James F. Black (M'71) was born in New York City, NY, on January 22, 1927. He received the B.S. degree in chemistry from Polytechnic Institute of Brooklyn, Brooklyn, NY in 1960.

From 1948 to 1972, he was at General Telephone and Electronics Laboratories, and its predecessor Sylvania Research Center, in Bayside, NY, working first on diffusion, precipitation, and recrystallization phenomena, and later specializing in III–V compounds. From 1960 to 1968, he conducted research programs in bulk crystal growth, LED's, diode lasers, materials for IMPATT devices and Hilsum–Gunn diodes, and use of lasers for infrared imaging and photoluminescence imaging. From 1968 to 1972 as Head, Compound Semiconductor Section, he was responsible for programs on liquid and vapor phase epitaxial growth, materials and device characterization, and process control technology. Since 1972, he has been a member of the Professional Staff at United Technologies Research Center, East Hartford, CT, where he has been engaged in silicon and gallium arsenide materials and device programs, including the fields of integrated optics, optoelectronics, microwaves and acoustic waves, and involving such devices as IMPATT's, grating couplers, FET's, LED's for fiber optics, high temperature rectifier diodes, and SAW and BAW filters.

Mr. Black is a member of APS, Electrochemical Society, and Sigma Xi. He has authored/co-authored over twenty technical publications.

A High-Power Dual Six-Port Automatic Network Analyzer Used in Determining Biological Effects of RF and Microwave Radiation

CLETUS A. HOER, MEMBER, IEEE

Abstract—**The design, calibration, and performance of a high-power (1-1000 W) automatic network analyzer based on the six-port concept are described for the 10–100-MHz range. Calibration is performed with a length of transmission line as the only impedence standard needed. A 10-mW thermistor mount is the standard of power. Imprecision in measuring reflection coefficient Γ is 0.0001 in magnitude and $0.005/|\Gamma|$ degrees in phase. Corresponding estimated systematic errors are 0.001 and $0.1/|\Gamma|$ degrees. Imprecision in measuring power is 0.01 percent of range (20 W, 200 W, or 1000 W) with an estimated systematic error of 1.25 percent of reading.**

I. Introduction

IN SPITE OF the existence of so-called "safe tolerance limits" to microwave radiation, there is a continuing interest in obtaining a more complete understanding of this subject. At the National Institute for Occupational Safety and Health (NIOSH), a program exists for evaluating the response of selected biological specimens to carefully measured and controlled electromagnetic fields with the objective of determining safe levels of RF and microwave radiation. The associated test chamber is designed in such a way as to provide fields which are predominantly either electric, magnetic, or selected combinations of both. This test chamber, shown schematically in Fig. 1, is a near-field synthesizer [1] consisting of a balanced, parallel-plate strip line to generate the electric field, and a rotatable single-turn inductor placed parallel to and midway between the plates to generate the magnetic field.

Manuscript received April 13, 1981; revised August 5, 1981. This work was supported in part by the National Institute for Occupational Safety and Health.

The author is with the Electromagnetic Technology Division, National Bureau of Standards, Boulder, CO 80303.

The purpose of this paper is to describe the design, calibration, and performance of a high-power automatic network analyzer (ANA) designed for NIOSH by NBS to measure the power and reflection coefficient at the E- and H-field input ports of this test chamber at power levels of 1–1000 W and frequencies of 10–100 MHz. Measurements at the inputs to the near-field synthesizer are made with two six-port reflectometers as shown in Fig. 1. The design of the reflectometers is based on the new six-port concept of measurement [2], [3]. Basically, for one six-port the concept states that the power and reflection coefficient at one-port of any linear network having six ports can be obtained from measurements of the power at four other ports when a signal is applied to the remaining port.

Six-port reflectometers were chosen as the measuring instruments in this application because of the following significant features which are not found in other automated measurement systems: 1) *simplicity* of the construction, operation, and calibration; 2) *superior accuracy* and precision; 3) *no lossy standards* required in the calibration; 4) *stability* of the calibration with time.

These features are elaborated on below.

U. S. Government work not protected by U. S. copyright

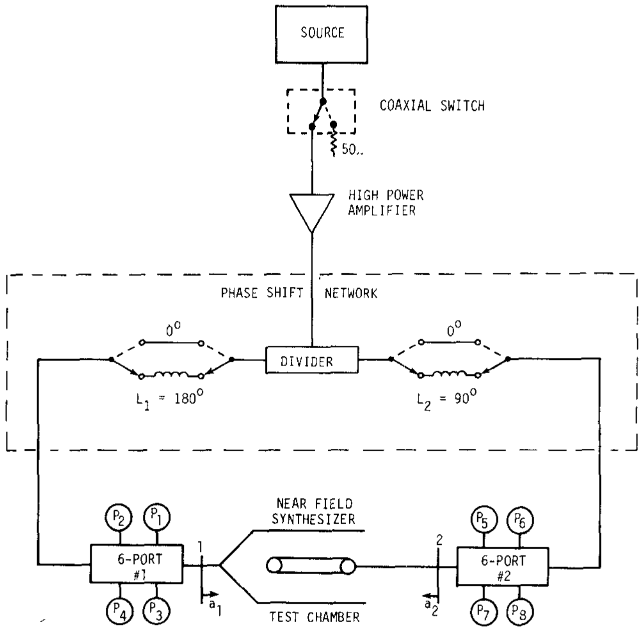

Fig. 1. Block diagram of the high-power ANA and the near-field synthesizer test chamber.

1) Simplicity: Only magnitude type detectors such as power detectors are used, in contrast to other ANA's which require more complicated detectors which must also measure phase. When using a six-port, phase angles are computed from the magnitude data.

The dual six-port ANA is relatively easy to automate and to maintain. All RF information is obtained from simple dc voltage measurements.

2) Superior Accuracy: The accuracy of the six-port ANA in automatically measuring network parameters approaches that achieved by the best fixed frequency, manually operated systems. For example, the uncertainty in measuring attenuation is less than 0.003 dB for low-loss attenuators up to 15 dB, and less than 0.2 dB at 60 dB. The uncertainty in measuring reflection coefficient is less than 0.001 with a precision better than 0.0001.

Built-in redundancy in the six-port ANA increases the accuracy and gives a measure of the quality of each measurement as it is made. This feature enables the operator to know immediately when the ANA is malfunctioning or needs recalibration, an important feature that is not available on other systems.

3) No Lossy Standards Required: Only *one* precision impedance standard is required to calibrate the ANA for attenuation, phase, reflection coefficient, or impedance measurements. This standard is a length of precision coaxial transmission line which is the most accurate impedance standard available in the 10–100-MHz range.

Unlike a lossy standard, such as a 50-Ω termination, a coaxial line can be used at high power levels without significant change in its parameters due to self-heating.

Only a single power standard is required for the absolute measurement of power, current, and voltage. This is a 10-mW standard thermistor mount which can be calibrated by NBS.

4) Stable-Calibration: Since the six-port components are all passive and the detectors are housed in a temperature-controlled housing, the calibration constants change slowly with time, thus eliminating the frequent recalibration commonly required by other ANA's. The six-port ANA should go several months without recalibration, in contrast with other ANA's which require recalibration every several hours.

II. System Description

A functional block diagram of the measurement system is shown in Fig. 1. The complete ANA is shown in Fig. 2. The components in the rack are identified in Fig. 3. The signal from the source is amplified and passed to the phase shift network where it is divided into two channels by the power divider. Each output from the phase shift network is passed through a six-port reflectometer to the near-field synthesizer. Six-port #1 measures the incident power and reflection coefficient at the input to the *E*-field plates of the synthesizer, and six-port #2 measures the incident power and reflection coefficient at the input to the *H*-field loop of the synthesizer. The power detectors are read and the switches are controlled by a programmable calculator.

A. Phase Shift Network

The purpose of the phase shift network is to change the phase angle of the two output signals a_1 and a_2 at the six-port measurement planes shown in Fig. 1. It is necessary to change the phase of a_2 relative to a_1 during calibration of the two six-port reflectometers and also during the measurement of two-port devices inserted between measurement planes 1 and 2 [6].

The phase shift network changes the phase difference between the two output waves a_1 and a_2 in four steps of roughly 90-degree increments. The circuit accomplishes this phase shift with two lengths of coaxial transmission line, L_2 and L_1, which have electrical lengths of roughly 90

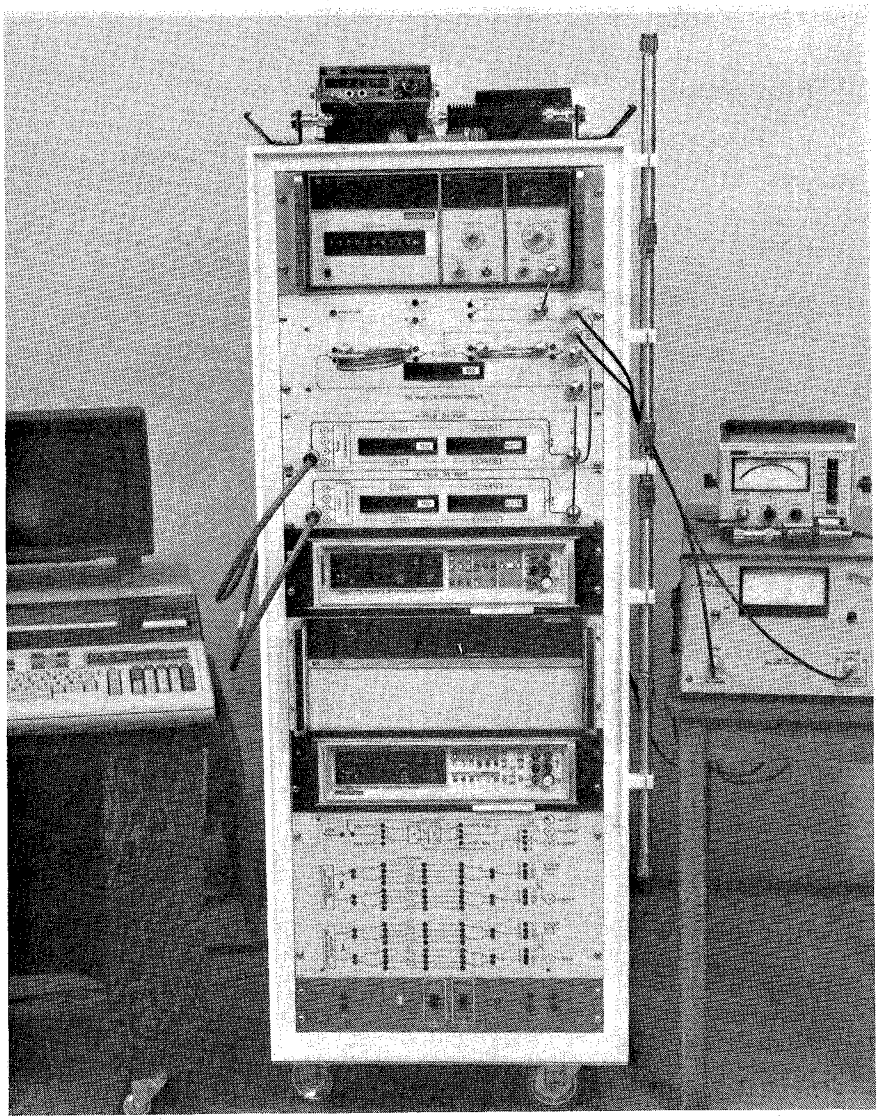

Fig. 2. Photograph of the high-power ANA with the desk top computer-controller on the left, and an amplifier and power monitor on the right.

and 180 degrees at the frequency of operation. The four possible combinations of switch settings give the phase of a_2/a_1 approximately equal to 0, 90, 180, and -90 degrees.

Since the phase shift through a coaxial transmission line is proportional to frequency, a single line cannot be used at all frequencies. Because the phase shift through the lines needs to be only *roughly* 90 and 180 degrees one length of line can be used over about a 2-to-1 frequency range. To cover the 10-to-100-MHz range requires four different lengths of line.

B. Six-Port Design

The six-port reflectometer design is shown in Fig. 4. The high-power signal is passed through the main line of a dual directional coupler having 30-dB coupling to the two sidearms. The coupler sidearm on the right of Fig. 4 couples to the emerging wave a, the other sidearm couples to the reflected wave b. These sidearm signals are further attenuated with one attenuator in each sidearm when the main-line power in either direction exceeds about 20 W. The level of attenuation is set by the calculator in 10-dB steps to keep the power level at the thermistor mounts within their optimum range of 1 to 10 mW. This results in three power ranges for levels up to 20, 200, or 1000 W in the main line.

Each sidearm signal is then passed through a set of low-pass filters to a number of hybrids and power dividers which provide four output signals that are different (independent) combinations of the waves a and b at the measurement plane [2], [4]. These four output ports are the four sidearms of the six-port reflectometer. The magnitudes of these four outputs are detected with thermistor-type power detectors. The power and reflection coefficient at the measurement plane are calculated from the readings of these four thermistor detectors.

A low-loss flexible coaxial cable is connected to the output port of each six-port and considered to be part of the six-port. The six-port measurement plane is the plane of the precision sexless 14-mm connector on the output end of this cable.

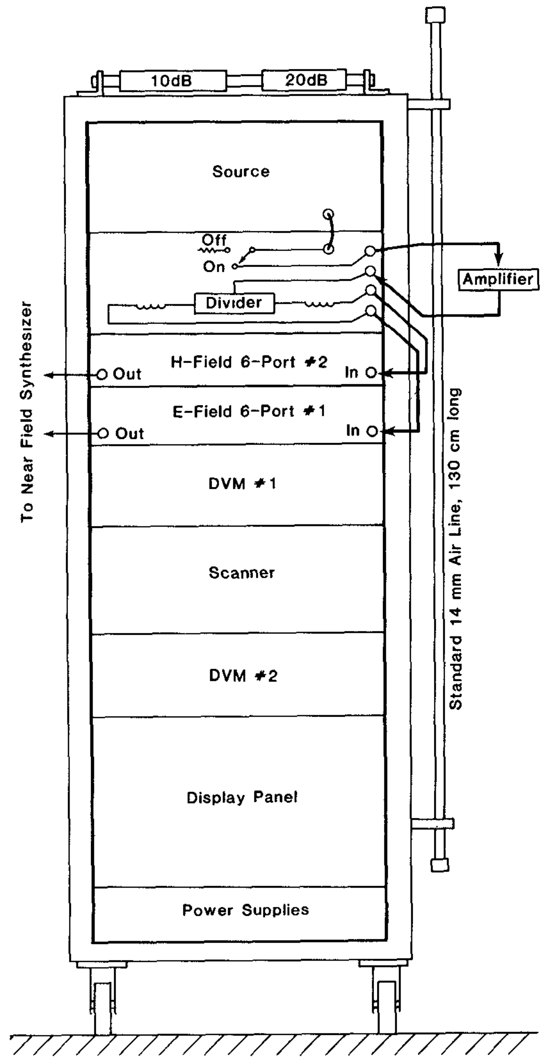

Fig. 3. Identifying components in the rack of Fig. 2.

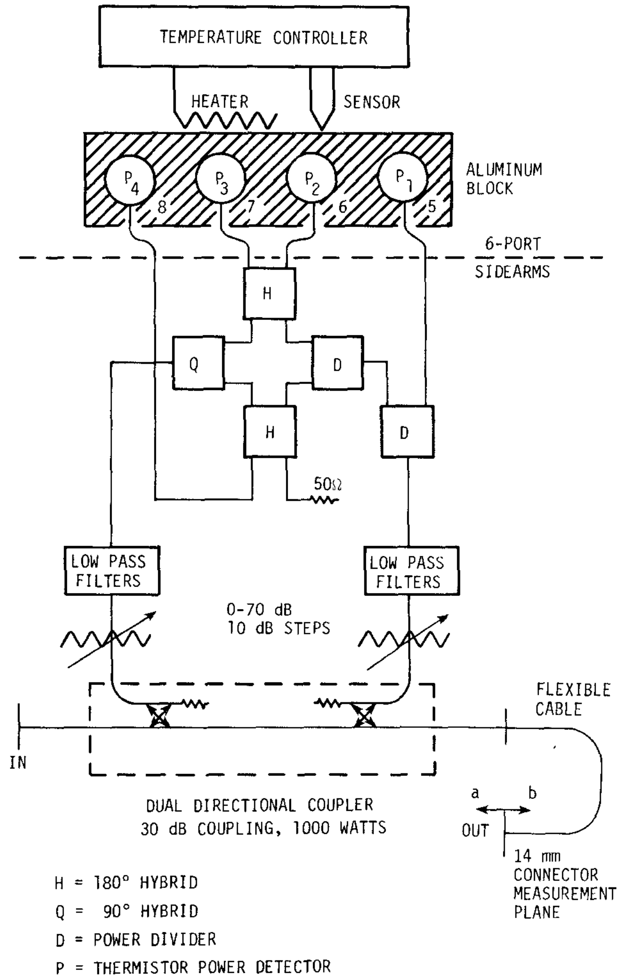

Fig. 4. Design of each six-port reflectometer.

C. Detectors

Thermistor-type detectors were chosen to measure the power at the six-port sidearms because they are the most accurate power detectors available when used with a precision self-balancing dc substitution power meter such as the NBS type IV design [5].

As shown in Fig. 4, each set of four thermistor mounts is enclosed in an aluminum block whose temperature is held constant to about $\pm 0.01°$C. Each thermistor is connected to its own power meter as shown in Fig. 5. The outputs of the eight power meters are connected to a scanner which can connect any one of the power meters to DVM #1 using channels 1 through 8. The DVM is in series with a reference voltage generator (RVG) which provides a stable offset voltage of about 2.3 V. The DVM actually reads the difference between the power meter output and this offset voltage. This difference is normally less than 300 mV which makes it possible for the DVM to measure this difference on its lowest, most sensitive (1-μV) range for greatest accuracy and resolution in measuring small values or changes in power. The value of the offset voltage is read by the DVM when the scanner is connected to the short which is on channel 0. These operations are done automatic .lly under control of the computer.

D. Filters

The low-pass filters in the block diagram of Fig. 4 are needed to eliminate harmonics generated by the source and the high-power amplifier. It is more practical to use low-pass filters on the sidearms of the coupler rather than one high-power filter preceding the six-port in the main line. Four low-pass filters are required in each sidearm to cover the 10–100-MHz range. The appropriate low-pass filters are switched into the sidearms automatically under program control.

Since the near-field synthesizer is a high-Q test chamber, it accepts only the fundamental frequency at which the chamber is tuned, thereby rejecting harmonics automatically.

E. Computer Control

The ANA is controlled by a programmable desktop computer. A block diagram of the computer-controlled components and other support equipment is shown in Fig. 6. The computer "talks" to the source, a scanner, and 2 DVM's through the interface bus (GP-IB). All coaxial switches and attenuators are controlled by applying 28 V dc from the power supply to the appropriate switches or

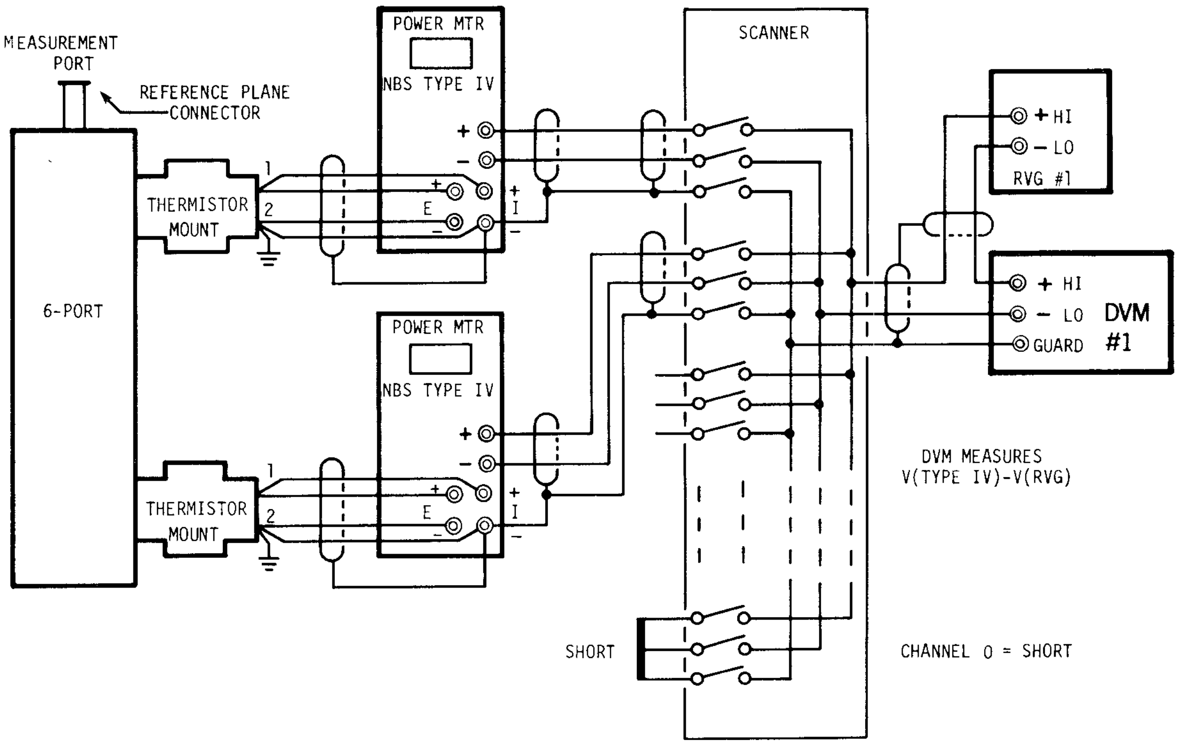

Fig. 5. Connections between each thermistor detector, power meter, scanner, DVM, and a stable offset voltage (RVG). Only two of the four power detectors on the six-port are shown.

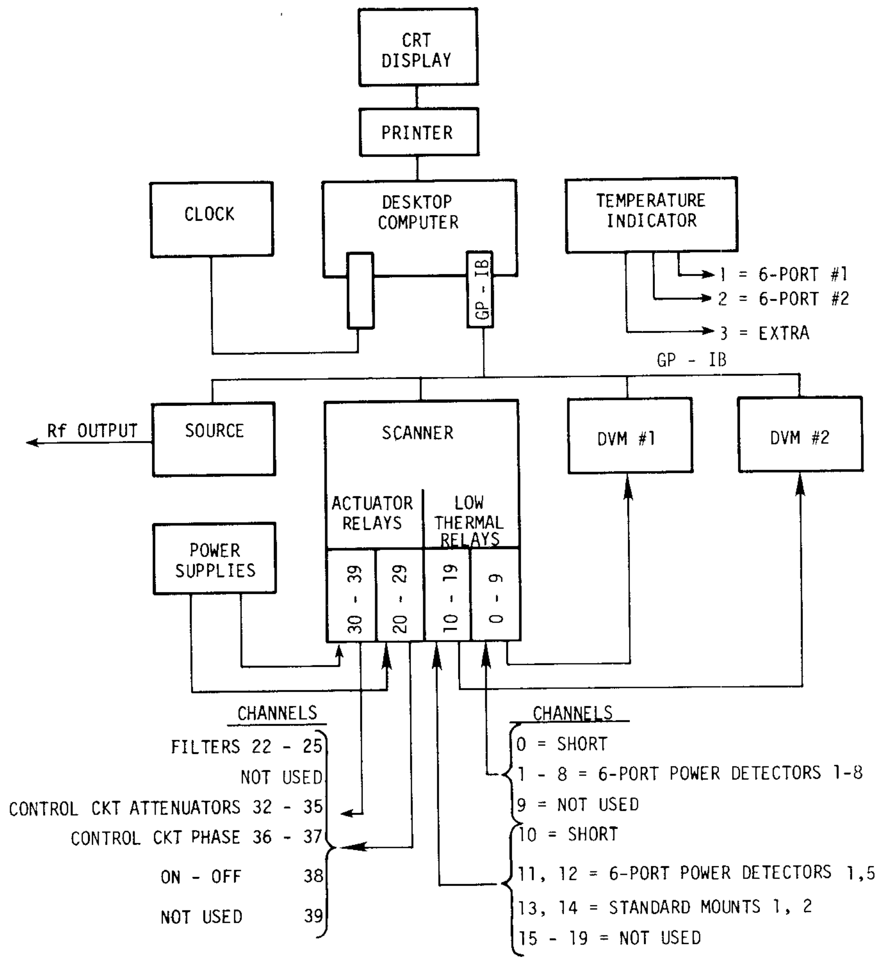

Fig. 6. Block diagram of the computer-controlled components and other support equipment for the ANA.

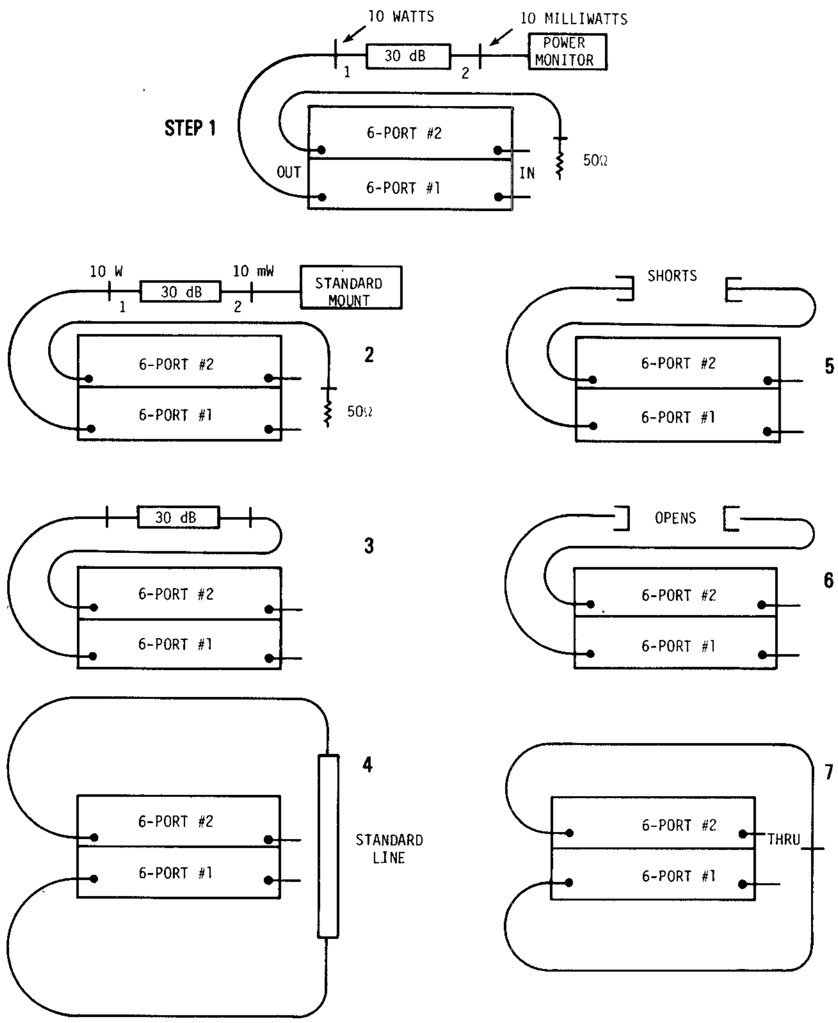

Fig. 7. Connections that the operator must make during calibration of the two six-port reflectometers.

attenuator cells through the scanner. The scanner also connects appropriate power meters to the DVM's.

When reading the voltages of the six-port sidearm power meters, both DVM's are triggered to take a reading at the same time. DVM #1 reads any sidearm power meter on six-port #1 or #2 while DVM #2 reads the power meter from one of the incident wave sidearm ports. The ratio of any sidearm power to the incident port sidearm power is independent of the power level. Measuring power ratios in this manner eliminates the need to level the signal at the six-ports.

III. Calibration

Before making measurements with the ANA, the six-port reflectometers must be calibrated at or near each frequency where measurements will be made. The steps in the calibration are displayed to the operator on the CRT of the calculator as outlined in Fig. 7. The input to each six-port is connected to the phase shift network as shown in Fig. 1 for all of these steps. All of the data taken during the steps shown in Fig. 7 are with each six-port on its low (20-W) range.

In step 1, the measurement port of six-port #1 is connected to one side of a 30-dB pad which has a power monitor connected to the other side. The operator adjusts the power level to obtain 10 mW at the monitor, and then replaces the monitor with a calibrated thermistor mount (power standard) as shown in step 2. Step 1 is simply a precaution to prevent overloading the power standard in step 2.

The data for determining the network parameters of the 30-dB pad are taken in step 3 where the pad is inserted between the two six-ports.

The power readings taken in steps 4, 5, and 7 are used in the "thru-reflect-line" calibration technique [3] to determine the six-port parameters needed for making Γ and S-parameter measurements. These parameters are then used to determine the loss and phase shift of the line and the reflection coefficients of the shorts and opens. The consistency of the values of line loss and phase shift from calibration to calibration and also with frequency is used as a check on the quality of the calibration. The calculated values of Γ of the short and opens also provide a check on the quality of the calibration as discussed later. The six-port parameters are then used with the data from step 3 to determine the S-parameters of the 30-dB pad. The pad

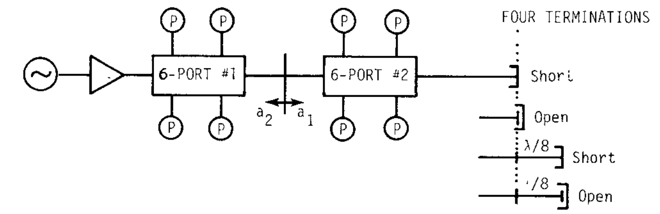

Fig. 8. Calibrating one power range on one six-port with a calibrated lower power range on the other six-port by reflecting the power back through the two six-ports with four reactive terminations having phase angles of 180°, 0°, 90°, 270°.

parameters plus the data from step 2 permit the six-port calibration to be completed so that both six-ports can now measure absolute power as well as reflection coefficient at their measurement planes on the Low (20-W) range.

Other power ranges are calibrated using a "bootstrap" technique after the last step while the "thru" connection is still made. The Mid (200-W) ranges are calibrated by the opposite six-port Low range, and the High (1000-W) ranges are calibrated by the opposite six-port Mid range.

In some applications it may be desirable to calibrate the six-ports at power levels which exceed the rating of the power divider in the phase shift network. The two six-ports can then be connected, as shown in Fig. 8. In this arrangement, the power from the source is reflected back through six-port #2 toward six-port #1 by four different reactive terminations such as a short, open, line+short, and line+open, where ideally the line would have an electrical length of 45° at the frequency being used. These four terminations create the same relative changes in the waves at the common measurement plane as that created by the phase shift network. The computer program gives the operator the option of calibrating the high power range using either the phase shift network or four external terminations. Four different lengths of lines are required to cover the 10-to-100-MHz range. These lengths are chosen so their useful frequency ranges which are about 2:1 coincide with the frequency ranges of the filters and the lines in the phase shift network.

IV. Precision and Accuracy

The performance of the dual six-port ANA is expressed here in terms of imprecision and systematic error [7]. The imprecision is a measure of repeatability, and will be defined as the standard deviation of a number of repeated measurements over a short period of time. The systematic error is an estimate of bias or offset.

The imprecision in measuring Γ is experimentally observed to be 0.0001 in magnitude and $0.005/|\Gamma|$ degrees in phase angle. The imprecision in measuring power is 0.01 percent of the power range.

A. Woods Bridge Comparison

The systematic error in measuring Γ was determined by comparing values of Γ obtained from the six-port to those values obtained from the NBS precision Woods bridge [8].

The reflection coefficient of four different high-power terminations having nominal $|\Gamma|=0.01$, 0.25, 0.50, and 1.0

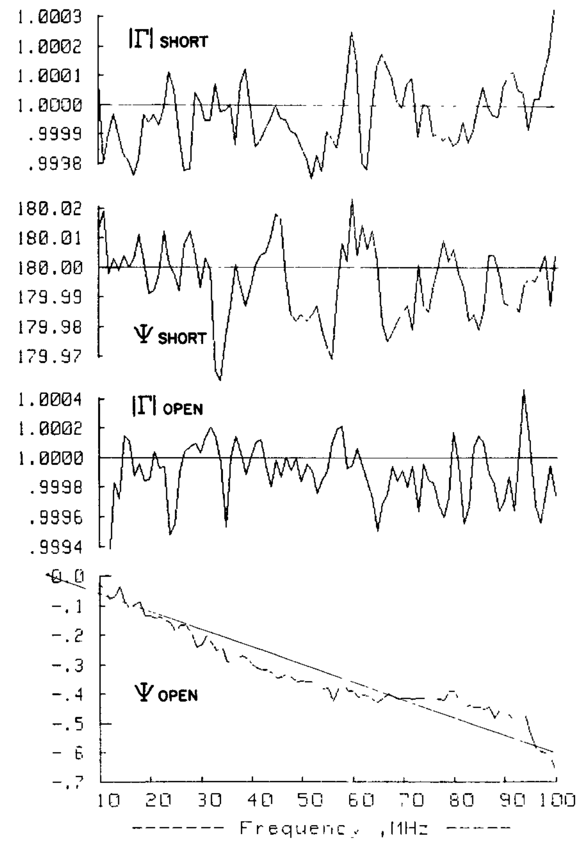

Fig. 9. Magnitude and phase angle ψ in degrees for the short and open as determined during the calibration.

were measured on the high-power dual six-port ANA at seven different power levels. These measurements were extrapolated to zero power to obtain values which were compared to values obtained on the Woods bridge, a low-power instrument. The extrapolated values of $|\Gamma|$ at zero power agreed with the Woods bridge low-power values to 0.001.

Imprecision in measuring phase angle is proportional to $1/|\Gamma|$. As $|\Gamma|$ gets small the imprecision gets worse. So instead of comparing values of phase angle ψ, values of the normalized phase angle $\psi\,|\Gamma|$ were compared which agree to less than 0.1 degree. The systematic error in ψ is therefore estimated to be less than $0.1/|\Gamma|$ degree.

B. Short, Open, and Standard Line

Another check on the systematic error is obtained every time the ANA is calibrated. Each calibration obtains new values of Γ for the short and opens, and also values of loss and phase shift through the 130-cm long standard line. The values of Γ for the short and an open are plotted in Fig. 9 for a calibration from 10 to 100 MHz in steps of 1 MHz. The straight line for ψ_{open} in Fig. 9 is the phase angle calculated from the capacitance of the open circuit cap (0.1631 pF) as measured at 1000 Hz. The plots of $|\Gamma|$ and phase angle versus frequency show a systematic error up to ± 0.0005 in $|\Gamma|$ and ± 0.1 degree in phase angle at some frequencies.

Plots of the loss and phase shift through the standard

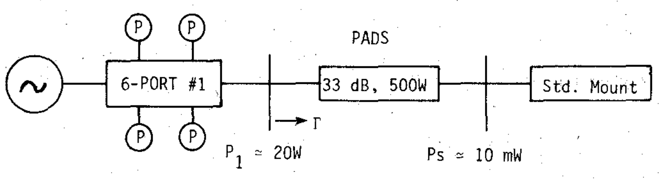

Fig. 10. Setup for determining how measurements on different ranges agree.

line are shown and discussed in [9] where they are used in determining the change in the characteristic impedance Z_0 of the line with frequency.

C. Two-Port Parameters

The imprecision in measuring the scattering parameters S_{11} and S_{22} of a two-port is the same as the imprecision in measuring Γ of a one-port termination. The imprecision in measuring S_{12} or attenuation is less than 0.001 dB up to 15 dB, increasing to 0.15 dB at 60 dB. The systematic error in measuring attenuation was not determined because the instability in the high-power pads due to changes with temperature and power level were greater than the errors we were trying to find in the six-port. A detailed investigation at 3 GHz of the errors in another dual six-port ANA concluded that the systematic errors were less than the imprecision [10]. Hopefully, that conclusion is valid for our high-power dual six-port ANA also.

D. Accuracy in Power

The accuracy of the ANA in measuring power is determined primarily by the 1-percent uncertainty with which NBS can determine the effective efficiency η_e of the standard thermistor mount. An addition 0.1 percent is added to this uncertainty to allow for the ± 0.1-percent variation of η_e with frequency, since a single average value is used in the computer program at all frequencies. Another 0.1 percent is added due to the estimated systematic error in measuring S_{12} of the 30-dB pad. Other errors are 0.03 percent due to the assumption that Γ of the standard thermistor mount is zero, and 0.02 percent due to errors in the Type IV power meter used with the standard mount. The total estimated systematic error in measuring power comes to 1.25 percent of the measured value.

E. Range Comparison

One way to determine how measurements on different power ranges agree is shown in Fig. 10. Power P_1 is measured on two different power ranges of the six-port while P_S is held relatively constant. Ratios of P_1/P_S measured on the Low and Mid ranges at 20 W agree to 0.15 percent. Increasing the attenuation from 33 to 43 dB, ratios of P_1/P_S measured on the Mid and High ranges at 200 W agree to 0.25 percent. The values of Γ measured on the Low and Mid ranges at 20 W agree to 0.001 in magnitude and 2 degrees in phase, where $|\Gamma| \simeq 0.01$. Values of Γ measured on the Mid and High ranges at 200 W agree to 0.002 and 5 degrees. All of the above differences are worst cases observed at test frequencies of 15, 25, 45, and 75 MHz.

V. Conclusion, Observations

A high-power automatic network analyzer has been constructed having accuracies comparable to low-power precision impedance bridges and power meters. The calibration technique described is applicable at any power level since no lossy standards are used. The technique for calibrating higher ranges with lower ranges is quite general and can be applied to any number of steps.

Acknowledgment

The author gratefully acknowledges the help of G. Engen who assisted in working out the calibration routines, R. Metzker who constructed the system, and W. Angevine, P. Fales, and R. Adair who assisted in the programming and checkout of the system.

References

[1] F. M. Greene, "Development and construction of an electromagnetic near-field synthesizer," NBS Tech. Note 652, May 1974.

[2] C. A. Hoer, "Using six-port and eight-port junctions to measure active and passive circuit parameters," NBS Tech. Note 673, pp. 23, Sept. 1975.

[3] G. F. Engen, "The six-port reflectometer: An alternative network analyzer," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-25, pp. 1075–1080, Dec. 1977.

[4] —, "An improved circuit for implementing the six-port technique of microwave measurements," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-25, pp. 1080–1083, Dec. 1977.

[5] N. T. Larsen, "A new self-balancing DC-substitution RF power meter," *IEEE Trans. Instrument. Measurements*, vol. IM-25, pp. 343–347, Dec. 1976.

[6] G. F. Engen and C. A. Hoer, "Thru-reflect-line: An improved technique for calibrating the dual six-port automatic network analyzer." *IEEE Trans. Microwave Theory Tech.*, vol. MTT-27, pp. 987–993, Dec. 1979.

[7] C. Eisenhart, "Expression of the uncertainties of final results," *Science*, vol. 160, pp. 1201–1204, June, 1968. Also published in *Precision Measurement and Calibration*, NBS Special Publ. 300, vol. 1, pp. 69–72, Feb. 1969.

[8] D. Woods, "A precision dual bridge for the standardization of admittance at very high frequency," *IEE* (London), vol. 104C, pp. 506–521, June, 1957.

[9] C. A. Hoer, On determining the characteristic impedance of a coaxial transmission line," to be published.

[10] ——"Performance of a dual six-port automatic network analyzer," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-27, pp. 993–998, Dec. 1979.

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 proper-

ties 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 and a co-worker, Glenn Engen, have been responsible for advancing the theory and application of the six-port concept to RF and microwave measurements. He and Engen received the Department of Commerce Gold Medal Award in 1976 for their development of the six-port concept.

Mr. Hoer is the author or coauthor of 36 technical papers and holds two patents.

Propagation Parameters of Coupled Microstrip-Like Transmission Lines for Millimeter-Wave Applications

SHIBAN K. KOUL AND BHARATHI BHAT

Abstract—**A variational expression is derived for the propagation parameters of coupled microstrip-like transmission lines for millimeter-wave applications using the "transverse transmission line" method. Numerical results are presented for the coupled inverted microstrip lines, and for the coupled suspended microstrip lines. The effects of the top and sidewalls and also of the finite thickness of strip conductors on the even- and odd-mode impendances are studied. The use of a dielectric overlay in equalizing the even- and odd-mode phase velocities is investigated.**

I. Introduction

Microstrip-like transmission lines, which incorporate an air gap between the dielectric substrate and the ground plane, such as the inverted microstrip and the suspended microstrip, are known to offer less circuit losses and less stringent dimensional tolerances compared with the conventional microstrip lines [1]–[3]. The same advantages accrue in the case of coupled microstrip-like transmission lines shown in Fig. 1 and its two special cases, namely; the coupled inverted microstrip lines and coupled suspended microstrip lines which result when $h_2=0$ and $h_3=0$, respectively. These structures, therefore, find applications in the design of filters and couplers at millimeter-wave frequencies. Smith [4] has analyzed the even- and odd-mode capacitances of the coupled lines on a suspended substrate based upon conformal transformation. Mirshekar-Syahkal and Davies [5] have analyzed shielded multilayer dielectrics with arbitrary coplanar conductors using spectral-domain approach.

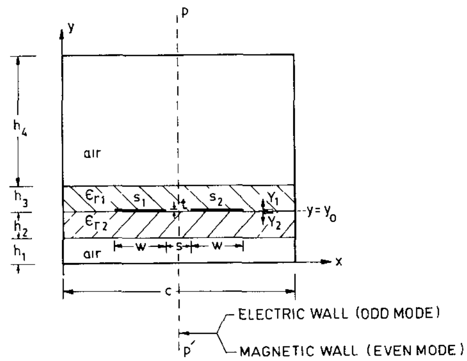

Fig. 1 Coupled sandwiched microstrip structure.

Manuscript received April 13, 1981; revised August 18, 1981.

The authors are with the Centre for Applied Research in Electronics, Indian Institute of Technology Delhi, Hauz Khas, New Delhi, 110016, India.

0018-9480/81/1200-1364$00.75 ©1981 IEEE