a function of position along the length of the radiating aperture. A separate plot of this type was obtained for every frequency and every change in guide dimensions.

(in a semilog plot) of the measured field distribution (in dB) versus z (in meters) yields the total attenuation constant α_T. If α_L is the measured value of the transmission loss without any leakage, then $\alpha_T - \alpha_L$ is the measured value of the leakage constant α in dB/m. The value of α_L is obtained by measuring the loss in a nonradiative dielectric waveguide using the same dielectric strip but with very wide parallel plates so that no leakage can occur.

In the block diagram of Fig. 3, the signal source is a square-wave modulated reflex klystron, which sends the power through a precision attenuator of the standard rotary vane type, from which the relative field distribution is read. The diode detector, calibrated to a square-law response, sends its output to a standard standing wave indicator amplifier to yield a suitable dB value reading.

The electric probe is a miniaturized coaxial line with an extended inner conductor; the outside diameter of the line is about 1 mm. Its outer surface is coated by absorbing material to reduce unnecessary radiation and reflection of waves passing through it. The probe is mounted on a movable rack mechanism that maintains the distance between the probe tip and the strip surface to within 0.001 in as the probe moves along the z direction.

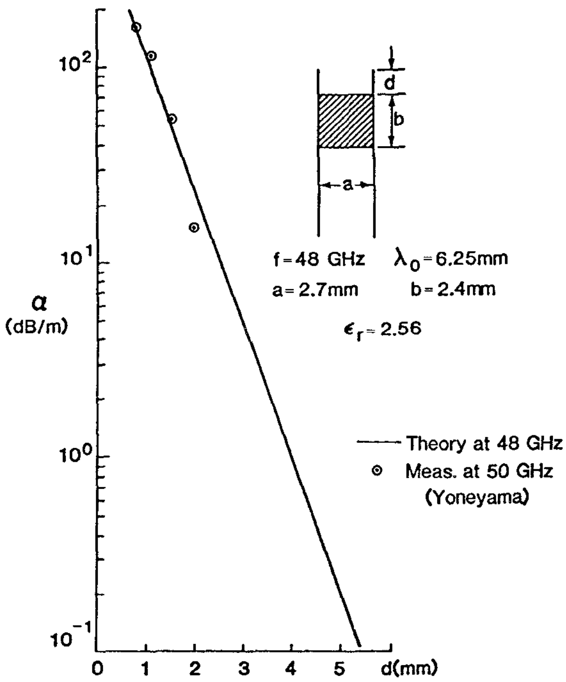

Fig. 5. Leakage constant α in dB/meter of the leaky-wave structure in Fig. 1(b) as a function of the distance d in mm between the dielectric strip and the radiating open end. Measurements taken by T. Yoneyama are also presented here.

TABLE I
MEASURED INTRINSIC LOSS (METAL AND DIELECTRIC) OF NRD WAVEGUIDE STRUCTURE WHEN LEAKAGE IS PREVENTED

freq. (GHz)	10.2	10.4	10.6	10.8
α (dB/m)	2.3	2.5	2.7	2.9

Fig. 4 presents a typical measured field distribution in the form of the semilog plot discussed above. There is a certain amount of ripple in the field distribution graph due to spurious reflections near the probe region. These ripples are not regular, and they cannot be eliminated entirely. However, the straight line that must be drawn through the average of the curve can be determined quite accurately.

III. EXPERIMENTAL RESULTS AND COMPARISONS WITH THEORY

Fig. 5 presents the leakage constant α as a function of d, the distance from the air–dielectric interface to the upper end. The results on this figure correspond to a set of geometric and constitutive parameters given by Yoneyama and Nishida in their original paper [2] on NRD guide. The theoretical curve on this figure is the same as that on Fig. 8(b) in part I. On Fig. 5 several experimental points have been plotted that were taken at 50 GHz. These points have been privately supplied by T. Yoneyama and obtained by probing the field with a unipole antenna along the aper-

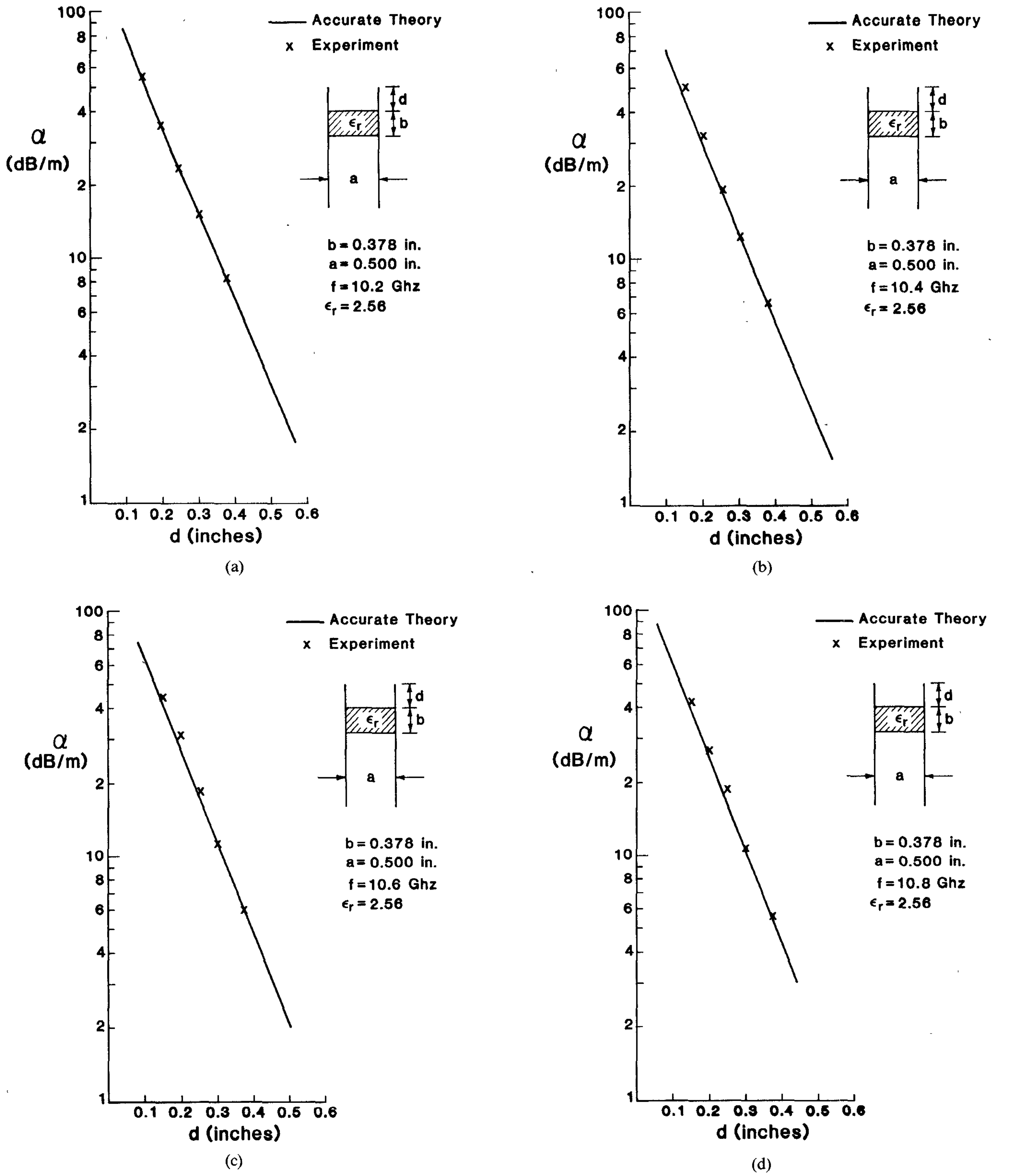

Fig. 6. Comparisons between our measured results and our theoretical calculations using the expressions derived in part I for the leakage constant α versus d at the frequencies (a) $f = 10.2$ GHz, (b) $f = 10.4$ GHz, (c) $f = 10.6$ GHz, and (d) $f = 10.8$ GHz.

ture. One can see that the experimental points follow the trend of the theoretical curve and that some of them agree quite well with it.

Our measurements of the leakage constant α as function of d were taken on a structure scaled to X-band. The values of plate separation a, dielectric strip width b, and relative dielectric constant ϵ_r were maintained the same throughout the measurements; these values are $a = 0.500$ in, $b = 0.378$ in,and $\epsilon_r = 2.56$. The different values of d were $d = 0.150$, 0.200, 0.250, 0.300,and 0.378, all in inches.

For each value of d, measurements were made at several frequencies.

For each of these cases, probe measurements were made as a function of the distance along the structure, and a plot similar to that in Fig. 4 was obtained. As explained above, the value of α was then determined from the slope of the straight line through the average of the curve. However, the intrinsic loss, comprised of the metal and dielectric losses, must be subtracted from the α determined from the plot in order to obtain the leakage loss itself. This intrinsic loss was measured for each frequency, following the method described above. Table I shows the intrinsic losses at 10.2, 10.4, 10.6, and 10.8 GHz. In the values for α reported below, therefore, the intrinsic loss values have already been subtracted from the directly measured ones.

In Fig. 6, we present comparisons between theoretical curves and these measured results. The solid lines in these figures all represent numerical data computed using the almost-rigorous theory derived in part I; the measured points are indicated by x's. In each figure, the leakage constant α is plotted as a function of the distance d; the different figures correspond to different values of frequency.

The agreement is seen to be *very good* over the whole range of values of d and over all the frequencies. The theory is essentially rigorous and systematic care was taken with respect to the measurements, so that the agreement found is not surprising but very gratifying.

References

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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 over 150 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 presently 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.

Han Qing was born in March 28, 1931, in Shanghai, China. He graduated from the Electrical Engineering Department of Beijing University in 1952 and the Department of Radio Engineering of Tsinghua University in 1959.

He has been involved in developing millimeter-wave components since the early 1960's. One of his contributions was the 8-mm reflex klystron, which has been in production since 1965 and is regarded as the first mm-wave source developed in China. He was with the Research Institute of Electronics of the Academy of Sciences of China until 1969. He is presently an associate professor in the Department of Radio Engineering at Huazhong University of Science and Technology, Wuhan, Hubei, China. As a visiting scholar to the United States, he did research on millimeter leaky-wave structures and microwave irradiation of living systems during 1982–83 at the Microwave Research Institute of the Polytechnic Institute of New York, Brooklyn, NY. His current interests are in the development of mm-wave dielectric waveguide components and antennas as well as integrated circuits in the infrared and optical wavelength range.

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Alberto Sanchez (S'81–M'82) was born in Zaragoza, Spain, in 1944. He received the degree of Licenciado en Fisica from the University of Zaragoza, Spain, in 1970, and the M.S. in electrophysics and the Ph.D. in electrical engineering from the Polytechnic Institute of New York in 1978 and 1983, respectively. From 1977 to 1982, he was engaged in research on millimeter-wave and optical integrated circuits as a research assistant with the Microwave Research Institute of the Polytechnic Institute of New York, Brooklyn, NY.

He joined the RCA Laboratories, Princeton, NJ, in 1982, where he was involved in the development of active printed circuit antenna arrays for Direct Broadcast Satellites (DBS) until 1986. He transferred to RCA Astro-Space Division in 1986, where he has been involved in different projects in beam forming network waveguide component design, dielectrically loaded horns, printed circuit antenna array feeds for MobilSat, and computer simulation of spacecraft electromagnetic interference.

Dr. Sanchez received the "Fundación Juan March" Scholarship for Advanced Studies in the U.S. in 1975. He is a member of the IEEE Microwave Theory and Techniques Society and the Antennas and Propagation Society.