UNITED STATES
DEPARTMENT OF
COMMERCE
PUBLICATION

NBS TECHNICAL NOTE 647

MICROWAVE ATTENUATION MEASUREMENT SYSTEM (SERIES SUBSTITUTION)

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MICROWAVE ATTENUATION MEASUREMENT SYSTEM (SERIES SUBSTITUTION)

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t. Technical note no. 647

U.S. DEPARTMENT OF COMMERCE, Frederick B. Dent, Secretary

NATIONAL BUREAU OF STANDARDS, Richard W. Roberts, Director

Issued February 1974

National Bureau of Standards Technical Note 647

Nat. Bur. Stand. (U. S.), Tech. Note 647, 28 pages (February 1974)
CODEN: NBTNAE

For sale by the Superintendent of Documents, U.S. Government Printing Office, Washington, D. C. 20402
(Order by SD Catalog No. C13.46:647) $0.35

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MICROWAVE ATTENUATION MEASUREMENT SYSTEM*

(SERIES SUBSTITUTION)

A dual detection microwave bridge circuit has been incorporated in a series substitution system for the measurement of microwave attenuation devices. The use of an optical rotary-vane attenuator in the system yields practical resolution and stability of 0.00005 dB from zero to 30 dB. The dual detection system has several favorable features: (1) it employs a single microwave source which reduces cost, (2) measurements are obtained without power stabilization of the microwave signal source, and (3) this waveguide configuration enables measurements of attenuation devices at any length with minimum of effort and movement of waveguide components.

The system configuration is convenient for both attenuation difference, and insertion loss measurements from zero to 70 dB over the WR90 waveguide band of 8.2 to 12.4 GHz.

Key words: Attenuation; measurement; rotary-vane attenuator; series substitution.

1. Introduction

A substantial amount of work has been done to develop various techniques for measuring attenuation in the microwave region. Each method has definite properties that enhance its choice for the measurement of a given range of attenuation or a specific interlaboratory standard. The i-f substitution [1] system has been developed to a high degree of

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*Presented at the Technical Applications Sessions of the IEEE Interlaboratory Convention, New York, March 22, 1971. This work was completed at the National Bureau of Standards, Boulder, Colorado, under the sponsorship of the Calibration Coordination Group of the Department of Defense.

excellence for the measurement of attenuation over a wide dynamic range. A major disadvantage of this system is the requirement of two microwave signal sources. The af system requires but one microwave signal source. Both of these advantages are combined in the attenuation systems known as the modified dc substitution [2] and the modulated sub-carrier [3] techniques.

A microwave series substitution attenuation system has been developed in the Electromagnetics Division of the National Bureau of Standards at Boulder, Colorado. Two advantages of the microwave series substitution technique of attenuation measurement are: (1) knowledge of the response law of the detectors is not required because the signal power in the detectors is constant for each null in the measurement process and (2) the resolution of the system remains constant through the entire range of measurement. The systems' resolution of measurement is several orders of magnitude greater than is necessary for calibrating commercially available attenuators.

This calibration system utilizes the NBS designed precision rotary vane attenuator as the reference standard [4]. The stability and resolution of this system is consistent with the 0.00005 dB resolution of the reference standard at 1 dB and exceeds that of the reference standard at values above 1 dB. The system uses a single microwave signal source and does not require a high degree of amplitude stability. The range of attenuation measurement for fixed or variable devices is 0 to 70 dB for this system in the frequency band of 8.2 to 12.4 GHz. Sources of error in the microwave attenuation measurement system and devices under test for attenuation difference and insertion loss measurements are discussed.

2. The Measurement System

This microwave attenuation measurement system employs two waveguide channels in a bridge network. Each channel has a waveguide detector and a low frequency (1 kHz arm). The standard attenuator and the attenuator under test are inserted in the same waveguide channel, and a reference attenuator in the other waveguide channel. A block diagram of the microwave attenuation calibration system is shown in figure 1. Fixed or variable devices may be used as the standard or reference attenuators.

With this microwave measurement system, a change in the attenuator under test is equal to the change required in the standard attenuator to rebalance the bridge. In order to make an attenuation measurement the following steps are required: (1) initially balance the bridge for a reference null, (2) make the desired change in the attenuator under test, and (3) rebalance the bridge with the standard attenuator.

The dual detection technique offers several unique features: (1) it employs a single source at the microwave frequency which reduces cost, (2) measurements are obtained without power stabilization of the microwave signal source, and (3) this waveguide configuration enables measurement of attenuation devices of any length with a minimum of effort and movement of waveguide components.

Figure 2 provides a more detailed block diagram of the system components that are used in NBS microwave attenuation measurement systems. The source of microwave power utilizes conventional isolation and frequency measuring auxiliary components, but the usual power stabilization required for precision measurement is not necessary. The main arm of directional coupler (A) connects to a level set attenuator and an isolator.

These components are followed by a pin-diode modulator that is driven by an audio signal source. The modulated signal feeds into directional coupler (B) which separates the signal to the two microwave arms of the bridges. The other arms of the bridge are the two dc biased detectors. The shorter microwave arm of the bridge contains the reference rotary-vane attenuator (for initial balance of the bridge), and an additional isolator before the waveguide detector.

The output port of the side arm of the directional coupler provides a 20 dB power loss to the reference attenuator. This reduction of the modulated signal enables the reference attenuator to be set at a lower value where higher resolution aids the resettability. In addition, the reduction of signal level prevents possible damage to the diode in the detector at small dB attenuation measurements.

In the longer arm of the bridge an isolator is followed by a tuner, a directional coupler, and a second tuner. These components make up the basic portion of a reflectometer as shown in the schematic diagram. The secondary arm of the directional coupler in the reflectometer [5] contains an isolator and a waveguide detector. The output of the detector is connected to a VSWR indicator for use in reducing the mismatch error [6] at the insertion point of the measurement system. One side of the insertion point for the standard attenuator is connected to the reflectometer by a precision waveguide section. The other side is connected to another precision section of waveguide and other waveguide components which isolate the standard attenuator from the attenuator under calibration. In order to obtain the isolation and matching desired, this fabricated section has a stub tuner and a precision section of waveguide at each end. The second port of the above fabricated waveguide section is used as one side of the matched insertion point for the attenuator under test. On the other side of the attenuator under test is located another precision section, a tuner, isolator, and another detector to complete the output of the longer arm of the microwave bridge.

The output signal of each detector in the microwave bridge couples to the input transformer of the null preamplifier. The output of the null preamplifier is coupled to a synchronous detection circuit [7] which provides the readout indication for the measurement of attenuation.

This attenuation measurement system can be constructed with commercially available waveguide components and instrumentation equipment. However, some of the instrumentation equipment used in this system was designed by NBS. The schematic drawings of two such components, the modulator driver and the null preamplifier, are shown in figures 3 and 4,* respectively.

3. The Standard Attenuator

The rotary-vane attenuator is a device which when fabricated with high precision can meet the criteria essential for an attenuation standard [8,9,10]. It operates at the same frequency as the device under test and has very low insertion loss at zero setting. This low insertion loss enables one to make a measurement of attenuation to 50 dB with less difficulty than is encountered with an i-f series substitution system employing a 30-MHz piston attenuator [1] as a standard.

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*Replacement of designated parts by others may affect system performance or the reproducibility of the results reported, and hence should be made with caution.

Three high resolution rotary-vane attenuators with optical readouts have been constructed at the NBS, and were tested over the range of zero to 50 dB. The tests were accomplished using three independent methods for making attenuation difference measurements [2,3,4]. The results of this testing indicate the three rotary-vane attenuators described have a realizable accuracy of 0.002 dB or better from zero to 20 dB. The estimated error from 20 to 50 dB is 0.002 to 0.025 dB, respectively.

Three errors related to the standard rotary-vane attenuator are incorrect vane alignment, resettability, and transmission errors. Incorrect vane alignment in the rotor causes a systematic error that is inherent in the rotary-vane attenuator. In addition, resettability of the attenuator dial by the operator must be included in the error analysis. In making an attenuation difference measurement with the (standard) rotary-vane attenuator the errors at the final setting may be written as

$$\varepsilon_{fo} + \varepsilon_{fI} = -40 \log_{10} \frac{\cos(\theta_f + \theta_{fo} + \theta_{fI})}{\cos \theta_f}$$

where θ_f is the vane-angle at the final setting to obtain the calculated attenuation, θ_{fo} is the vane-angle error made by the operator at the final setting, and θ_{fI} is the inherent vane-angle error [11,12].

The estimated rotor vane-angle alignment error (θ_{fI}) is about 18 seconds and the operator resettability angle error (θ_{fo}) is about 2 seconds. Figures 5a and 5b show the estimated limits of attenuation error due to alignment and resettability for dial settings of 10 to 70 dB. These errors are 0.03 and 0.003 dB, respectively, for the 50 dB dial setting at 9.0 GHz. Total attenuation error due to alignment and resettability at the initial or zero dial setting is estimated to be less than 0.01 microbels or 6.8 nanobels.

The transmission error or deviation from $\cos^2$ law caused by insufficient maximum attenuation in the center vane can be determined by measuring the maximum attenuation of the standard. The transmission error is given by [10]

$$\varepsilon_t = -20 \log(1 + e^{-\alpha \ell} \tan^2 \theta)$$

where $e^{-\alpha \ell}$ is determined from the maximum attenuation, and θ angular value of the center vane at given dial setting. The transmission or internal leakage error is estimated to be about 0.003 dB at the 50 dB dial setting for a maximum attenuation value of 120 dB. Refer to figure 5c for the estimated limits of the transmission error of the optical attenuator at dial setting from 10 to 70 dB.

Leakage of the standard rotary-vane attenuator used in this system was more than 120 dB [4] below the incident power due to liberal use of microwave absorbing material in the design of the housing and rotating joints. Leakage in the waveguide system can be kept to a minimum by using waveguide components that have flat, smooth surfaces and well mated flanged joints.

In order to reduce what appeared to be a ground loop problem, mica was placed between the flanges of each detector mount and adjacent isolator. The increase in space between the flanges of the detector introduced another problem of leakage. However, both problems were finally resolved by the use of mica at the flanges of the pin diode modulator.

4. Errors of the Measurement System

Prior to each calibration the waveguide insertion points of each system are tuned with a reflectometer to reduce possible mismatch errors. The series substitution system requires the tuning of two insertion points as one includes the working standard (refer to figure 2). The tunable reflectometer [5] included in the waveguide system provides a means for matching the insertion points. Thus, the mismatch error [6] causing uncertainty in the measurement of attenuation can be minimized by these tuning techniques. The mismatch error is estimated to be 0.002 dB for a system VSWR of 1.01 at the insertion point and an attenuator VSWR of 1.05.

To insure reliable matching of the open ports at the insertion points, the ports should be aligned prior to tuning so that excess movement or re-alignment is not necessary. In addition, the waveguide components should be mounted on laboratory benches [13] that hold the waveguide in a rigid position and provides the stability required for precise measurement.

The device under test may be connected in cascade with the standard attenuator at the same insertion point. Then, cascade mismatch errors [14,15] must be considered in addition to the mismatch errors at the insertion point.

Instability of the signal source can cause deviations that appear on the output recording chart as system drift. In figure 6 the stability of the NBS microwave measurement system is illustrated by the recording of the null detector output for a 12-minute run at a nominal value of 30 dB in each microwave arm. Full scale deviation on the strip chart corresponds to 0.002 dB and each line is 5 microbels (10^{-5} decibels). The maximum deviation is shown to be ± 10 microbels from the reference during the 12 minute run.

A preliminary estimate of the random uncertainties for the microwave attenuation measurement system is based on experimental data taken on five transfer standards. An average estimate of σ is 0.0010 dB for 125 determinations made during the interval of twelve months. The estimate of σ for the 75 determinations of insertion loss of the fixed transfer standards was 0.0013 dB and the estimate of σ for the 50 determinations of attenuation difference of the variable transfer standards was 0.0006 dB.

It has been demonstrated with this microwave attenuation system that amplitude changes of 10 dB at the signal source resulted in deviations of less than 0.001 dB at the null detection output.

5. Attenuation Measurements of Transfer Standards

Direct comparison was made in attenuation measurements between the series substitution method using the optical rotary-vane attenuator as a standard, and the i-f substitution method employing the 30-MHz piston as the standard. In order to obtain a comparison in both insertion loss and attenuation difference, fixed and variable waveguide attenuators were used as transfer standards.

To compare the insertion loss measurements, two NBS designed fixed attenuators [16] were measured for insertion loss in each system. Table I presents a comparison of the insertion measurements obtained by the microwave series substitution and the i-f substitution methods. The table shows that the difference between the insertion loss measurements are 0.004 dB for attenuator (A) and 0.003 dB for attenuator (B).

A commercially available rotary-vane attenuator was calibrated for attenuation difference between the values of 5 to 50 dB by each method at 9.0 GHz. The measured values of attenuation difference for the dial settings of 5, 10, 15, 20, 30, 40 and 50 dB are shown in table II. The deviation in the measured values of attenuation difference between the two methods varied from 0.002 to 0.013 dB for the dial setting of 5 to 50 dB.

In order to evaluate the microwave series substitution system at high attenuation, a fixed waveguide standard of a nominal value of 70 dB was measured. Previously this fixed waveguide standard was measured in the microwave attenuation calibration system by the i-f substitution method at three frequencies in the X-band region. Table III gives the insertion loss results obtained between the series substitution and the i-f substitution systems at 9.0, 9.8, and 11.2 GHz. The differences between the measured values of 70 dB do not exceed 0.07 dB.

6. Conclusion

The NBS microwave attenuation measurement system provides stability, resolution, accuracy, and ease of operation in the measurement of attenuation difference and insertion loss.

The null detection employed in this system has a unique feature in that the signal power at the detector is constant for each null in the measurement process. Thus, exact knowledge of the response law of the detector is not required, and resolution remains constant over the range of the measurement.

The NBS microwave attenuation measurement system permits qualified metrologists to make an intrinsic evaluation of the standard rotary-vane attenuator without additional attenuation standards. Details of this method of evaluating the rotary-vane attenuator will be presented in a forthcoming paper.

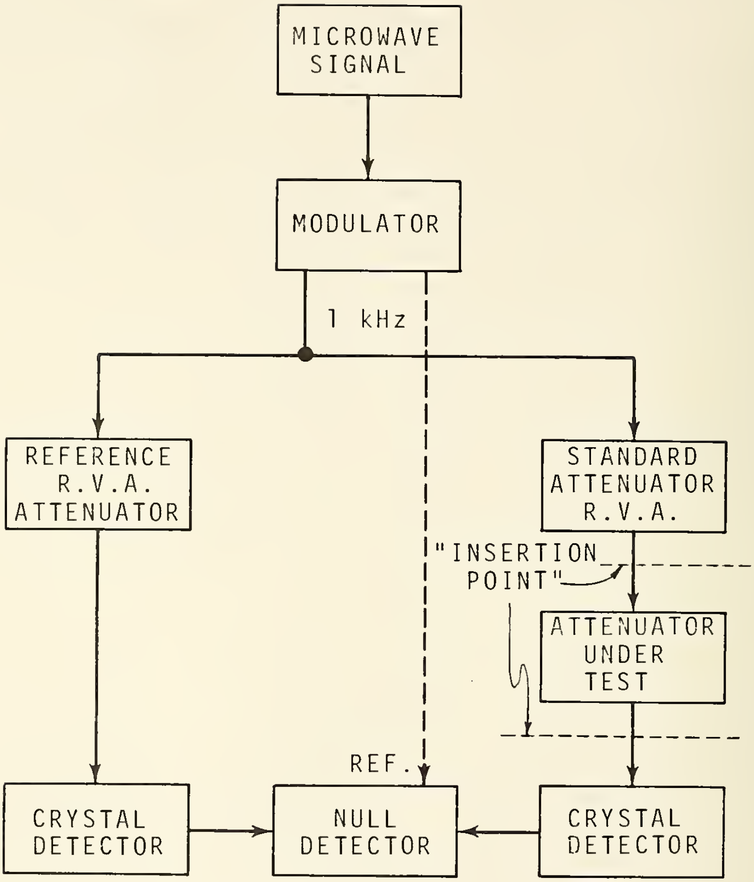

Figure 1. Block diagram of microwave attenuation calibration system.

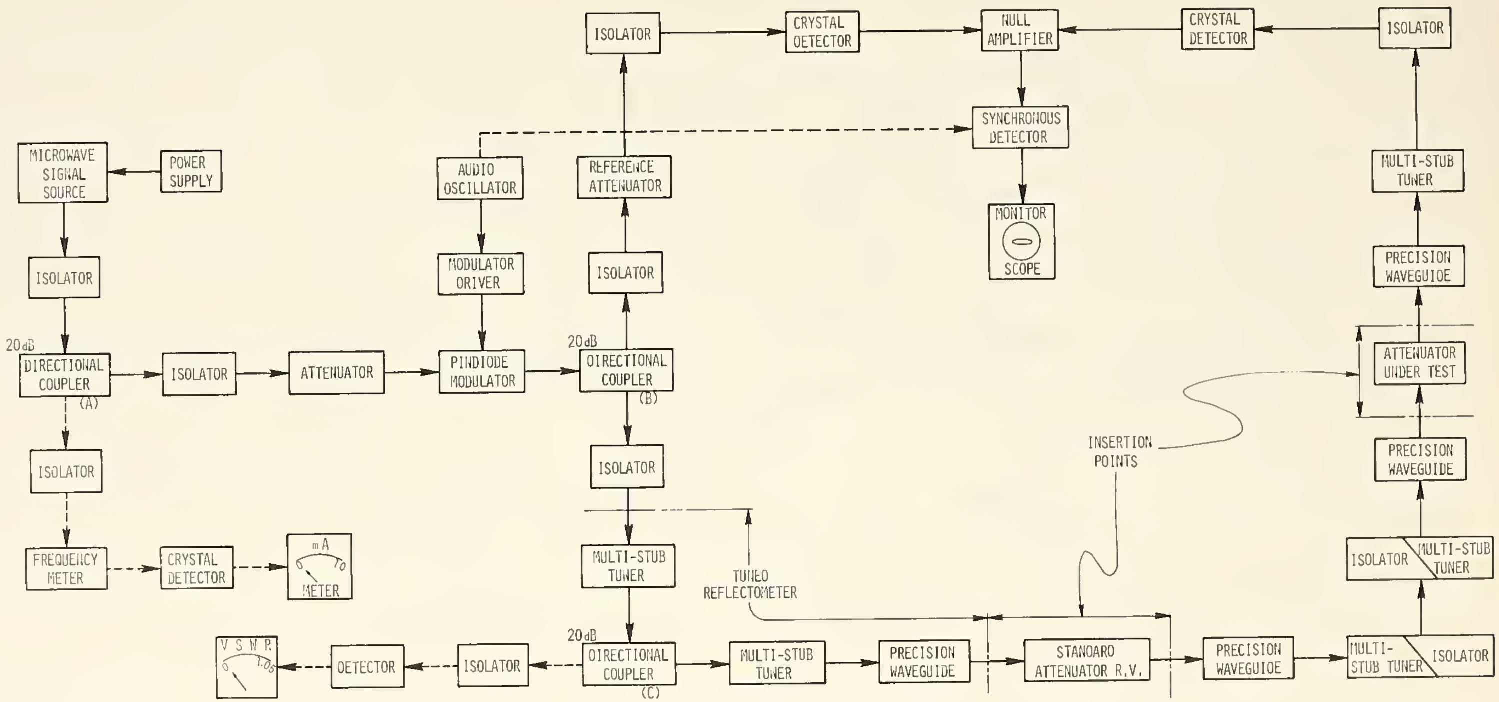

Figure 2. Detailed block diagram of microwave attenuation calibration system.

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Pin Modulator Driver

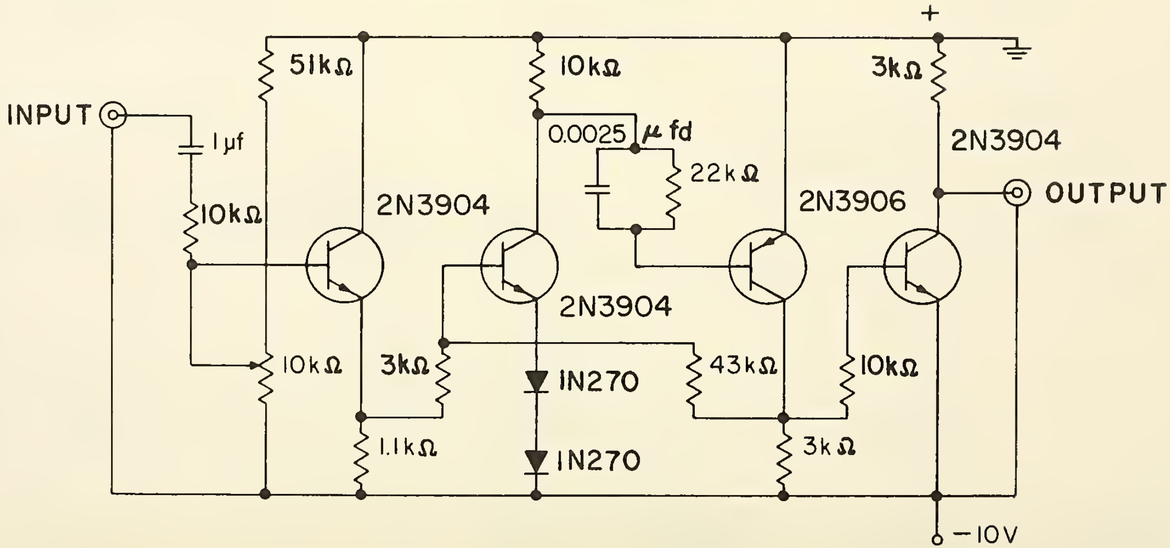

Figure 3. Schematic diagrams of pin diode modulator driver and power supply.

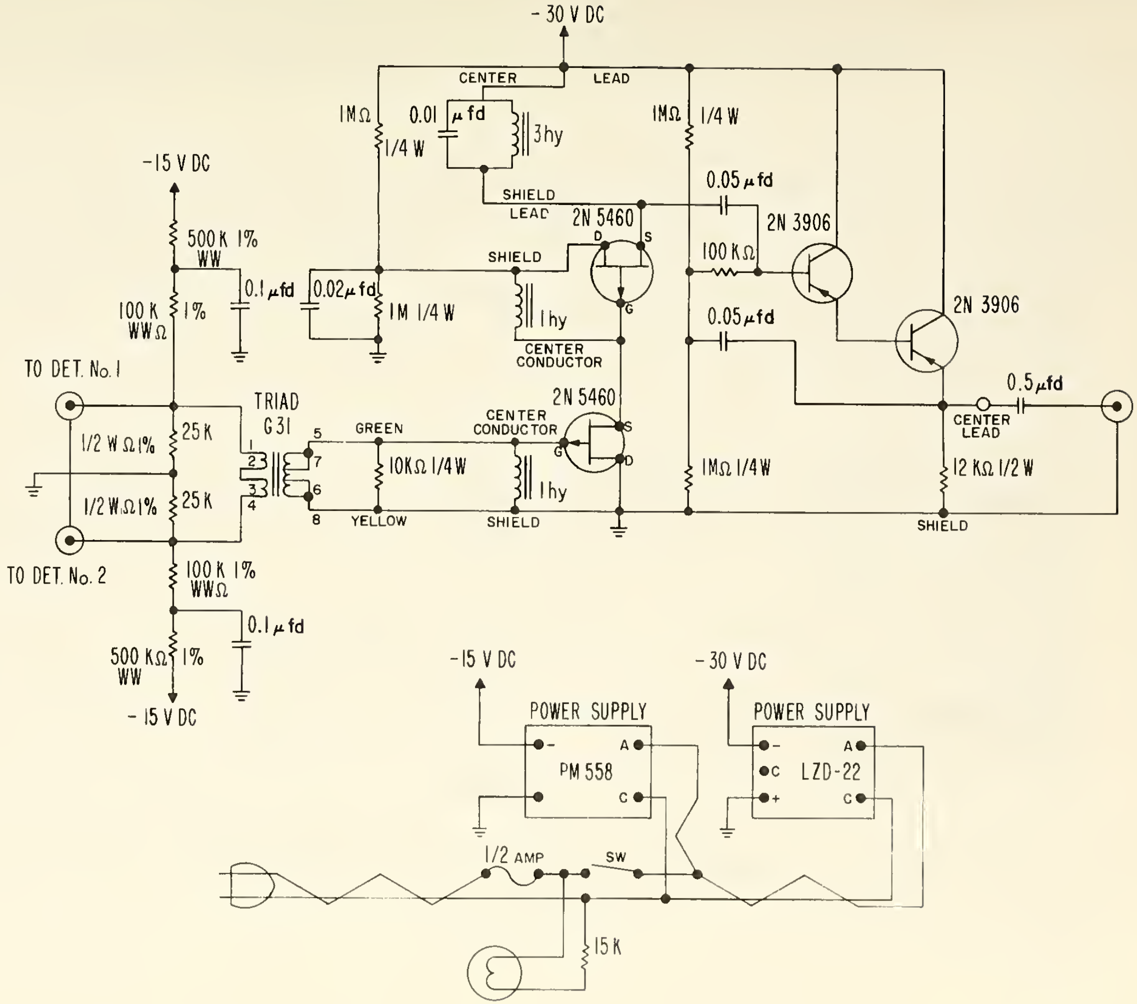

Figure 4. Schematic diagram of the circuit for the null preamplifier.

ESTIMATED LIMITS - SYSTEMATIC ERRORS

DECIBELS

	10	20	30	40	50	60	70
(A)	0.0026	0.005	0.0080	0.0170	0.0300	0.048	0.085
	ROTOR AND STATOR ALIGNMENT (18") 9.0 GHz						
(B)	0.0003	0.0005	0.0010	0.0016	0.0030	0.005	0.010
	RESETTABILITY (2")						
(C)	0.000018	0.000078	0.00026	0.00086	0.0027	0.0086	0.027
	INSUFFICIENT ATTENUATION OF CENTER VANE (120dB MAX)						

Figure 5. Estimated limits of systematic errors for the optical-rotary-vane attenuator.

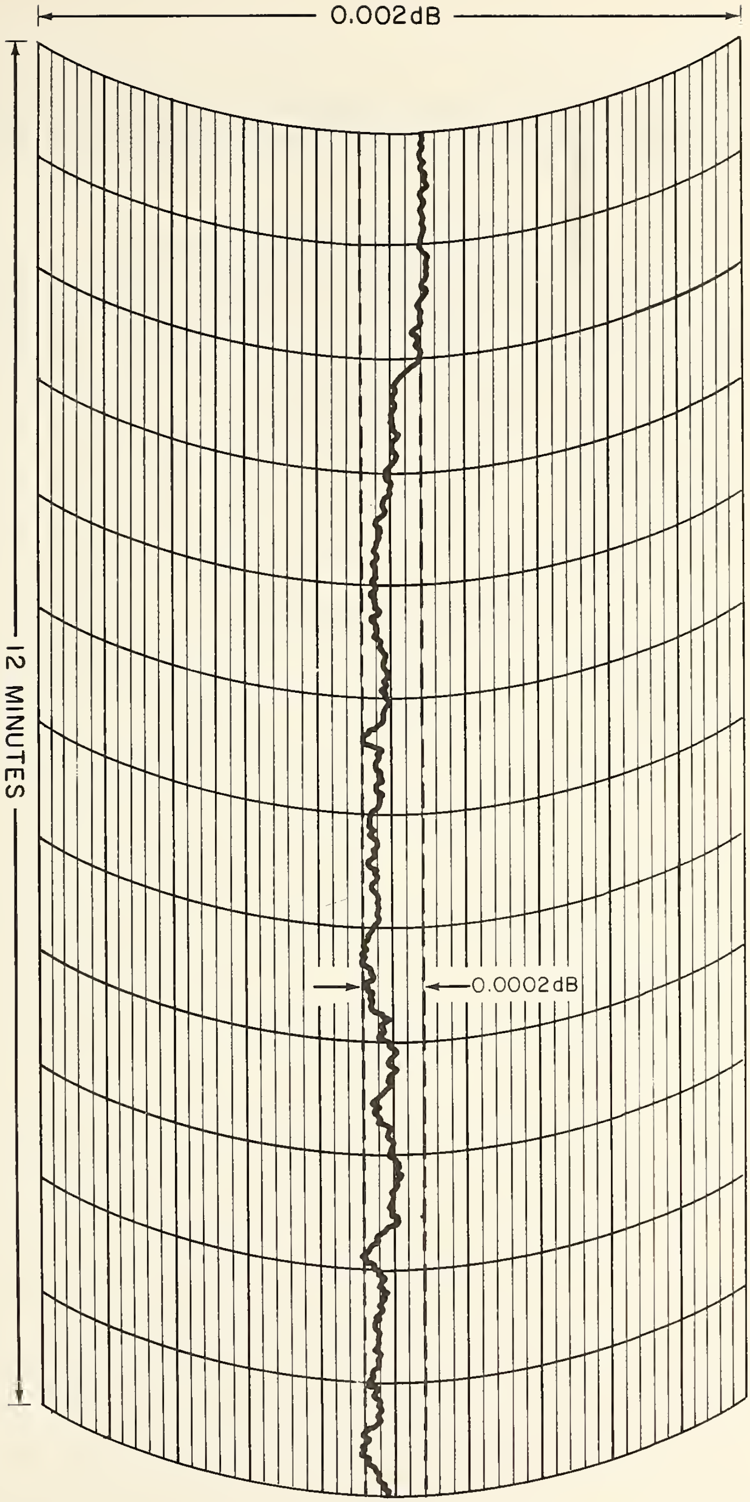

Figure 6. A recording showing the system stability at 30 dB measurement level.

Table I. Insertion loss measurements of fixed attenuators A and B by the i-f and series substitution methods at 9.0 GHz.

Nominal Value dB	Average Measured Insertion Loss dB	Estimated Limits of Systematic Error dB	Computed Standard Error dB
	Fixed Attenuator A		
3.000 (i-f sub.)	3.087	0.011	0.0024
3.000 (ser. sub.)	3.091	0.005	0.0012
	Fixed Attenuator B		
4.600 (i-f sub.)	4.620	0.011	0.0012
4.600 (ser. sub.)	4.622	0.005	0.0008

Table II. Attenuation difference measurements of a variable attenuator by the i-f and series substitution methods at 9.0 GHz.

Nominal Value dB	Average Measured Attenuation Difference dB	Estimated Limits of Systematic Error dB	Computed Standard Error dB
5 (i-f sub.)	5.005	0.011	0.0004
5 (ser. sub.)	5.001	0.005	0.0004
10 (i-f sub.)	9.997	0.011	0.0014
10 (ser. sub.)	9.992	0.005	0.0008
15 (i-f sub.)	15.013	0.014	0.0014
15 (ser. sub.)	15.015	0.005	0.0010
20 (i-f sub.)	20.014	0.014	0.0016
20 (ser. sub.)	20.012	0.010	0.0010
30 (i-f sub.)	30.024	0.018	0.0016
30 (ser. sub.)	30.030	0.012	0.0014
40 (i-f sub.)	39.991	0.024	0.0030
40 (ser. sub.)	39.996	0.020	0.0012
50 (i-f sub.)	49.981	0.043	0.0036
50 (ser. sub.)	49.994	0.038	0.0032

Table III. Insertion loss measurements of a fixed attenuator by the i-f and series substitution methods at 9.0, 9.8 and 11.2 GHz.

Frequency GHz	Insertion Loss in dB	
	i-f sub.	ser. sub.
9.0	68.39	68.32
9.8	70.24	70.29
11.2	71.77	71.79

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FORM NBS-114A (1-71)

U.S. DEPT. OF COMM. BIBLIOGRAPHIC DATA SHEET	1. PUBLICATION OR REPORT NO. NBS TN-647	2. Gov't Accession No.	3. Recipient's Accession No.
4. TITLE AND SUBTITLE Microwave Attenuation Measurement System (Series Substitution)			5. Publication Date February 1974
			6. Performing Organization Code
7. AUTHOR(S) Wilbur Larson and Eugene Campbell			8. Performing Organization
9. PERFORMING ORGANIZATION NAME AND ADDRESS NATIONAL BUREAU OF STANDARDS, Boulder Labs. DEPARTMENT OF COMMERCE Boulder, CO 80302			10. Project/Task/Work Unit No. 2724460
			11. Contract/Grant No.
12. Sponsoring Organization Name and Address Same as #9.			13. Type of Report & Period Covered
			14. Sponsoring Agency Code

15. SUPPLEMENTARY NOTES

16. 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 dual detection microwave bridge circuit has been incorporated in a series substitution system for the measurement of microwave attenuation devices. The use of an optical rotary-vane attenuator in the system yields practical resolution and stability of 0.00005 dB from zero to 30 dB. The dual detection system has several favorable features; (1) it employs a single microwave source which reduces cost, (2) measurements are obtained without power stabilization of the microwave signal source, and (3) this waveguide configuration enables measurements of attenuation devices at any length with minimum of effort and movement of waveguide components.

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17. KEY WORDS (Alphabetical order, separated by semicolons)

Attenuation; measurement; rotary-vane attenuator; series substitution.

18. AVAILABILITY STATEMENT	19. SECURITY CLASS (THIS REPORT)	21. NO. OF PAGES
[x] UNLIMITED.	UNCLASSIFIED	28
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