measurement port, or assumes that it is substantially larger than that required at $P_3 \cdots P_6$, this eliminates the requirement to make $\alpha$ as large as possible. Ordinarily, in this mode, the connections at the left side of the coupler should be reversed, and the desired signal levels and values of $|q|$ realized through the choice of coupling values and possibly attenuators.

## III. Visual Display of Reflection Coefficient

In addition to obtaining a numerical output, to which the various corrections have been applied, it is frequently useful to have a real-time oscilloscope display of the results, even at a substantially reduced accuracy. For the ideal circuit of Fig. 2, one has

$$\frac{P_5 - P_6}{P_4} = \sqrt{2}\ \mathrm{Re}\ (\Gamma_l) \tag{5}$$

while

$$\frac{P_5 + P_6 - P_3 - P_4}{2P_4} = \sqrt{2}\ \mathrm{Im}\ (\Gamma_l). \tag{6}$$

Thus if $P_3 \cdots P_6$ are available in analogue form, and assuming the system is leveled so that $P_4$ is constant, one can obtain signals proportional to the real and imaginary parts of $\Gamma_l$ by a simple addition.

## IV. Summary

As compared with earlier six-port circuits, the one in Fig. 2, together with its variants, requires fewer components and is inherently lossless. This, in turn, reduces the power input requirements. Moreover, the "$q$" values, which it provides, more nearly approach the ideal. Although only a limited amount of practical experience has been realized with this circuit, to date, the preliminary results have been encouraging. In particular, this circuit has been implemented in WR-15 waveguide, and is described in an accompanying paper [3].

## V. References

[1] G F. Engen, "The six-port reflectometer: An alternative network analyzer," *IEEE Trans. Microwave Theory Tech.*, this issue, pp. 1075–1080.
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# A Semiautomated Six Port for Measuring Millimeter-Wave Power and Complex Reflection Coefficient

MANLY P. WEIDMAN

***Abstract*—A six-port system has been developed and applied to the precision measurement of power and complex reflection coefficient in WR-15 (50–75 GHz) waveguide. The system is automated except for frequency and switching control for the signal source. This system provides a time-saving factor of at least five as compared to a tuned reflectometer with little, if any, degradation in accuracy.**

## Introduction

PRESENT state-of-the-art systems for measuring power or reflection coefficients at NBS in the WR-15 waveguide size consist of tuned three- or four-port reflectometers. The tuned system does not lend itself to broadband, stepped frequency measurements. The six-port system described in this paper does lend itself very well to stepped frequency measurements and was chosen for this reason. The system has only been evaluated at six frequencies in the range 55 to 65 GHz, but the extension of its use to broadband measurements should be straightforward. As it presently exists, it still provides a time-saving factor of at least 5 to 1 over tuned reflectometers. The measurement uncertainties of the six-port system are equivalent to those obtained using a tuned reflectometer with the possible exception of a slight reduction in the accuracy of reflection coefficient magnitude for small reflection terminations ($|\Gamma| < 0.01$).

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## System Design

The six-port system illustrated in Fig. 1 was chosen as the basis for the measurement system. The basic theory for this configuration has been described by Engen [1]. All detectors,

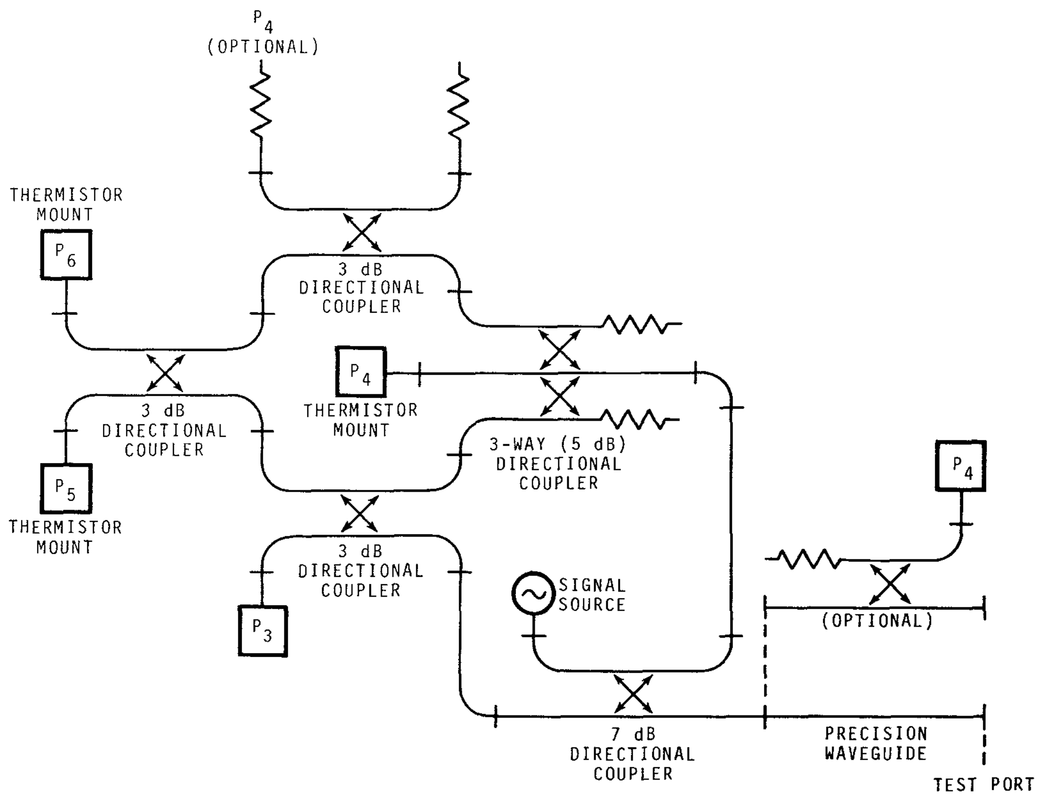


Fig. 1. Six-port waveguide system.

shown as $P_3$ to $P_6$, are thermistor mounts. This configuration makes maximum use of the power available from the signal source, i.e., there is a minimum of power absorbed by terminations other than the four thermistor mounts, and the coupling values shown equalize the available power among the thermistors on arms 3 to 6, and also at the test port. Terminating type power meters or passive terminations are connected to the test port, and the six-port system, when calibrated, is used to measure such parameters as effective efficiency and reflection coefficient for these devices.

The system in Fig. 1 differs slightly from that described in the reference, and the reason for this change is that there are no commercially available two-way, equal-phase power splitters available in the WR-15 waveguide size. In lieu of a two-way power splitter, the three-way directional coupler, shown in Fig. 1, was used. The three-way coupler provides another port at which the $P_4$ detector can be attached, and is the configuration used for the evaluation given in this paper. There did not appear to be any major difference in system performance for any of the $P_4$ detector locations.

Also shown in Fig. 1 is another optional $P_4$ detector location on the side arm of a conventional three-port directional coupler connected at the test port. With the $P_4$ detector in this position, the thermistor–coupler combination can be measured as a feed-through type power meter, and then removed from the six-port system and used independently. With this optional configuration, the six port, including the thermistor-coupler combination, measures the equivalent generator reflection coefficient and the available power at the output port of the thermistor–coupler combination.

Detector $P_4$, in any of the three locations in Fig. 1, couples primarily to the incident wave at the test port. Thus, it is used as the detector for leveling the signal source. Thermistor mounts $P_3$, $P_5$, and $P_6$ couple to both incident and reflected waves at the test port. Coupling is closer to the incident wave (approximately 3 dB) than to the reflected wave for reasons of simplification in the solution of six-port equations.

Engen [1] has shown that the detector responses are given by

$$P_3 = |A|^2 |b|^2 |\Gamma_l - q_3|^2 \tag{1}$$

$$P_4 = |D|^2 |b|^2 |1 - \Gamma_l \Gamma_g|^2 \tag{2}$$

$$P_5 = |E|^2 |b|^2 |\Gamma_l - q_5|^2$$

$$P_6 = |G|^2 |b|^2 |\Gamma_l - q_6|^2$$

where $|b|^2$ and $\Gamma_l$ are the incident power and reflection coefficient at the test port. $A$, $D$, $E$, and $G$ are constants of a particular configuration, and $\Gamma_g$ is the equivalent generator reflection coefficient [2]. The parameters $q_3$, $q_5$, and $q_6$ are complex, with magnitude and phase determined by the three 3-dB couplers and the 3-way coupler in Fig. 1. Ideally, for this system, 1) $|\Gamma_g| = 0$, 2) $|q_3| = |q_5| = |q_6|$, 3) the difference in phase between $q_5$ and $q_6$ would be 90°, and 4) the phase difference between $q_3$ and $q_5$ would be 135°. In the actual measurement system, $|\Gamma_g|$ was greater than 0.1; $|q_3|$, $|q_5|$, and $|q_6|$ differed by over 100 percent; and the phase difference between $q_3$ and $q_5$ was as much as 30° from the ideal. This did not significantly degrade the system performance.

The automatic data acquisition and processing portion of the system is shown in Fig. 2, and consists of NBS Type II

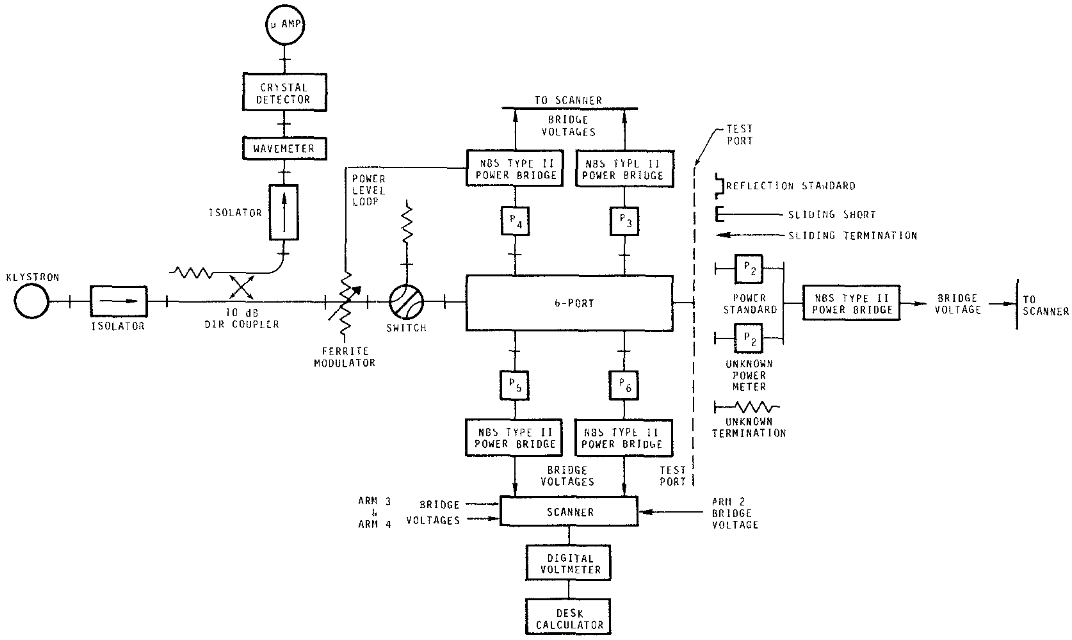


Fig. 2. Block diagram of complete six-port system.

power-measuring bridges for all thermistor mounts, a scanner for selecting bridge voltages, a digital voltmeter, and the calculator for reading the bridge voltage information, calculating substituted dc powers and system constants.

## Software Design

The software for this system was designed to direct an operator through the calibration and measurement procedure, collect all necessary data, calculate system constants, and perform various error correcting functions. The program is in BASIC and, with all constants defined for one frequency, utilizes almost 8000 words of calculator memory.

The details of the software design are not included in this paper, but a brief description of the calibration procedure is given here. The calibration procedure consists of collecting power meter data for a minimum of five sliding short positions, three sliding load positions, one reflection coefficient standard, and one terminating power standard, all connected to the test port. After the calibration process is completed, measurements can be made on unknown power meters or reflections connected to the test port.

## System Evaluation

An evaluation was performed to determine both random and systematic uncertainties in measuring power and reflection coefficient. It was found that there was no significant degradation in measurements compared with a tuned reflectometer.

Using the data taken to date, it is estimated that $\pm 1.5$ percent power measurements can be made with this system. The standard deviation for measuring the effective efficiency of an unknown thermistor mount is estimated to be $\pm 0.20$ percent. The estimate of standard deviation for reflection coefficient magnitude measurements is $\pm 0.002$ and $\pm 0.5$ to $\pm 3.0$ degrees in phase. The systematic uncertainty for reflection coefficient magnitude or phase measurements made on this system were limited by the reflection standard and precision section used in system calibration rather than the technique. It was found that systematic uncertainties of $\pm 0.005$ are not unreasonable for the system in its present form.

The estimates of standard deviation are based on a series of complete system calibrations. No frequency control was applied to the signal generator other than using a $\pm 0.1$ percent wavemeter to initially set the frequency. Significant improvements in uncertainties for both power and reflection coefficient measurements are to be expected with more system refinements.

## Conclusions and Summary

The six-port system works as well as an established, state-of-the-art technique for measuring power and reflection coefficient in the millimeter wave region. Its advantages are elimination of the need for complex tuning procedure and frequency conversion, and the use of relatively inexpensive, commercially available hardware.

## Acknowledgment

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## References

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