NBSIR 81-1650

WR-10
SINGLE SIX-PORT
MEASUREMENT SYSTEM

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U.S. DEPARTMENT OF COMMERCE, Malcolm Baldrige, Secretary
NATIONAL BUREAU OF STANDARDS, Ernest Ambler, Director

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A six-port system has been developed and used to measure effective efficiency (η_e) and complex reflection coefficient (Γ) in WR-10 (75-110 GHz) waveguide at frequencies in the 93.5-96.5 GHz range. The system is automated except for the control of the mm-wave klystron source. This report includes a brief description and background of the measurement system and a preliminary analysis of uncertainties.

1.0 Introduction

The design of the WR-10 single six-port system is based on a previous system in WR-15 waveguide [1] and the work of C. Hoer and G. Engen [2, 3]. The WR-10 system utilizes a commercially built, integrated, dielectric waveguide circuit as part of the six-port network. In the WR-15 system, the six-port network was built up from discrete commercial, metallic waveguide components (directional couplers). The integrated dielectric waveguide circuit appears to give better performance, although over a limited bandwidth--approximately 10 percent. The remainder of the system (source type, instrumentation, and software) is the same as the WR-15 system. Thermistor mounts are used as detectors along with NBS Type IV power meters. Sliding and fixed terminations together with calibrated (microcalorimeter) thermistor mounts are used to calibrate the six-port for measurement of reflection coefficient, Γ, and effective efficiency, η_e, of thermistor mounts. Figure 1 is a block diagram of the measurement system, and Figure 2 is a schematic of the six-port network.

2.0 Measurement Results and Error Analysis

2.1 Random Errors

A series of nine separate, complete calibrations were performed on the system at 94.5 GHz with one of the working standard thermistor mounts (measured in microcalorimeter) used as a standard for effective efficiency and a quarter-wave short as the standard for reflection coefficient. A second working standard thermistor mount, which had also been measured in the microcalorimeter, was treated as an unknown.

The unknown was reconnected and measured three times on each of nine occasions over a period of two weeks. Estimates of the between-occasion and within occasion standard deviations were obtained from a one way random effects model. The estimated standard deviations for η_e are 0.00124 within occasions and 0.00192 between occasions. The respective values for Γ magnitude are 0.00105 and 0.00296. The estimated standard deviation of a single measurement is obtained by adding the component standard deviations in quadrature. These estimates are 0.00229 with approximately 12 degrees of freedom for η_e and 0.00314 with approximately nine degrees of freedom for Γ magnitude. Using Student's t value with a conservative eight degrees of freedom at the 99% confidence level times the single measurement standard deviations yields the reported limits to random error. These limits are 0.00768 for η_e and 0.01053 for Γ magnitude.

The random uncertainties are reported in Table I along with the systematic uncertainties.

The estimated offset between the mean value of η_e as measured on the six-port for the thermistor mount used as the unknown and the mean value from the microcalorimeter is 0.002%. The estimated systematic uncertainty for the possible offset based on 2 times the standard error of the difference between the two mean values is 0.25%. (Therefore, the estimated offset is not statistically significant).

2.2 Systematic Errors

For η_e measurements using the six-port system, the systematic error results from the error in the microcalorimeter measurement of η_e for the two working standards and a mismatch loss uncertainty resulting from a systematic error in Γ. The ±1.2% error from the microcalorimeter in Table I includes both random and systematic components (see WR-10 microcalorimeter paper). The two components have been added algebraically here and are treated as a systematic uncertainty for the six-port system. (The conservative approach has been used since the random errors are based on limited sample size).

Although no definite offset showed up in the mean of the nine measurement occasions for η_e on the six-port, compared to measurements on the microcalorimeter, there could be an uncertainty, for other Γ's, caused by the fact that there is a systematic error in the measurement of Γ. This error in Γ reflects itself through the measurement of mismatch loss ($M_{g\ell}$) in determining η_e. The mismatch loss in terms of Γ is

$$M_{g\ell} = \frac{\left(1-|\Gamma_g|^2\right)\left(1-|\Gamma_\ell|^2\right)}{|1-\Gamma_g\Gamma_\ell|^2}, \qquad (1)$$

where g and ℓ denote generator and load respectively.

The effective efficiency for a device under test is calculated using the equation

$$\eta_{eu} = \frac{M_{gs}}{M_{gu}} \cdot K = \frac{(1-|\Gamma_g|^2)\ (1-|\Gamma_s|^2/|1-\Gamma_g\Gamma_s|^2}{(1-|\Gamma_g|^2)\ (1-|\Gamma_u|^2)/|1-\Gamma_g\Gamma_u|^2} \cdot K \qquad (2)$$

In eq (2), η_{eu} is the effective efficiency of the device under test, M_{gu} and M_{gs} are the respective mismatch losses for device under test and standard, and K is a function of the substituted dc powers and the value of η_e for the standard.

Using the values from Table I for Γ magnitude systematic error, it can be shown that for typical Γ_g and Γ_ℓ, this results in a ±0.16 percent uncertainty in $M_{g\ell}$ and also in η_e, since η_e is directly affected by $M_{g\ell}$. This uncertainty was calculated using worst case phase conditions for Γ_g and Γ_ℓ and with $|\Gamma_g| = 0.07$ and $|\Gamma_\ell| = 0.25$. The systematic error in η_e for a device under test caused by a systematic error in $M_{g\ell}$ shows up in the ratio of $M_{g\ell}$'s for standard and device under test. The numerators of the two $M_{g\ell}$'s ratios in eq (2) (ℓ is u or s) will go in the same direction (high or low), whereas the denominators can go either direction. To be on the safe side and include all possibilities, the value for estimated systematic error in $M_{g\ell}$ in Table I is double the ±0.16 percent value for one determination of $M_{g\ell}$.

The primary source of systematic error in the measurement of reflection coefficient (Γ) is caused by the fact that the section of waveguide used for the sliding termination does not have perfect WR-10 dimensions. Using the dimensional tolerances for the mandrel on which this precision waveguide section was electroformed and eq (14) from [4],

$$\Delta\Gamma = 2\left[\left(\frac{\lambda_g}{\lambda_c}\right)^2 \frac{|\Delta a|}{4a} + \frac{\sigma}{(1+\sigma)^2}\,\frac{|\Delta_b|}{b}\right] \tag{3}$$

where $\Delta_a = \Delta_b = \pm 2.5\ \mu\text{m}$, $a = 2.54$ mm, $b = 1.27$ mm, $\sigma = \text{VSWR} = \frac{1+\Gamma}{1-\Gamma}$.

In this case, $\Delta\Gamma$ is approximately ±0.0013 for $|\Gamma|$ near zero. The uncertainty decreases for higher reflection coefficients. Another source of uncertainty is the fact that the quarter-wave short is not perfect. If $|\Gamma|$ for the quarter-wave short is assumed to be 0.998 ±0.002 (conservative assumption), the uncertainty in $|\Gamma|$ would be ±0.002 times $|\Gamma|$. No claim for Γ phase (systematic uncertainty) is made here, but dimensional considerations again apply. Phase of Γ is not normally used in single six-port applications.

Conclusion

The WR-10 single six-port system appears to be in a satisfactory operating state, and ongoing measurements with both working standards and two check standards will be used to obtain more long-term data for the system, for purposes of establishing statistical control.

References

[1] Weidman, M. P., A Semiautomated Six-Port for Measuring Power and Complex Reflection Coefficient, IEEE Trans. Microwave Theory Tech., vol. MTT-25, No. 12, Dec. 1977.

[2] Engen, G. F., An Improved Circuit for Implementing the Six-port Technique of Microwave Measurements, ibid.

[3] Engen, G. F., Calibrating the Six-Port Reflectometer by Means of Sliding Terminations, IEEE Trans. Microwave Theory Tech., vol. MTT-26, No. 12, Dec. 1978.

[4] Yates, B. C. and Larson, W., Millimeter Attenuation and Reflection Coefficient Measurement System, NBS Tech Note 619, July 1972.

TABLE 1

Measurement Uncertainties for Single Six-Port

Uncertainty	η_e	$\|\Gamma\|$
Systematic:		
Microcalorimeter	±1.20%	
$M_{g\ell}$ (From Γ)	±0.32%	
Possible offset between mean of calorimeter and mean of 6-port	±0.25%	
Precision Section		±0.0013
λ/4 Short		$\pm 0.0020 \times \|\Gamma\|$
Total Systematic	±1.71%	$\pm(0.0013 + 0.0020 \times \|\Gamma\|)$
Random:		
For η_e $\dfrac{(t_{.005,8}) \times s}{\bar{\eta}_e} \times 100$		
and for $\|\Gamma\|$ $(t_{.005,8}) \times s$		
Six-port	±0.86%	±0.0105
Total Random and Systematic	±2.63%	$\pm(0.0118 + 0.0020 \times \|\Gamma\|)$

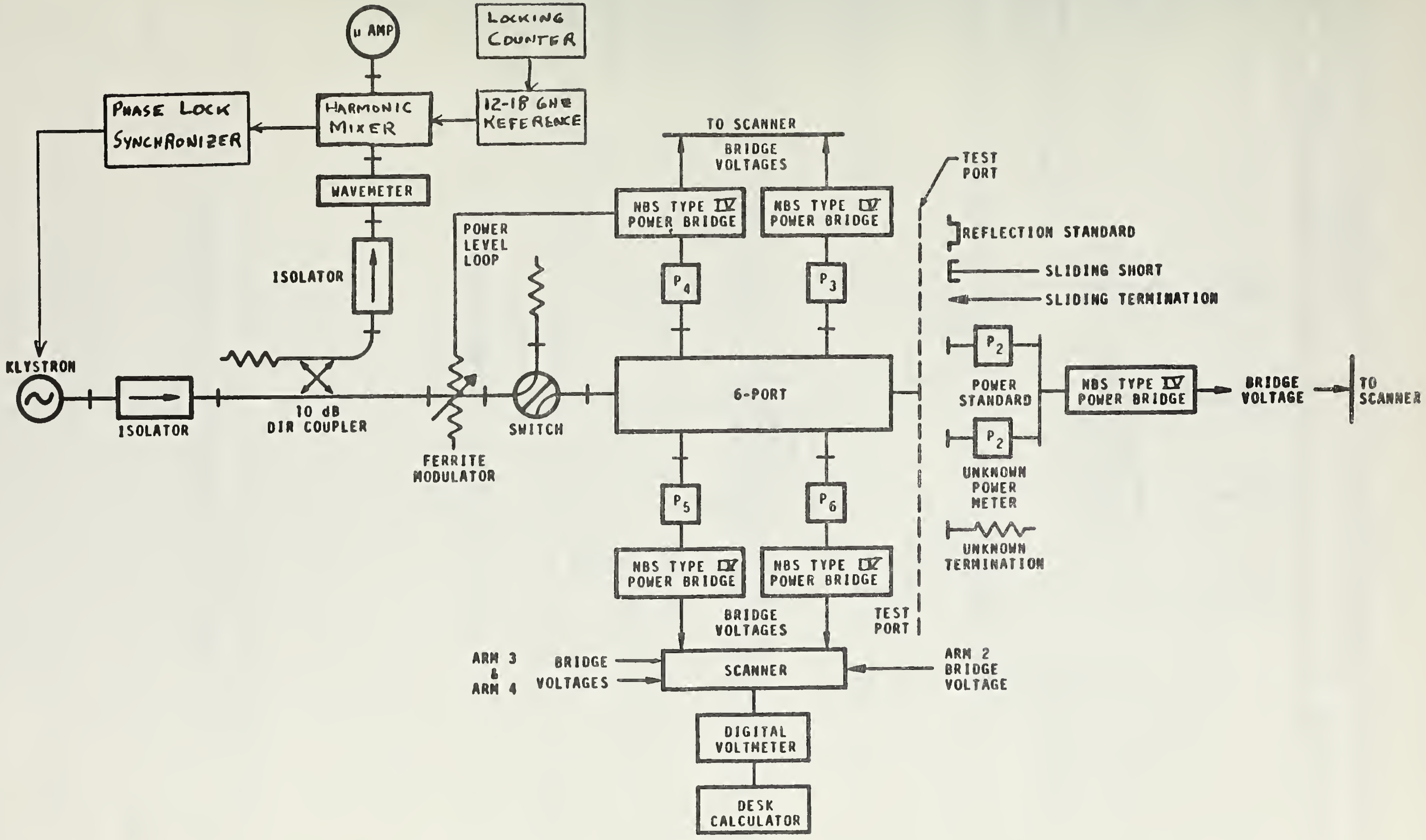

Figure 1. Block diagram of single six-port system.

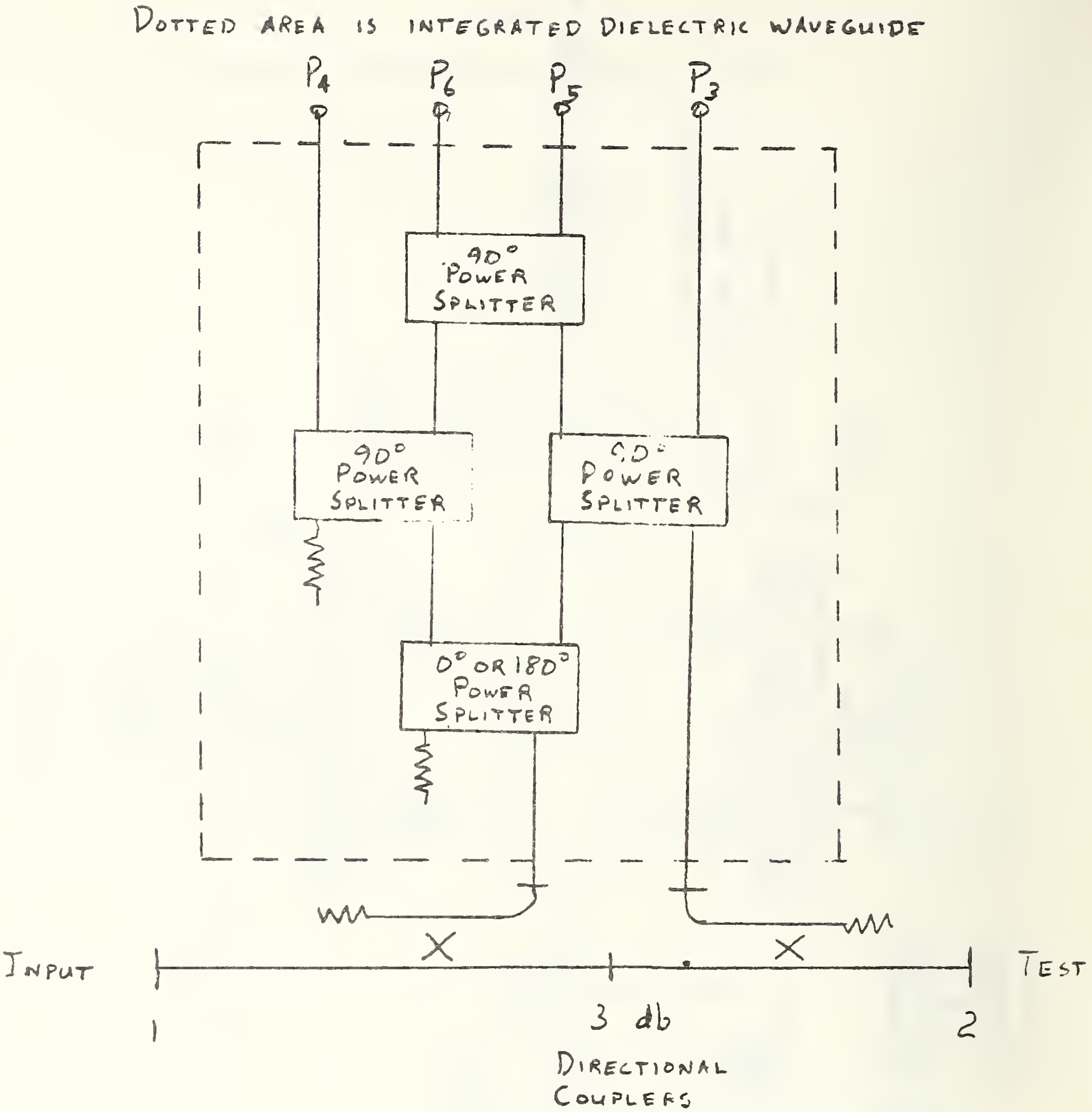

Figure 2. Schematic of six-port network.

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☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)*

A six-port system has been developed and used to measure effective efficiency (η_e) and complex reflection coefficient (Γ) in WR-10 (75-110 GHz) waveguide at frequencies in the 93.5-96.5 GHz range. The system is automated except for the control of the mm-wave klystron source. This report includes a brief description and background of the measurement system and a preliminary analysis of uncertainties.

12. KEY WORDS *(Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)*

mm wave measurements; reflection coefficient; six-port measurement system; thermistor mount calibration.

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