An Automated Six-Port for 2–18-GHz Power and Complex Reflection Coefficient Measurements

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Abstract—an automated six-port power measurement system is described which provides measurements of complex reflection coefficient of coaxial devices, and calibration in efficiency of bolometer mounts, from 2 to 18 GHz. System calibration, based on the use of sliding terminations, is discussed, and measurements of NBS-calibrated standards are summarized.

INTRODUCTION

THE CONCEPT of broad-band RF power and reflection coefficient measurement has been documented by several researchers. Engen [1]–[3], Hoer [4], and Woods [5] have established a thorough theoretical base for the six-port measurement technique, and Lance and Seal [6] have presented a physical interpretation of the phasor signals within the six-port. Also, several systems based on the six-port concept have been described [7], [8] which indicate that such systems can be built with broad-band, commercially available components, and that accurate complex microwave parameters can be obtained using only amplitude information. This paper describes a six-port system providing power calibration of one-port devices from 2 to 18 GHz.

THE SIX-PORT JUNCTION

The configuration of the six-port itself is shown in Fig. 1. Here, the "Q" and "D" components represent stripline quadrature hybrids and power dividers, respectively. Assuming ideal components and equal path lengths at the outputs of $D_1$ and at the inputs of $Q_3$, the wave amplitudes and relative phase relationships at the detector ports are as shown. We have defined the incident and emergent wave amplitudes at the test port as $a_2$ and $b_2$, respectively. In general, the power at port 3 can be written as

$$P_3 = |Aa_2 + Bb_2|^2.$$  (1)
Similarly, the powers at ports 4, 5, and 6 can also be expressed in terms of $a_2$ and $b_2$:

$$P_4 = |Ca_2 + Db_2|^2$$
$$P_5 = |Ea_2 + Fb_2|^2$$
$$P_6 = |Ga_2 + Hb_2|^2.$$  

The quantities $A, \cdots, H$ are constants of the six-port. In the configuration of Fig. 1, thermistor mount detectors are located at ports $P_3, \cdots, P_6$, with $P_4$ ideally proportional to the emergent wave $b_2$ at the test port (i.e., $C = 0$). Equations (1)–(4) can be written in terms of the reflection coefficient $\Gamma_f$ at the measurement plane [2], and the following equations are obtained:

$$|\Gamma_f - q_3|^2 = \frac{\left|D/P_3\right|^2}{\left|\frac{P_3}{P_4}\right|}$$
$$|\Gamma_f - q_5|^2 = \frac{\left|D/P_5\right|^2}{\left|\frac{P_5}{P_4}\right|}$$
$$|\Gamma_f - q_6|^2 = \frac{\left|D/P_6\right|^2}{\left|\frac{P_6}{P_4}\right|}$$

where $q_3 = -B/A$, $q_5 = -F/E$, $q_6 = -H/G$, and $\Gamma_f = a_2/b_2$. These are the equations of three circles in the complex $\Gamma_f$ plane, with centers at distances of $|q_3|$, $|q_5|$, and $|q_6|$ from the origin, and with radii proportional to the square roots of the ratios $P_3/P_4$, $P_5/P_4$, and $P_6/P_4$, respectively. Ideally, these three circles intersect in a single point, corresponding to $\Gamma_f$. Also, $|q_3| = \sqrt{2}$, $|q_5| = |q_6| = 2$, and the relative spacing of the $q$-points would be $135^\circ$-$90^\circ$-$135^\circ$. Actually, in making measurements with the automated system, the $q$-point magnitudes varied with frequency by more than 50 percent, and their relative spacing varied at least $80^\circ$, without any serious loss of accuracy or precision. At 8 GHz and a nominal 3.0 mW at $P_4$ and a sliding short at the test port, $P_3$, $P_5$, and $P_6$ typically vary between 0.3 and 9.5 mW, or approximately 15 dB.

**Hardware**

The system configuration is shown in Fig. 2. All instruments are under the control of an HP 9825 desk-top computer via the IEEE-488 interface bus. An iterative process is used to set the signal source to the desired frequency. The source is phase-locked and externally leveled, using an RF sample provided by a 10-dB directional coupler located within the six-port housing. Amplitude leveling and control are achieved using a bolometer mount/NBS Type-II power bridge combination, and a programmable D/A converter. An RF switch following the sampling coupler provides RF ON/OFF, and allows the source to remain phase-locked throughout the measurement process.

Bolometer mount detectors are attached to the four measurement arms of the six-port. Each mount, in turn, is connected to an NBS Type-IV power bridge, and the resulting dc output is measured with a programmable digital voltmeter. The signals are routed through a network of low-thermal relays, and each is in series with a precision dc reference voltage generator (RVG) connected so that the DVM reads the difference between the bridge voltages and the RVG output. This is done so that the DVM remains on its lowest range, with a resolution of 1 μV. Additional Type-IV power meters are provided, for use when the various standard and unknown bolometer mounts are connected to the measurement port.

**Calibration and Software**

The calibration procedure for this system closely follows a technique described by Engen[9] which is based upon the use of sliding terminations. In practice, the system response is observed 1) with at least one known impedance (e.g., a flat
short), 2) at each of nine sliding short positions, and 3) at each of five sliding load positions. Although fewer positions may be used, this combination is an effective compromise between excessive calibration time due to measurements at many positions, and loss of resolution and accuracy due to too few data points.

A six-port to four-port reduction is then performed at each frequency by an HPL program which requires approximately 20 kbytes of memory. Computation time averages about 18 s/frequency. Calibration parameters are displayed on a CRT screen as they are calculated, allowing the operator to monitor the progress and integrity of the calibrations. These parameters are then stored on a floppy disk, for later recall as needed.

For power measurements, the system response is observed with an NBS-calibrated bolometer mount connected to the test port. Using the power equation approach, Hume et al. have shown that the following relation is valid [10]:

$$\eta_u = \eta_s P_{bu} M_{gs}$$

where $\eta_u$ and $\eta_s$ are effective efficiencies of the unknown and standard bolometer mounts, $P_{bu}$ and $P_{bs}$ are the substituted dc power in the unknown and standard mounts, and $M_{gu}$ and $M_{gs}$ are real mismatch factors describing the power transfer from the test port to the unknown and standard mounts, respectively. Here, $P_{bu}$ and $P_{bs}$ are measured directly, and normalized with respect to the power at $P_A$, which is proportional to the power available from the generator.

**PERFORMANCE**

Repeated measurements of NBS-calibrated type-N bolometer mounts and reflection standards suggest a short-term (<1-day) standard deviation of less than 0.1 percent in effective efficiency, less than 0.001 in reflection coefficient, and 0.1° to 1.5° in phase angle. Similar measurements made over a two-month period using the same calibration constants indicate a long-term (day-to-day) standard deviation of less than 0.25 percent in effective efficiency and less than 0.002 in reflective coefficient.

A typical measurement session usually begins with the measurement of one or more NBS check standards to monitor the system performance. The system is recalibrated at the appropriate frequencies when the check standard measurements indicate an error of more than ±0.5 percent in effective efficiency, or more than ±(0.010 + 0.001 $f$ (GHz)) in reflection coefficient. It is expected that these performance parameters can be improved upon considerably, by adding RF amplifiers and the appropriate filters, and with additional refinements in the software to reduce data acquisition times.

**SUMMARY**

A 2–18-GHz single six-port power and reflection coefficient measurement system is described which is calibrated by the use of sliding terminations, an impedance standard, and a standard bolometer mount (for power). The system, including the six-port junction itself, is composed of commercially available broad-band components, and all instruments are controlled by a desk-top computer. Analysis indicates a precision in measuring bolometer mount effective efficiencies and one-port reflection coefficients at least comparable to the total uncertainties assigned by the NBS.

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**REFERENCES**


