A Dual Six-Port Network Analyzer Using Diode Detectors

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Abstract —The performance of a dual six-port network analyzer using diode detectors is described. The network analyzer operates over the 2–18-GHz band using commercially available low-barrier Schottky diodes. The paper describes the process for calibrating the diodes for deviation from square law. Measurement results are presented showing the accuracy and precision of the six-port network analyzer when measuring 1-port and 2-port devices.

Key words: attenuation measurements, automated network analyzer, impedance measurements, microwave network analyzer, network analyzer, and six-port.

I. Introduction

One of the advantages of a six-port network analyzer is that it uses simple RF power detectors, such as diodes, bolometers, or thermistors, to measure complex network parameters. Most of the six-ports built at the National Bureau of Standards (NBS), to date, have used thermistor detectors. The reason for this is the predictably "square-law" behavior of thermistors. Thermistors, however, also have their disadvantages. For example, thermistors typically require RF input power of 1 to 10 mW, or more, for optimum performance. The RF input to the analyzer, however, must be of the order of 0.1 to 1 W to achieve the required power level at the thermistor detectors. Thus, the nominally 10-mW synthesizers must be amplified before they are useful.

Thermistors also require self-balancing bridges or dc substitution power meters for accurate power measurements, which add an additional cost and complexity to the system. Diode power detectors, on the other hand, operate at much lower power levels, typically 10 μW or below. This lower power requirement is particularly attractive for systems operating at frequencies where power amplifiers are costly and noisy. The disadvantage of diodes is that they are square-law devices only at low power. At the higher powers, the diode output voltage becomes a linear function of RF input voltage. Thus, if accurate power measurements are to be made, the diode must somehow be calibrated to account for the deviation from square law [1]. The suitability of diode detectors for six-port network measurements is discussed in previous publications [2], [3].

This article describes a dual, six-port network analyzer using diode detectors. The analyzer operates over the 2–18-GHz frequency band, using commercially available low-barrier Schottky diodes. The process for calibrating the diodes for deviation from square-law is described, and measurements are presented showing the performance of the network analyzer when measuring 1-port and 2-port devices.

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II. System Description

A block diagram of the network analyzer is shown in Fig. 1. The 2–18-GHz source is low-pass filtered to remove second and higher harmonics. Following the filter, a 3-dB power divider sends half of the power to the six-ports and half to a thermistor detector. The thermistor is used to calibrate the diodes for deviation from square law. Following the RF on/off switch, the signal is sent to a 90° hybrid $Q1$, and a second 90° hybrid $Q2$. These components generate the 0, 90, 180, and 270° phase shifts in $a2/a1$ that are necessary for system calibration and 2-port measurements [4], [5]. The circuit also equally divides the signal, sending half of the remaining power to each six-port.

A block diagram of the six-port itself is shown in Fig. 2. The RF input is first sent through two 90° hybrids. The reason for using two hybrids, here, is to provide RF isolation between diode detectors. The remainder of the six-port is composed of three 90° hybrids and two 180° hybrids, which provide the proper phase relationships for the RF detectors P_0 through P_4. In reality, the device shown is a seven-port. However, only 4 of the detectors are used. The fifth detector is a spare that is used to isolate problems and provide added redundancy in planned future work. Note that there are dc blocks prior to each RF detector. These blocks are essential, in that they provide dc isolation between diodes. Erroneous measurements occur without these blocks because of a dc interaction between detectors.

A more detailed description of the diode detection circuitry is shown in Fig. 3. Each detector consists of a low-barrier Schottky diode followed by a load resistor R_L. The value of R_L is chosen to minimize the temperature sensitivity of the diode [2]. Values for R_L were determined by individually measuring the temperature sensitivity of each diode and range from 2.8 to 4.5 K. The temperature sensitivity of the diodes with the temperature-compensating load resistor is typically of the order of 8×10^{-4} V/K, or less. The detected dc voltage from each diode is amplified by a commercially available chopper-stabilized instrumentation amplifier with a gain of 100.

All the six-port components are encased within two

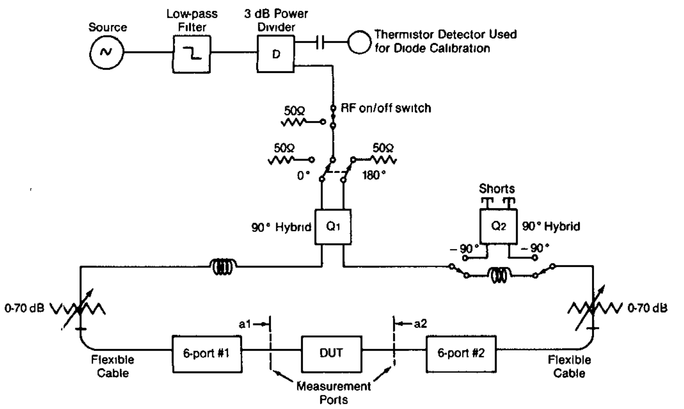

Fig. 1. System block diagram.

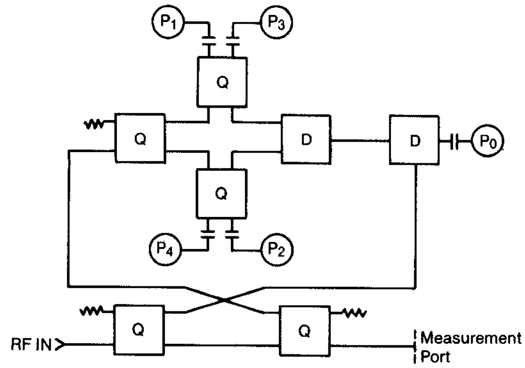

Fig. 2. Six-port block diagram.

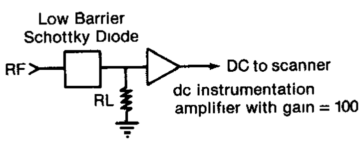

Fig. 3. Detector block diagram.

metal boxes. The inner box is thermally insulated and maintained at 31°C by a heater and proportional temperature controller. The outer box is at room temperature, which typically varies from 23°C to 26°C. The diodes are encased within an aluminum block, located inside the inner box. Temperature variations of the inner block are typically of the order of 0.05°C. The measurement ports on the six-ports are APC-7 connectors, and all devices measured are also fitted with that type of connector.

The six-port network analyzer is automated and controlled by a desktop computer. The dc voltages from each six-port detector are measured with a $6\frac{1}{2}$ digit voltmeter. A computer-controlled commercial scanner is used to switch and connect the various dc voltages to the voltmeter. Only one digital voltmeter is used in the current system. The power at the thermistor is measured with an NBS, type II, bridge.

III. Diode Calibration

All of the diodes are calibrated *in situ* after the six-ports have stabilized at their normal operating temperature. To calibrate the diodes, each six-port is terminated with a 50-Ω load, and the source power is varied over a 20-dB range, in 1-dB steps. The 50-Ω load does not produce a maximum power level at all diode detectors. Thus, to insure that no diode exceeds its calibrated range, the diodes are calibrated at a source power 6 dB greater than the power level at which they are normally operated. For each step, the diode dc output voltage and power at the thermistor detector are recorded. These data are then fitted, using a least-squares fit, to a diode model equation of the form

$$P = Kv^{(1 + b_1 v + b_2 v^2 \cdots b_n v^n)} \tag{1}$$

where P is the power at the thermistor detector, and

$$v = q(V - V_o) \tag{2}$$

where V is the diode output voltage, and V_o is the diode output voltage when $P = 0$. The quantities K, q, b_1, b_2, and b_n are constants determined by fitting the measured data to the model equation. The reader is referred to a report by Hoer *et al.* for a detailed description of the diode model equation and the diode calibration process [6].

All of the measurements described in this report were made using $n = 4$ in (1). The maximum power to any of the diodes during the calibration process is 50 μW. The deviation from square law at this input power is typically 2 dB. During network parameter measurements, the diodes typically operate at 30 μW maximum to insure that they remain within their calibrated range.

Tests have shown that the diode calibrations are reasonably stable with time. All the measurements presented in this paper were made with a diode calibration more than five months old. The diode calibration is also reasonably independent of frequency. A diode calibration made at a midband frequency will generally provide satisfactory results across the entire 2–18-GHz band. All of the 2–18-GHz data presented in this paper were made using a 3.5-GHz diode calibration. Diode calibration should not be confused with the six-port calibration, which determines the pertinent six-port constants [1]. The six-ports were, of course, calibrated at each frequency where tests were performed.

IV. System Performance

The stability of the network analyzer versus time is demonstrated in Figs. 4 and 5. For these tests, a short was connected to each of the dual six-ports and measurements of the reflection coefficient Γ were made every 10 min over a 50-h period. The test frequency is 3.5 GHz. The shorts remained connected to the measurement system throughout the entire period. Fig. 4 shows the magnitude of the reflection coefficient, whereas Fig. 5 plots the angle. The variations in magnitude are of the order of ±0.0001, while variations in angle are of the order of ±0.03°. The variation in angle is caused by expansion and contraction of the measurement port with room temperature, which, for this period, ranged from 22.9 to 25.4°C.

The performance of the network analyzer as a function of frequency is demonstrated in Fig. 6. Shorts were again connected to each of the six-ports and measurements of Γ were made at discrete frequencies across the 2–18-GHz band. The magnitude of Γ, from these tests, is shown in

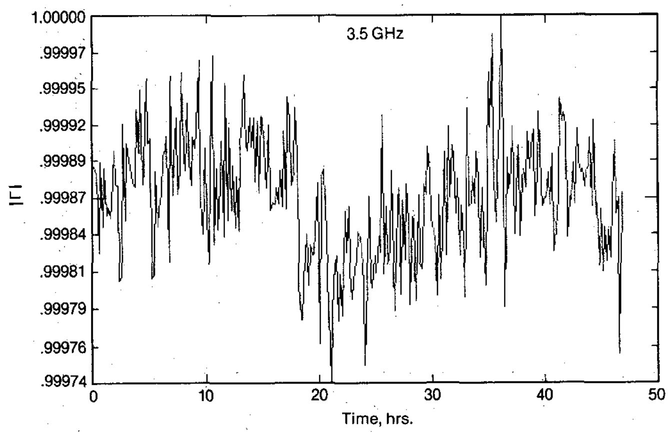

Fig. 4. Magnitude of the reflection coefficient of a short versus time.

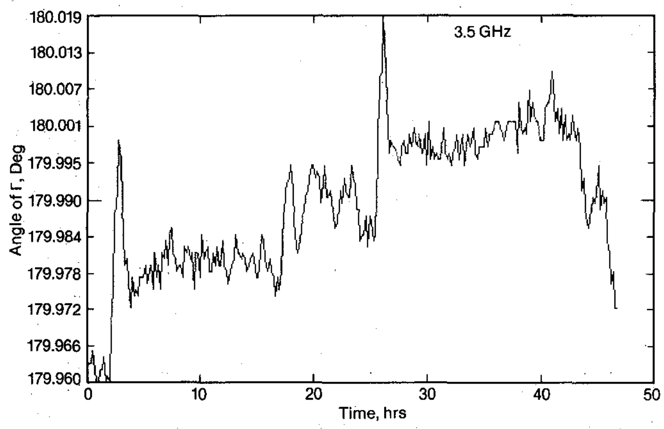

Fig. 5. Angle of the reflection coefficient of a short versus time.

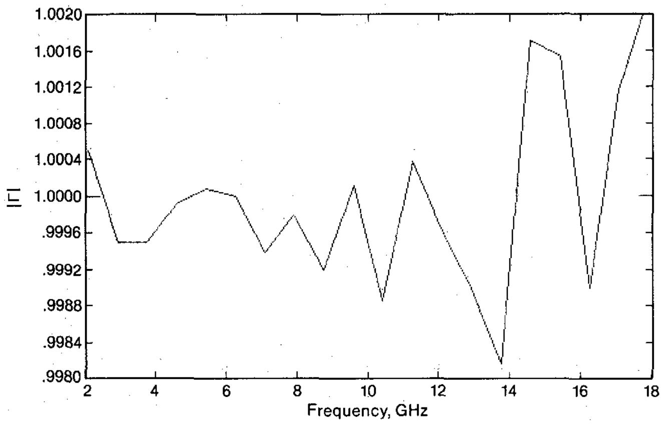

Fig. 6. Magnitude of the reflection coefficient of a short versus frequency.

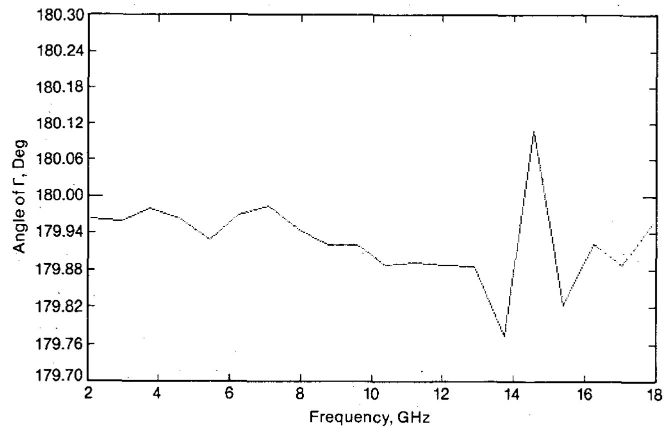

Fig. 7. Angle of the reflection coefficient of a short versus frequency.

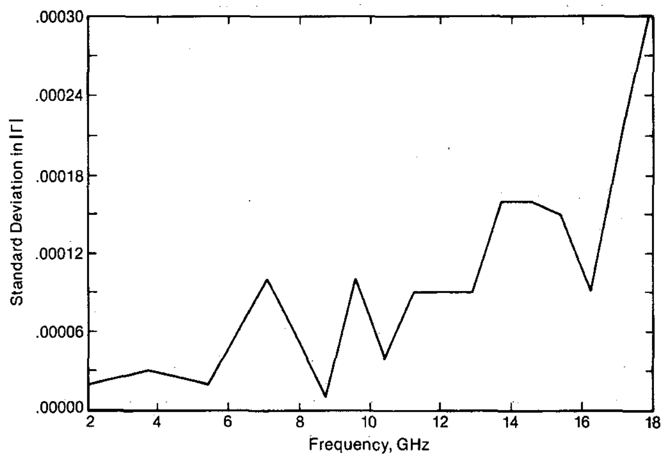

Fig. 8. One standard deviation in the measurement of |Γ| versus frequency.

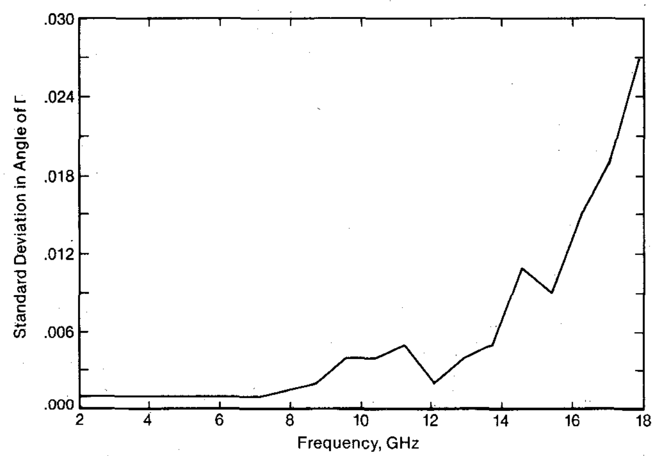

Fig. 9. One standard deviation in the measurement of the angle of Γ versus frequency.

Fig. 6, while the angle is shown in Fig. 7. The magnitude of Γ is 1±.002 at the higher frequencies, and 1±.0004 at the lower frequencies. The standard deviation in the measurement of magnitude is shown in Fig. 8. The standard deviation in the angle is shown in Fig. 9. The standard deviation, throughout this report, is obtained from ten repeated measurements.

Normally, the power at the measurement port is set to 30 μW. This is the maximum power permitted to insure that the diodes remain within their calibrated range. Figs. 10 and 11 show how the system performs as the power is decreased from 30 to 0.05 μW.

Fig. 10 plots the magnitude of Γ as a function of power, while Fig. 11 shows the standard deviation in the magnitude of Γ. The increase in the standard deviation at the lower powers is due to the decreasing signal-to-noise ratio at the detectors. It is interesting that reasonably accurate

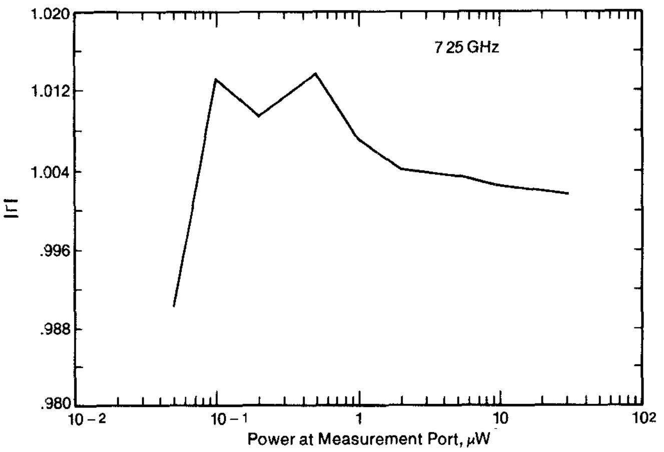

Fig. 10. Magnitude of the reflection coefficient of a short versus power at the measurement port.

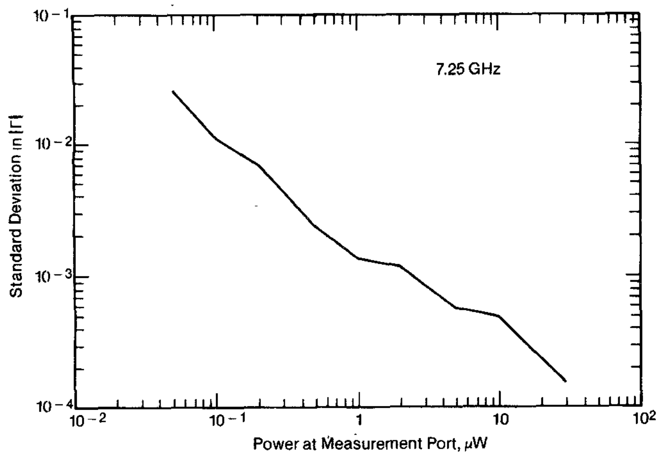

Fig. 11. One standard deviation in the measurement of |Γ| versus power at the measurement port.

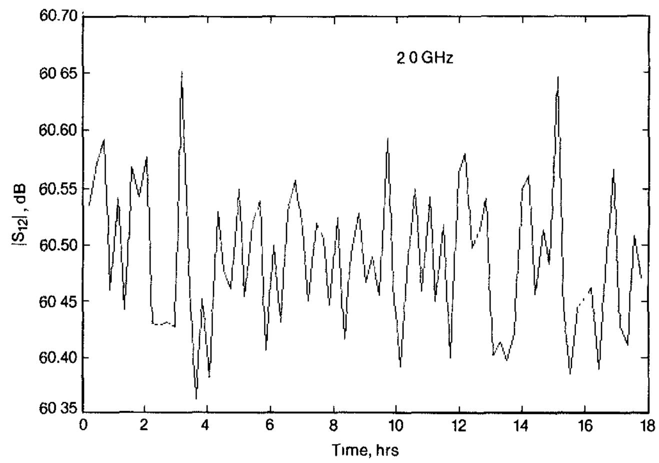

Fig. 12. Measurement of S_{12} of a 60-dB attenuator versus time.

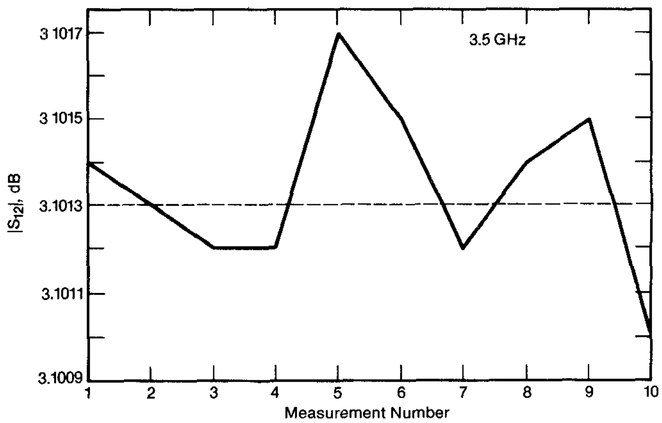

Fig. 13. Measurement of S_{12} of a 3-dB attenuator versus measurement number.

measurements can be made even with the power at the reference port as low as 0.1 μW.

So far, the measurements described have all been made with shorts. The reason for this is that the accuracy of the results can easily be determined, since the reflection coefficient of a short is precisely known. The remainder of this report will look into the system's capabilities when measuring attenuators.

One test performed was to repeatedly measure a 60-dB attenuator, at 2 GHz, over an 18-h time period. This test shows the stability of the system over the longer time periods. A plot of the magnitude of S_{12} as a function of time is given in Fig. 12. The attenuator remained connected to the six-ports throughout the entire time period to insure that there would be no changes due to connector movement. As can be seen, the average value of attenuation is 60.5 dB. One standard deviation in the measurement is typically 0.07 dB. The NBS automated network analyzer (ANA) measured the same attenuator at the same frequency as 60.6 dB. The difference of 0.1 dB is within the uncertainty limits of the NBS ANA.

Fig. 13 shows the precision in measuring a 3-dB attenuator. For this test, ten repeated measurements were made at 3.5 GHz, without disconnecting the attenuator from the system. The average value of attenuation is 3.1013 dB, with one standard deviation in the measurement of 0.0002 dB. The attenuator was measured on the NBS automatic network analyzer as 3.105 dB. The difference of 0.0037 dB is within the uncertainty of the NBS ANA.

The precision in the measurement of S_{12} on a six-port is a function of factors such as frequency, source noise, harmonics, etc. Fig. 14 shows one standard deviation in the measurement of the magnitude of S_{12} as a function of S_{12}. The shaded area shows the range of values typically obtained at frequencies below 8 GHz. The measurement precision of the current system is particularly sensitive to source power variations, since only one digital voltmeter is used. Simultaneous sampling of the detector outputs with two digital voltmeters can decrease the system's sensitivity to source power variations.

V. Conclusions

The performance of the diode six-port network analyzer is consistent with expectations. The advantages of using diodes are the simplicity of the system and the lower power requirements. The diode calibration process was found to be relatively stable with time, and reasonably independent of frequency. One disadvantage of the current system is

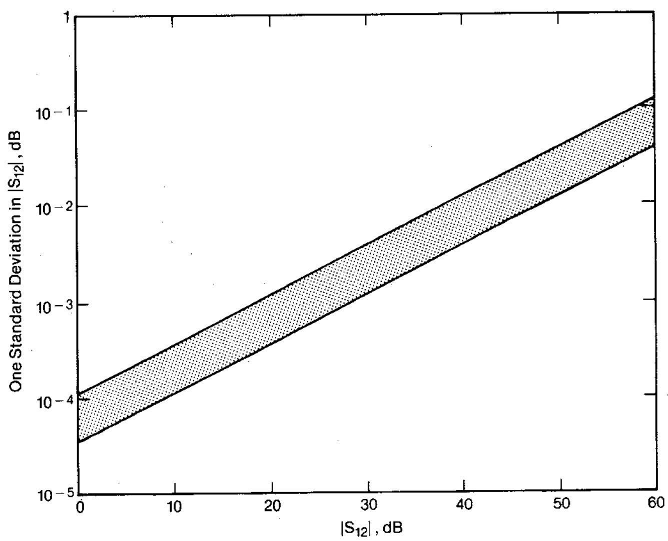

Fig. 14. One standard deviation in the $|S_{12}|$ versus $|S_{12}|$.

that one thermistor is still required to calibrate the diodes. The findings that precision six-port measurements are possible with calibrated diode power detectors is consistent with those reported by other experimenters [2], [3].

The data show that relatively accurate measurements can be made using diode detectors. Measurements of a short are typically

$$|\Gamma| = 1.000 \pm 0.001$$

or better. Similiarly, the precision in the measurement of a 60-dB attenuator is of the order of ± 0.1 dB or better, while the precision in measuring a 3-dB attenuator is of the order of 0.0002 dB or better.

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Cletus A. Hoer (S'66–M'67) was born in Westphalia, MO in 1933. He attended Weber State College, Ogden, UT, and Sophia University, Tokyo, Japan, while serving in the U.S. Air Force from 1950 to 1954. He received the B.S. degree in engineering physics and the M.S. degree in electrical engineering, both from the University of Colorado, Boulder, in 1959 and 1967, respectively.

He joined the Boulder Laboratories, National Bureau of Standards, Boulder, CO, in 1956 where he was first engaged in developing instrumentation for measuring properties of magnetic materials at high frequencies. In 1962, he transferred to the High Frequency Impedance Standards Section, where he did research and development work on inductance standards, impedance bridges, inductive voltage dividers, attenuators, and directional couplers. In 1972, his emphasis shifted to developing Josephson junction detectors for precision RF attenuation measurements. Since 1974, he has been working on the theory and application of the 6-port concept to RF and microwave measurements. He and a co-worker, Glenn Engen, received the Department of Commerce Gold Medal Award in 1976 for their development of the 6-port concept. Mr. Hoer is the author or coauthor of 36 technical papers and holds two patents.