An Accurate Millimeter Wave Loss and Delay Measurement Set*

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Summary—A millimeter wave loss and delay measurement set has been built which combines large dynamic range with high accuracy. Up to 80-db loss and 100-nsec envelope delay can be measured in the 50–60-Gc range. The accuracy for 0–40-db loss measurements is ±0.05 db while beyond that accuracy is progressively diminished to ±0.9 db at 80 db. Delay accuracy for low-loss devices (0–20 db) is ±0.2 nsec.

The measurement method employs rapid comparison switching, heterodyne detection, precision IF loss and delay standards. The method, the test set and some new microwave components are described. Sources of measurement error are discussed and some typical measurements are included.

I. Introduction

THE MILLIMETER wave spectrum has received much attention in connection with a proposed circular waveguide communication system at the Bell Telephone Laboratories. In the development of this system, as in all communication systems, a variety of precision test equipment is required for the accurate measurement of significant transmission parameters. This equipment can also serve as a tool to aid in component design. However, since operation in the millimeter band is relatively new and much of the test equipment not available, a program was undertaken to develop the necessary precision equipment.

As part of this program, an insertion loss and envelope delay measurement set was built which combines high accuracy with large range. Up to 80-db loss and 100-nsec envelope delay can now be measured in the 50–60-Gc band. The accuracy for 0–40-db loss is ±0.05 db; beyond that, accuracy is progressively diminished to ±0.9 db at 80 db. Delay accuracy for low-loss devices (0–20 db) is ±0.2 nsec over the entire 100-nsec range.

II. Measurement Method

High accuracy and large range are attained with a substitution heterodyne measurement scheme using rapid RF and IF comparison switching along with calibrated IF loss and delay standards. In addition, high-gain, narrow-band IF amplification and differential null detection are employed. This method, used successfully in lower-frequency test sets,[1] has been applied for the first time to the millimeter frequency range.

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[1] D. Leed and O. Kummer, "A loss and phase set for measuring transistor parameters and two-port networks between 5 and 250 MC," *Bell Sys. Tech. J.*, vol. 40, pp. 841–884; May, 1961.

A. Loss Measurement

Fig. 1 describes the basic loss-measuring setup. Comparison switching at a $12\frac{1}{2}$-cps rate alternately places the unknown and reference path in the microwave circuit and the loss standard and reference path in the IF circuit. A microwave balanced-converter and an AFC controlled local oscillator generate a fixed 10-Mc intermediate frequency. After high gain narrow-band amplification, the IF signal is fed into the switched detector; there signal levels, proportional to the loss through the reference path and the loss through the unknown path, are sampled and stored on two capacitors. A differential dc amplifier and null meter then indicates the degree of level inequality between the two. Sufficient loss is inserted with the IF loss standard until a null indication results. At this point, the loss through the unknown path equals the loss through the reference path, allowing the unknown loss to be read directly from the calibrated standard.

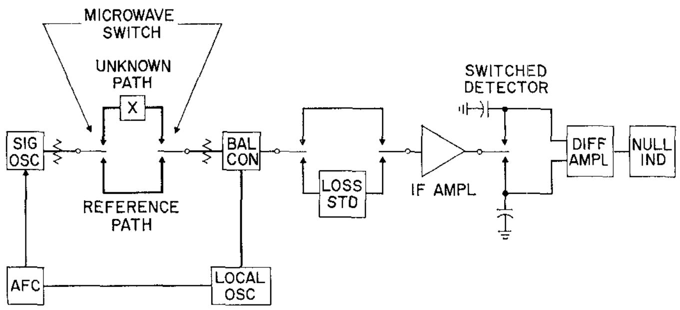

Fig. 1—Basic loss-measuring method.

B. Delay Measurement

Envelope delay of a network is defined as the slope of the phase vs frequency characteristic at a particular frequency ω_0:

$$\tau = \left.\frac{\partial \phi}{\partial \omega}\right|_{\omega_0} \text{ in seconds.}$$

If τ varies with frequency, then delay distortion is present in the network; delay distortion being defined as the deviation from constancy of τ.

Both quantities can be measured by a technique first presented by Nyquist and Brand in 1930[2] in which the

[2] H. Nyquist and S. Brand, "Measurement of phase distortion," *Bell Sys. Tech. J.*, vol. 9, pp. 522–549; July, 1930.

phase slope is approximated by

$$\left.\frac{\partial\phi}{\partial\omega}\right|_{\omega_0} \cong \left.\frac{\phi_1 - \phi_2}{\omega_1 - \omega_2}\right|_{\omega_0}$$

where

ϕ_1 is the phase shift experienced by signal ω_1
ϕ_2 is the phase shift experienced by signal ω_2
ω_0 is the median of ω_1 and ω_2.

This approximation can be measured by generating a two-tone RF signal, ω_1 and ω_2, and feeding it through the unknown network where each tone experiences a shift in phase due to the network characteristic. This phase shift factor can be recovered by demodulation of the two-tone signal. The difference frequency term that emerges is

$$\sin\left[(\omega_1 - \omega_2)t + (\phi_1 - \phi_2)\right].$$

A phase comparison between the above signal and the reference, sin $(\omega_1-\omega_2)t$, results in an output proportional to $(\phi_1-\phi_2)$. This factor divided by $(\omega_1-\omega_2)$, a known fixed quantity, then gives the envelope delay.

Fig. 2 describes the basic delay-measuring setup employing this technique. Delay is measured by recovering the envelope of a two-tone RF signal and measuring its phase shift with respect to a reference envelope. The two-tone microwave signal is generated and fed simultaneously into the unknown and reference paths. Comparison switching alternately replaces the unknown device with an equal length of waveguide and at the same time switches the delay standard in and out of the IF reference path.

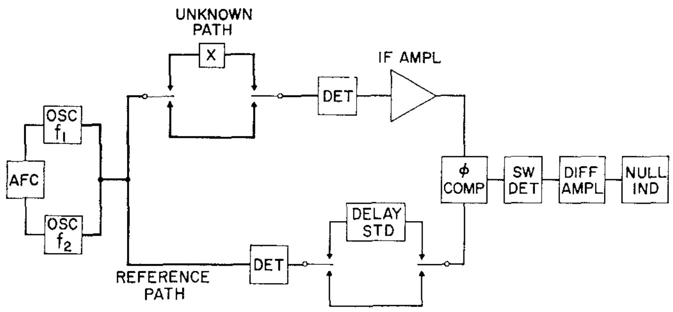

Fig. 2—Basic delay-measuring method.

The envelope resulting from the two-tone signal in the unknown path is recovered by a detector and fed into the phase comparator. The reference envelope is recovered by a second detector and similarly fed into the phase comparator. During half of the switching cycle, the signal through the unknown is compared to the signal through the delay standard. The other half of the switching cycle is used for zeroing purposes which permits a reference phase comparison. Voltages proportional to the two phase comparisons are sampled and again stored on two capacitors. A differential dc amplifier and null meter are used to indicate when the phase difference between the two readings is zero. This occurs when sufficient delay has been inserted with the IF standard to equal the delay of the unknown device. Delay in nanoseconds is then read directly on the calibrated standard.

C. Advantages of Measurement Method

A number of significant advantages result from this measurement method:

1) Rapid comparison switching permits the use of a common measurement path for both the reference and the unknown. Slow systematic drifts or random instabilities in any of the active or passive components are common to both measurements; hence, they cancel.
2) Heterodyning results in a fixed and conveniently low intermediate frequency which allows narrow-band IF amplification and consequent reduction in thermal noise. It also permits operation of the measurement standards at a single frequency, for which the adjustable attenuator can be calibrated against LF standards.
3) Differential null detection allows a very sensitive measurement balance, independent of absolute signal level.

III. Test Set Circuits

Fig. 3 represents the complete block schematic of the test set, elaborating upon the simplified diagrams previously described and showing the combined loss and delay measurement circuits. A photograph of the completed set is shown in Fig. 4.

A. Loss Measurement

Two backward-wave oscillators generate the necessary microwave signals: BWO F1 provides the test signal and BWO F2 provides the local oscillator signal. In addition, the automatic frequency control (AFC) circuit maintains an exact 10-Mc difference between the two signal frequencies.

The test signal is fed through a manual microwave switch into the comparison switching paths. There, a microwave switch alternately inserts high loss in the reference path and in the unknown path at a $12\frac{1}{2}$-cps rate. During half of the switching cycle, the Unknown (X) is placed in the circuit and during the second half of the cycle, the reference path is in the circuit.

The local oscillator signal is fed directly into a balanced converter where it mixes with the test signal to produce a 10-Mc intermediate frequency.

Following the converter is the first IF circuit consisting of a 10-db preamplifier, a loss standard and a level-controlling attenuator. The preamplifier, acting as a buffer, provides a good impedance for the loss standard which is switched into the IF path in synchronism with RF switching. When the reference path is in the RF circuit, the loss standard is in the IF path. The level

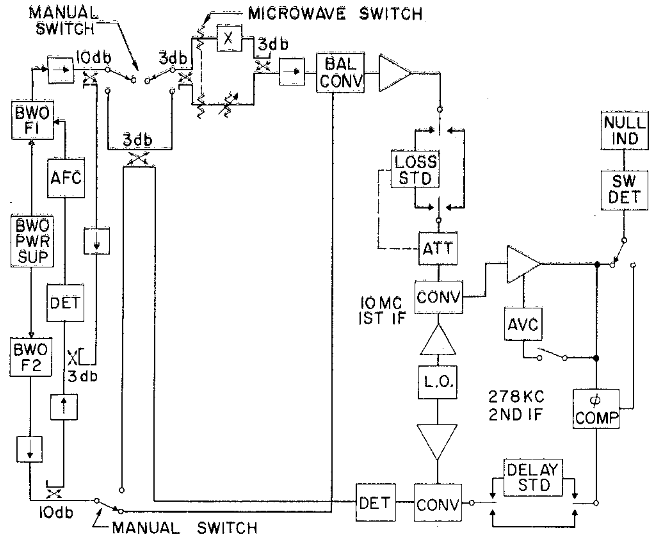

Fig. 3—Block schematic of over-all test set.

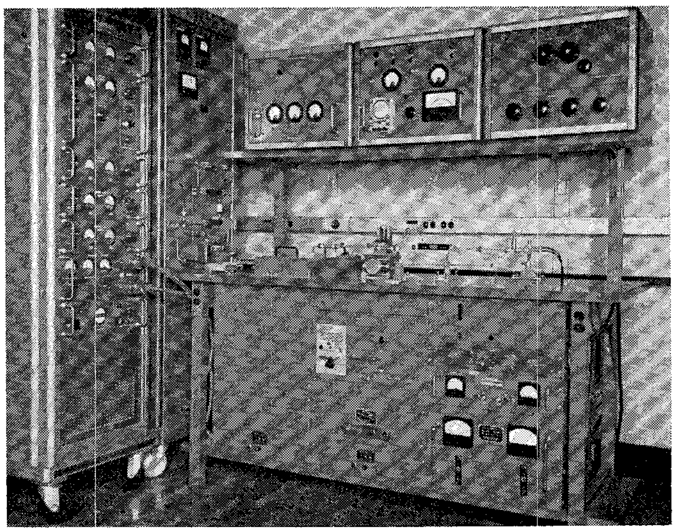

Fig. 4—Millimeter wave loss and delay test set.

control attenuator in the common path is ganged to the loss standard to maintain a constant signal level into the 10-Mc converter. There, the 10-Mc IF is converted to a 278-kc second intermediate frequency where narrow-band amplification is introduced with a 278-kc linear amplifier. The amplified signal is then fed into the null detection circuit which indicates when the loss through each path is equal.

B. Delay Measurement

In order to make delay measurements, the microwave circuit must be changed. This is accomplished with manual switching which combines the two microwave signals in a 3-db directional coupler to produce a two-tone microwave signal for the upper and lower paths.

In the upper path, the Unknown and Reference are alternately switched into the circuit. The balanced converter is now connected as a single input detector and the two-tone signal beats with itself generating a 10-Mc intermediate frequency. The first intermediate frequency is then converted to a 278-kc second intermediate frequency where it is amplified in an AVC amplifier and fed into the phase comparator.

In the lower path, the two-tone microwave signal is fed into a reference detector where a 10-Mc intermediate frequency is produced and is subsequently converted to a 278-kc reference. At this point, a delay standard is switched into the circuit in synchronism with the Unknown.

Both the upper and lower paths are connected to the phase comparator which generates a zero output when the signals from the two paths are in quadrature. During the reference comparison period, an output proportional to phase difference is registered. During the next switching period, the unknown is inserted and its output is registered. A null indication occurs when the phase shifts are equal.

In the phase comparator, a quadrature phase corrector is used to automatically maintain a 90° relation between the two input phasors. This circuit is added to insure that the balance condition and the quadrature relation occur simultaneously, since the phase comparator is most sensitive when the phasors are in quadrature.

C. Significant Circuit Components

This measurement set could not have been realized were it not for a number of devices developed for the millimeter wave program at the Bell Telephone Laboratories; namely, a backward-wave oscillator capable of generating 50 mw in the 50–60-Gc band,[3] broad-band detectors,[4] broad-band isolators[5] and low reflection pads.

In addition, the following units were specifically developed for the set:

1) Rotary Microwave Switch (Fig. 5): This switch consists of a semicircular loss card mounted on a motor-driven wheel. The loss card, passing through slots in two pieces of waveguide, alternately absorbs the power in one path and then the other. Mechanical tolerances on the switch were carefully controlled and microwave absorbers were placed in significant areas to greatly reduce radiation and crosstalk. As a result, the on-off ratio is better than 90 db and the VSWR at input and output ports is below 1.04. The switch is used in conjunction with two 3-db directional couplers which provide the necessary power split. The over-all assembly has a path asymmetry of ± 0.1 db over the band.

2) Manual Microwave Switches: The two manual switches permit a change in the microwave circuit paths to convert from the loss to the delay function.

[3] D. O. Melroy, "A 50 mw BWO and $\frac{1}{2}$ watt TWT for CW Operation Over the 50–60 KMC Band," presented at the IRE WESCON Convention, Paper #27-4; 1961.

[4] W. M. Sharpless, "Wafer-type millimeter wave converters," *Bell Sys. Tech. J.*, vol. 35, pp. 1385–1402; November, 1956.

[5] C. E. Barnes, "Broad-band isolators and variable attenuators for millimeter wavelength," IRE TRANS. ON MICROWAVE THEORY AND TECHNIQUES, vol. MTT-9, pp. 519–523; November, 1961.

Both switches are high-quality units with low VSWR (below 1.04) and low leakage (better than 90 db).

3) *Automatic Phase and Frequency Control Circuit (Fig. 6):* This AFC Unit controls the frequency of Oscillator F1 with respect to Oscillator F2 by a combination of Automatic Phase and Automatic Frequency Control loops.[6] APC insures that the two BWO's are exactly offset by 10 Mc so that a well-defined intermediate frequency will result. AFC serves to ease the manual lock-in procedure and also limits the APC circuit to a unique locking point.

The composite loop has a hold range of ± 6 Mc which is adequate to compensate for short-term frequency instabilities in the signal sources. However, capture range is ± 0.7 Mc which requires a manual locking procedure for each change of measurement frequency. The loop then holds its lock for the duration of the measurement.

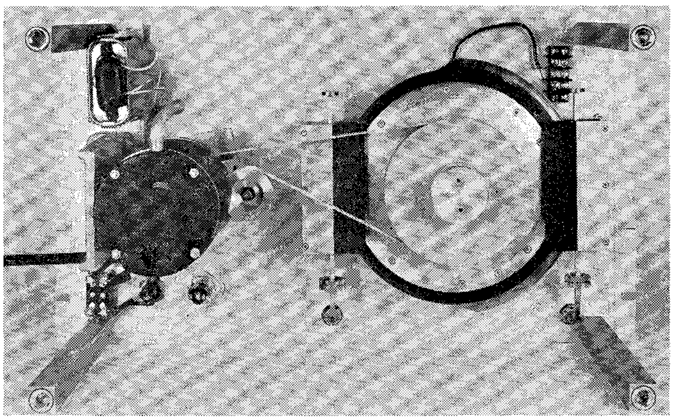

Fig. 5—Rotary microwave switch.

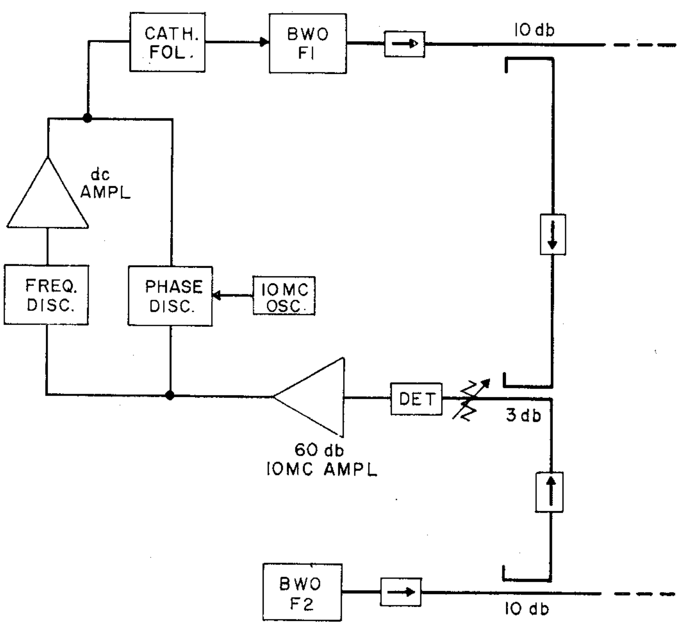

Fig. 6—Automatic phase and frequency control circuit.

[6] D. Leed, "Automatic frequency control circuit," U. S. Patent No. 2,610,297; December 14, 1948.

IV. Sources of Measurement Error

The sources of error in a measurement system are the same as those which plague all communication systems, namely: signal-to-noise ratio, detector linearity, accuracy of standards, system stability, and mismatch. In the design of this test set, efforts were taken to minimize the errors from all these factors.

A. Signal-to-Noise Ratio

Maximum signal level is limited by the characteristics of the first detector. Optimum operation of this unit calls for 1 mw of local oscillator power and this, in turn, requires that the maximum test signal level be limited to -20 dbm to insure a high degree of detector linearity.

System noise consists of coherent crosstalk and thermal noise. The former requires a 40-db SNR for ± 0.1-db error and the latter, a 14-db SNR for the same error. Thermal noise, determined by the minimum system bandwidth and the system noise figure, was minimized by using the narrowest practical IF bandwidth and the best available broad-band, millimeter, balanced detector.[4] An IF bandwidth of 3 kc, corresponding to a -139-dbm noise level, was made possible by employing a phase-locked frequency control loop. The balanced detector and first IF amplifier contributed a 16-db front-end noise figure.

Allowing a minimum SNR of 14 db, the system dynamic range (exclusive of crosstalk) is:

$$\begin{aligned}\text{Dynamic range} &= N_T - S/N + S - NF \\ &= 139 - 14 - 20 - 16 = 89 \text{ db.}\end{aligned}$$

Crosstalk is a more serious limitation. Care was taken to shield the BWO's to prevent radiation from BWO to BWO, and from high power levels to low signal points in the microwave circuit. In addition, the design of the rotary microwave switch minimized crosstalk within the switch assembly and leakage from without.

From sources other than the switch, spurious signal level into the first detector was -125 dbm. For 40-db loss measurements, maximum error from crosstalk was ± 0.03 db due to the 90-db crosstalk figure of the switch. From 40-db to 80-db loss measurements, crosstalk margin within the switch was held to 50 db by the addition of known values of loss in the reference path. Thus, the switch no longer was the limiting factor. Other crosstalk paths predominate so that for an 80-db loss measurement, the margin was 25 db which can cause maximum errors of ± 0.5 db.

B. Detector Linearity

Converter linearity is essential for accurate comparison of microwave loss with an IF standard in a heterodyne system. It minimizes dynamic error in loss measurements and level-to-phase conversion in delay measurements. A high degree of dynamic linearity can be achieved simply by limiting the maximum value of the microwave test signal to -20 dbm, the local oscillator being held constant at 0 dbm. Level-to-phase conversion, on the other hand, is more troublesome and requires additional considerations. When making delay measurements, there is no local oscillator signal in the microwave detector. It operates as a square-law AM rectifier and is subject to level variations between each half of the comparison measurement cycle. In this set a distortionless (delay) microwave attenuator was added in the reference path permitting level equalization prior to the first detector, thereby minimizing level-to-phase conversion in the detectors. In addition, an AVC amplifier was used to maintain a constant absolute signal level into the Phase Comparator removing this circuit as an error source.

The final detector is free from the linearity problem. It must possess high sensitivity and high stability for indicating a null balance when equality of loss or delay exists. This was achieved by using a high-gain chopper-stabilized $12\frac{1}{2}$-cps amplifier, a synchronous detector and a chopper-stabilized null indicator.

C. *Accuracy of Standards*

At the very heart of the comparison technique is the measurement standard. Heterodyning to a convenient intermediate frequency was done to provide narrow-band amplification and a fixed frequency at which to operate the standard. A high-quality variable coaxial attenuator operating at the 10-Mc intermediate frequency serves as the loss standard. This attenuator can be set in steps of 0.01 db to any loss from 0 to 51.1 db. It was calibrated at 10 Mc and found to be accurate to ± 0.01 db at any setting.

The delay standard consists of a four-quadrant phase shifter calibrated in nanoseconds and operating at 278 kc, a convenient frequency for high accuracy. The unit was measured at 278 kc and found to be accurate to within ± 0.2 nsec over the entire 100-nsec range and better over small portions of the range.

D. *System Stability*

Systematic (thermal, etc.) drifts or random instabilities plague all measurement systems. They are appreciably reduced in a comparison measurement. All active devices in this system are in the common measurement path. Instabilities that occur at a rate slower than the switching rate affect both measurements equally and cancel. Random instabilities at a more rapid rate are averaged out in the final narrow-band detector.

E. *Mismatch*

Errors due to mismatch at the measurement ports have been adequately treated in the literature[7] and will not be discussed here. Using isolators and two 5-db low reflection pads, measurement ports having at least 35-db return loss are assured. This results in a maximum mismatch error of ± 0.05 db and ± 0.1 nsec when measuring low-loss devices having return losses of 20 db.

[7] Leed and Kummer, *op. cit.*, pp. 880–883.

V. Confirmation of Test Set Accuracy

Absolute confirmation of the test set accuracy requires loss and delay standards with greater accuracy than that of the test set itself. At the time of confirmation, microwave delay standards of sufficient accuracy were available in lengths of RG 98/U waveguide whose delay characteristics were easily calculable. However, for loss measurements, adequate standards were not believed to be available. At best, the relative loss of a rotary vane attenuator was believed to be most accurate. The loss characteristic, being a known function of vane angle, could not be expected to be accurate on an absolute basis, but for differential changes with the dial indications readable to 0.01 db, it was believed that changes in loss could be predicted in this attenuator with good accuracy. Subsequent measurements have borne out this belief.

Measurement accuracy, therefore, was determined in the following fashion: an estimate was made of the error-producing factors; measurements were made using the above-mentioned loss and delay "standards"; bootstrap measurements were made to determine high loss accuracy; and finally, the theoretical estimate was compared with the measured results.

A. *Estimate of Errors*

An estimate of known sources of error, excluding mismatch, added up to ± 0.04 db for 0–40-db loss measurements and increased progressively to ± 0.9 db for 80-db measurements. Delay errors added up to ± 0.2 nsec for 0–100-nsec measurements on devices with 0–20-db loss.

B. *Delay Standard Measurements*

A section of RG 98/U waveguide exactly one-half meter in length with a shorted termination was used to make the effective path length one meter long. The results are tabulated in Table I(A). The statistical average of the measurements was in excellent agreement with the theoretical values. There was, however, an uncertainty of ± 0.2 nsec.

Additional measurements (Table I(B)) were performed on two lengths of waveguide in tandem with an over-all path length of 64 inches. Again there was excellent agreement.

C. *Loss Standard Measurements*

Loss measurements were performed on two rotary vane attenuators from 0–30 db. The attenuator dials were readable to 0.01 db over the range 0–10 db, although data up to 30 db is included. The measurements are tabulated in Tables II and III. It is apparent that the measured values are slightly, but consistently, on the low side compared to the dial indications.

The question then arises: is the test set in error, or are the attenuator dials in error? If this were an inherent test set error, then it would also be evident in bootstrap measurements where the two attenuators are measured in tandem. This experiment was performed. Equal loss levels were set on the attenuator dials and the sum of both was measured. The sum of the individual measurements (determined from Tables II and III) was then compared to the measured sum and recorded in Table IV.

There is no consistent error between the measured sum and the sum of the individual measurements. In fact, the data is in much better agreement than the dial vs measured values in Tables II and III. Hence, it is reasonable to assume that the bootstrap measurements are the more reliable measure of the test set's accuracy. It is also reasonable to assume that the apparent error between dial indications and measured values is due to a slight angular error in dial calibration.

The measurements in Table IV show that from 0–10-db (5.00+5.00) loss, the maximum difference in measured and arithmetic sum is 0.06 db with the average difference being 0.02 db. From 10–40-db (20+20) loss, the maximum difference is 0.17 db and the average differ-

TABLE I

DELAY STANDARD MEASUREMENTS

(A) Delay in 1.00 Meter of RG 98/U Waveguide

Frequency	Theoretical delay	Measured delay
50 Gc	5.4 nsec	5.4±0.15
55	4.9	5.0±0.2
60	4.6	4.6±0.1

(B) Delay in 1.62 Meter of RG 98/U Waveguide

Frequency	Theoretical delay	Measured delay
50 Gc	8.8 nsec	9.0±0.2
55	7.8	7.8±0.2
60	7.4	7.3±0.1

TABLE II

LOSS STANDARD MEASUREMENTS—ATTENUATOR NO. 1

Dial reading	Measured loss in db		
	52 Gc	55 Gc	59 Gc
0.00	0.00	0.00	0.00
1.00	1.00	0.99	1.00
2.00	1.98	1.98	2.00
3.00	2.96	2.96	2.96
4.00	3.93	3.95	3.95
5.00	4.96	4.95	4.97
6.00	5.94	5.94	5.96
7.00	6.94	6.93	6.95
8.00	7.91	7.91	7.92
9.00	8.91	8.89	8.91
10.00	9.91	9.89	9.94
15.00	14.87	14.85	14.87
20.00	19.96	19.88	19.96
25.00	24.71	24.72	24.75
30.00	29.77	29.75	29.79

TABLE III

LOSS STANDARD MEASUREMENTS—ATTENUATOR NO. 2

Dial reading	Measured loss in db		
	52 Gc	55 Gc	59 Gc
0.00	0.00	0.00	0.00
1.00	0.96	0.97	0.97
2.00	1.96	1.97	1.96
3.00	2.91	2.92	2.93
4.00	3.92	3.93	3.91
5.00	4.94	4.92	4.93
6.00	5.93	5.89	5.90
7.00	6.93	6.89	6.89
8.00	7.90	7.88	7.88
9.00	8.92	8.89	8.89
10.00	9.94	9.92	9.93
15.00	14.88	14.86	14.85
20.00	20.03	20.00	20.02
25.00	24.93	24.90	24.94
30.00	30.18	30.20	30.23

TABLE IV

LOSS STANDARD MEASUREMENTS—ATTENUATOR NO. 1 AND ATTENUATOR NO. 2 IN TANDEM

Dial readings	52 Gc		55 Gc		59 Gc	
	Measured sum	Sum of ind. meas.	Measured sum	Sum of ind. meas.	Measured sum	Sum of ind. meas.
0.00+ 0.00	0.00	0.00	0.00	0.00	0.00	0.00
1.00+ 1.00	2.00	1.96	1.94	1.96	1.94	1.96
2.00+ 2.00	3.99	3.94	3.95	3.95	3.95	3.96
3.00+ 3.00	5.94	5.97	5.89	5.88	5.88	5.89
5.00+ 5.00	9.96	9.90	9.92	9.87	9.93	9.90
7.00+ 7.00	13.85	13.97	13.89	13.82	13.81	13.84
10.00+10.00	19.94	19.95	19.93	19.81	19.91	19.87
15.00+15.00	29.73	29.75	29.73	29.71	29.82	29.72
20.00+20.00	39.82	39.99	39.87	39.88	39.90	39.98
25.00+25.00	49.35	49.64	49.66	49.62	49.78	49.69
30.00+30.00	59.10	59.95	59.83	59.95	60.90	60.02

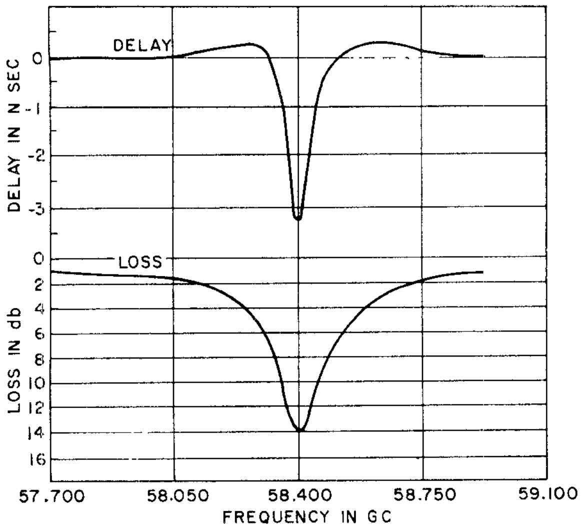

Fig. 7—Insertion loss and delay distortion characteristic of a narrow-band rejection filter.

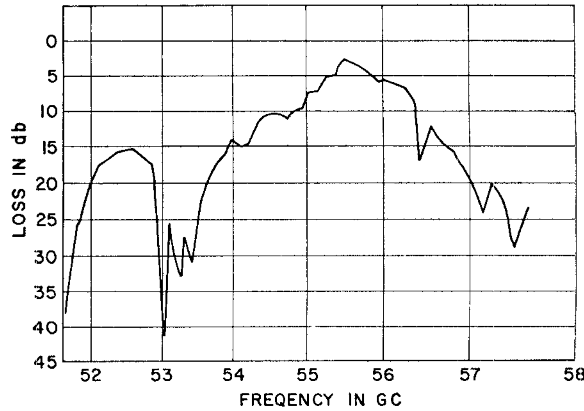

Fig. 8—Loss characteristic of a channel-dropping filter.

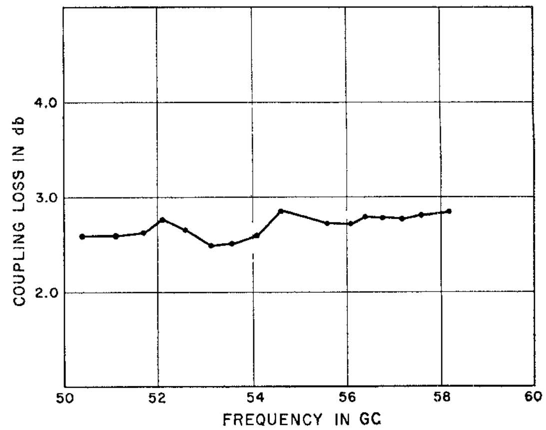

Fig. 9—Auxiliary port coupling characteristic of a 3-db directional coupler.

ence is 0.06 db. This data actually compares the results of two separate measurements with a third. Therefore, the maximum error in any one measurement could be one third of the maximum difference. When it is also considered that this difference includes the effects of attenuator resettability, mismatch and test set accuracy, it is reasonable to conclude that the inherent test set accuracy for any one measurement is better than ± 0.05 db from 0–40-db loss levels.

Bootstrap measurements from 40–60 db are also included in Table IV. The maximum difference in this range is 0.88 db. An additional high-loss measurement of 80 db was performed at various frequencies using three previously calibrated attenuators. The measured sum differed from the sum of the individual values by as much as 1.4 db.

D. Comparison of Theoretical and Measured Results

The theoretical estimate of errors for 0–40-db loss was in close agreement with the errors encountered in actual measurements. From 40–80 db, the estimate was found to be greater than measured errors. Delay measurement error was also in good agreement with the estimate. The accuracy of the test set (exclusive of mismatch) can, therefore, be stated as follows:

Loss Accuracy $= \pm$ 0.05 db (0–40 db loss)

$= \pm$ 0.9 db (at 80 db)

Delay Accuracy

$= \pm$ 0.2 nsec (0–100 nsec and 0–20–db loss).

VI. Typical Measurements

This test set permits highly accurate comparison measurements between an Unknown and a section of RG 98/U waveguide equal in length to the Unknown. Several components were measured on this comparison basis.

Fig. 7 gives results of the loss and delay distortion measurements on a narrow-band rejection filter. Fig. 8 is an example of loss measurements, over a broad frequency, on a channel-dropping filter. In this case, points were measured by manually sweeping the test frequency and performing the measurement only where significant loss changes occurred. And finally, Fig. 9 gives measured results on a 3-db directional coupler.

VII. Conclusions

A millimeter wave loss and delay measurement set has been developed which allows 0–80-db loss measurements and 0–100-nsec delay measurements. This test set, probably the first of its kind in the 50–60-Gc band, has an inherent accuracy as high as that in similar test sets at much lower frequencies. The accuracy realized is $\pm .05$ db for 0–40-db loss diminishing to ± 0.9 db at 80-db loss. Delay measurements are accurate to ± 0.2 nsec.

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