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Improved Sweep Frequency Techniques for Broadband Microwave Testing

THE introduction of reflectometer methods and of the voltage-tuned microwave sweep generator$^{1-3}$ made available to the microwave engineer what has become a popular tool for rapidly gathering quantitative information on microwave device performance over broad frequency ranges. Over a period of time several improvements in techniques have been made and are presented in this article. These new techniques apply to measurements both of reflection coefficient and of attenuation. They are suitable for rapid and accurate full-range production testing of microwave components on a go-no go basis. They have been in use in the -hp- microwave test department for several years; indeed, it has been through the efforts of that department to insure the utmost in quality for -hp- microwave components that most of these "full range" testing methods have been refined to their present form.

There are many cases in the industry today where microwave components leave a manufacturing plant still containing narrow band "resonance" type absorptions or reflections that are outside the limit specified by the manufacturer. It is obvious in these cases that the production tests were made on a point-by-point basis and that the narrow-band "spike" was missed. Indeed, it would be very expensive to test the components at the number of single frequencies required to insure the absence of narrow resonances. -hp-, on the other hand, in line with its philosophy of "inexpensive quality," uses these sweep-frequency methods on production components to assure full-range performance.

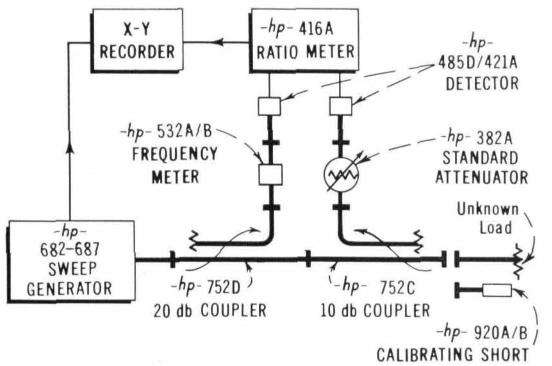

Fig. 1. *Improved microwave equipment set-up for making swept-frequency measurements of reflection coefficient. Use of precision attenuator in reflection arm enables a calibrated grid to be established for desired range of reflection coefficient. Use of attenuator in this way gives higher calibration accuracy than calibrating by using a known reflection to terminate main line.*

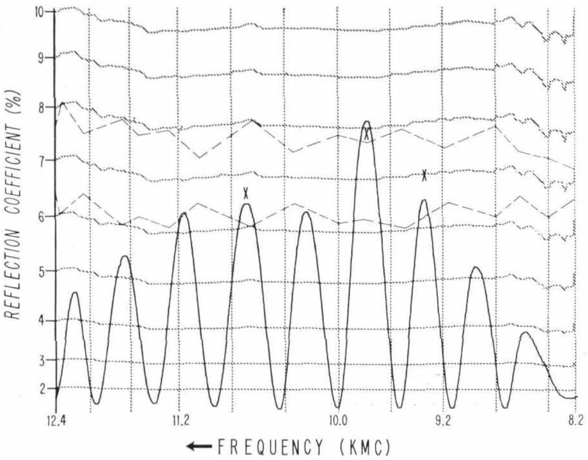

Fig. 2. *Typical swept-frequency reflection-coefficient measurement made using set-up of Fig. 1. Measurement can be recorded on transparent paper so that calibration grid, once made, can serve as an underlay for many measurements. Dashed lines between 6 and 8% show error limits of measuring system for a true 7% reflection coefficient, the go-no go value in this case. X's show true value of three largest reflections as measured by single-frequency set-up of Fig. 4.*

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[1] J. K. Hunton and N. L. Pappas, "The -hp- Microwave Reflectometers," Hewlett-Packard Journal, Vol. 6, No. 1-2, Sept.-Oct., 1954.

[2] Peter D. Lacy and Daniel E. Wheeler, "Permanent Record and Oscilloscope Techniques with the Microwave Sweep Oscillator," Hewlett-Packard Journal, Vol. 9, No. 1-2, Sept.-Oct., 1957.

[3] Peter D. Lacy and Daniel E. Wheeler, "A New 8- 12 KMC Voltage Tuned Sweep Oscillator for Faster Microwave Evaluations," Hewlett-Packard Journal, Vol. 8, No. 6, Feb., 1957.

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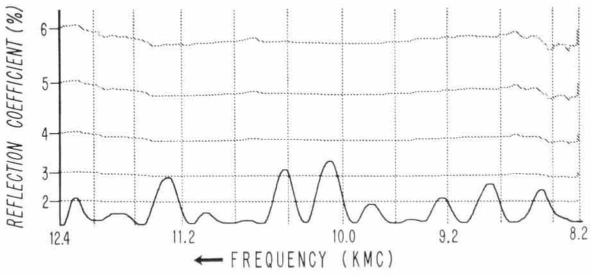

Fig. 3. *Reflection coefficient measurement made of typical -hp- Model X382A rotary attenuator for comparison with non-hp- unit shown in Fig. 2. Specified maximum reflection for this unit is 7%. Full-range measurements such as this are standard -hp- production-test practice so that "out-of-spec" performance is precluded.*

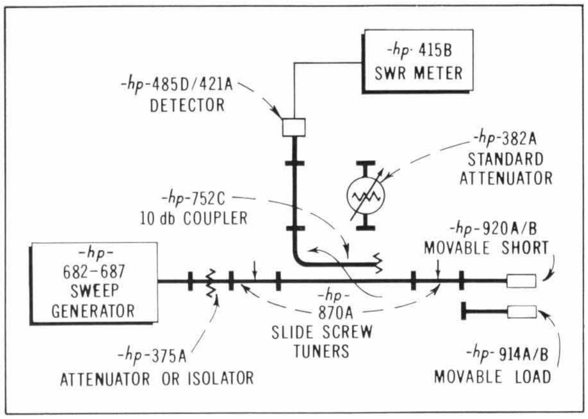

Fig. 4. *Equipment set-up for making precise single-frequency measurements to evaluate "gray areas" that may be encountered in swept measurements made by set-up of Fig. 1.*

The most important improvement in testing methods is the incorporation of a calibration standard attenuator in systems used for reflection or attenuation measurement. With this standard attenuator set at various values, a grid of calibration lines is first recorded for the system with successive sweeps of the generator. Thereafter, measured data recorded over the calibration grid can be read without the usual errors caused by imperfect detector characteristics. In fact, well-matched detectors obeying a square law are no longer required with these refined methods of measurement.

REFLECTION MEASUREMENT

The set-up for sweeping measurements of reflection coefficient is shown schematically in Fig. 1. This set-up is a standard reflectometer system in which one directional coupler-detector combination monitors the incident wave at the load and the other directional coupler-detector monitors the wave reflected from the load. The ratio is measured by a ratio meter and data plotted as a function of frequency on an X-Y recorder. As mentioned before, the significant change over previously described techniques is the addition of the calibration standard—a rotary attenuator on the secondary arm of the second coupler. Use of the attenuator as a standard gives greater accuracy than the use of a standard reflection on the main line. The wavemeter is included to set the sweep frequency limits.

To calibrate the system at a standard reflection coefficient Γ, a short is placed on the load end of the system and the rotary attenuator is set at $20 \log 1/\Gamma$ db. The ratio meter range switch and gain control are adjusted to give a convenient reading at about three-quarters scale on the meter. Adjustment of the X-Y recorder gain can be made to give an appropriate Y scale factor by changing the rotary attenuator setting and noting the change in Y position. With the attenuator set again at $20 \log 1/\Gamma$ the signal source is swept through the frequency band and the standard plot for reflection coefficient Γ is recorded. Other standard plots above and below this value are also made with appropriate settings of the standard attenuator. Components are now tested by putting them on the system in place of the short, setting the rotary attenuator to zero db and allowing the signal source to sweep through the frequency band. A separate sheet of transparent paper is used on the recorder for each component tested. The test plots can then be read superimposed on the standard plots.

Fig. 2 shows reflection coefficient test data obtained on a rotary waveguide attenuator of other than -*hp*- manufacture when set at zero attenuation. In this case the specification on SWR is 1.15 or 7% reflection. The calibration underlay (light lines) contains standard plots for 2, 3, 4, 5, 6, 7, 8 and 9% reflections. The test data is shown as a heavy line. Above and below the 7% standard plot are shown dashed curves representing the limits of the measurement error of the system. This system error can be determined from the characteristics of the system components. The chief contribution to the error is the directivity of the second directional coupler which can be accurately measured over the frequency band. A more subtle error which can't be accurately pinned down is the one resulting from multiple reflections or mismatch losses because both the load on the system and the standard attenuator setting are changed in going from calibration conditions to measurement conditions. An analysis by a flowgraph[4] shows that this error for the arrangement and equipment indicated in Fig. 1 will never exceed 5% of the calibration reflection coefficient. Almost negligible by comparison to the sources of error already mentioned is the calibration error of the standard attenuator. This can be measured over the frequency range and applied as a correction or it can be allowed for in the limits of error of the system. The plus and minus error added to the standard Γ plot is, then, $[1/\ (\text{antilog}\ D/20) + .05\,\Gamma + (\Delta A/8.686) \times \Gamma\ ]$. D is the coupler directivity in db and ΔA is the specified standard attenuator accuracy in db.

SINGLE-FREQUENCY REFLECTOMETER METHOD

The test data in Fig. 2 which was obtained on an attenuator not manu-

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[4] J. K. Hunton, "Analysis of Microwave Measurement Techniques by Means of Signal Flow Graphs," IRE Trans. on Microwave Theory and Techniques, March, 1960, pp. 206-212.

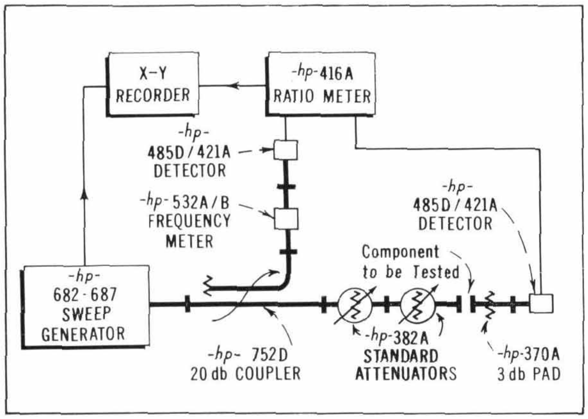


Fig. 5. *Equipment set-up for making swept-frequency measurements of attenuation. Calibration grid for attenuation measurements can be made by using one attenuator to establish desired attenuation region and second one to add small values to desired level.*

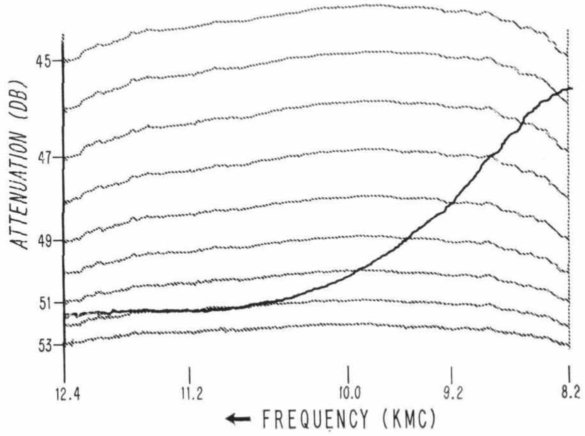


Fig. 6. *Measurement of attenuation made using set-up of Fig. 5. Measurement made of non-*hp*- attenuator measured in Fig. 2 with dial now set for 50 db. As in Fig. 2, measurement can be recorded on transparent paper so that one calibration grid can serve for many measurements.*

factured by -*hp*- exhibits fairly sharp peaks apparently caused by the reflections of the two end transitions combining in phase. A point-by-point test method could very easily miss the worst peak which is "out of specs". The crosses shown in the figure represent more accurate data obtained by the precise single frequency reflectometer method. In Fig. 3 reflection coefficient data on a Hewlett-Packard Model X382A rotary attenuator is shown for comparison. The set-up for the precise single frequency reflectometer method is shown schematically in Fig. 4 and is intended for use on rejected components whose swept data falls in the error limit region at certain frequencies. A sliding short is first placed on the load end of the system and the generator tuner is adjusted until moving the short causes no variation in the Model 415B SWR meter reading. The short is then replaced with a sliding load and the load tuner is adjusted until no variation in the SWR meter reading occurs as a result of sliding the load. These procedures eliminate the effects of residual reflections and directivity in the system. The meter is now calibrated at 100% reflection with the short. However, deviation of the detector from square-law at the measurement level must be determined. This can be done with the rotary attenuator standard and applied as a later correction to the meter reading. An alternative method which is more accurate but more laborious calibrates the system with a standard reflection load of suitable value whose reflection coefficient has been accurately calculated.

ATTENUATION MEASUREMENT

The set-up for sweep frequency attenuation measurements is shown in Fig. 5. It is convenient to use two rotary attenuator standards — one for setting the gross level and the other for adding small attenuations to this level. With the detector connected directly to the second attenuator a set of calibration lines is recorded. Fig. 6 shows a typical calibration (light lines) at 49 db ± 4 db. One standard attenuator is set at 45 db and the other at 0, 1, 2, 3, 4, 5, 6, 7, 8 db in turn for each of 9 sweeps to obtain accurate calibrations. For extreme accuracy corrections can be applied for inaccuracies in the attenuation standards used. The component to be tested is now placed between the second attenuator and the 3 db pad ahead of the detector. Both standard attenuators are set to zero and the component data is recorded. The heavy line in Fig. 6 is an attenuation plot of the same attenuator used as an example in Fig. 2 with the dial now set at 50 db.

The maximum attenuation which can be measured with this system is dependent upon the power output of the sweep generator. Typically, 50 db is the practical limit. However, the range can be extended to 70 db by adding a 1-watt travelling wave amplifier after the sweep generator.

Besides the calibration error of the standard attenuators there is a system error resulting from mismatches or multiple reflections. This error is of the order of 20 log $(1+\Gamma_s\Gamma_d+\Gamma_s\Gamma_1+\Gamma_2\Gamma_d)$, where Γ_s is the specified reflection coefficient of the standard attenuator, Γ_d is the specified reflection coefficient of the detector with pad, and Γ_1 and Γ_2 are the input and output reflection coefficients of the attenuator being tested. In a typical waveguide system this amounts to 0.2 db if Γ_1 and Γ_2 are of the order of 0.1.

Another set-up for making swept attenuation measurements involves the use of a second directional coupler. The second detector and standard attenuators are placed on the secondary arm of this second 20 db directional coupler. The procedure is the same as before. Calibration is made with the two couplers joined and measurement is made with the component under test between the two couplers. The system error is independent of the mismatch of the device under test because of the 20 db isolation provided by the second coupler. The mismatch errors are related instead to the reflection coefficient of the secondary arm of the coupler. Typically, 0.2 db is the order of magnitude for a waveguide system. The maximum

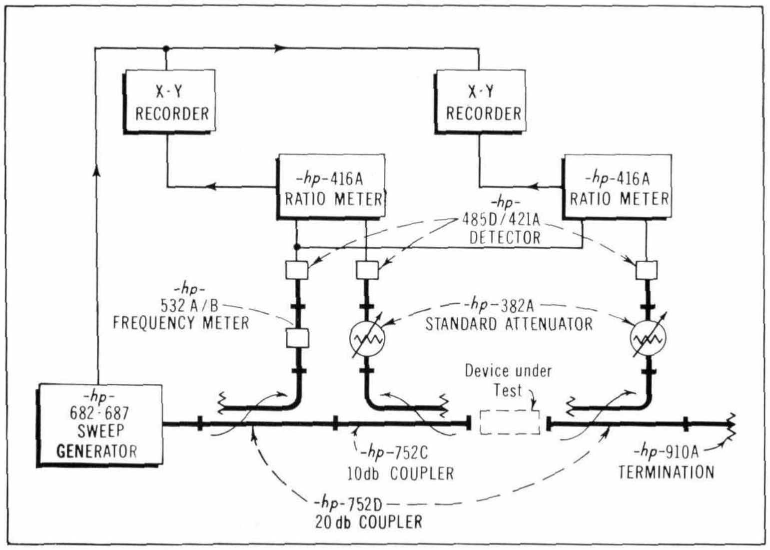
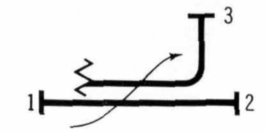


Fig. 7. *Equipment set-up for simultaneously measuring reflection and attenuation of component under test.*



$$\text{COUPLING} = 20 \log \left| \frac{1}{S_{31}} \right|$$

$$\text{DIRECTIVITY} = 20 \log \left| \frac{S_{31}}{S_{32}} \right|$$

S_{31} = Wave amplitude out at port 3 for unity input at port 1 with port 2 perfectly terminated.

S_{32} = Wave amplitude out at port 3 for unity input at port 2 with port 1 perfectly terminated.

Fig. 8. *Definitions for directional coupler having one auxiliary arm terminated internally.*

measurable attenuation is, of course, reduced by 20 db, making the method most applicable to measurement of lower attenuation devices with higher reflection.

Fig. 7 shows a system that uses the two-directional-coupler method in simultaneously measuring the reflection and the attenuation of a component. The reflection and attenuation portions of the measuring system share the first directional coupler and each has its own ratio meter and recorder. Calibrations and measurements are made in accordance with techniques already described.

MEASUREMENT OF COUPLER DIRECTIVITY

Both the coupling and the directivity of a directional coupler can be measured on a sweep-frequency basis. Fig. 8 shows the basic definitions for a directional coupler whose auxiliary arm has one end terminated internally. The coupling can be measured by terminating port 2 with a load of low SWR and using the method of Fig. 5 to measure the attenuation between ports 1 and 3. The measurement of directivity is somewhat more complicated. A direct measurement of the port 2 to port 3 attenuation is difficult because it is very high and because it is very sensitive to the SWR of the load which would be used to terminate port 1.

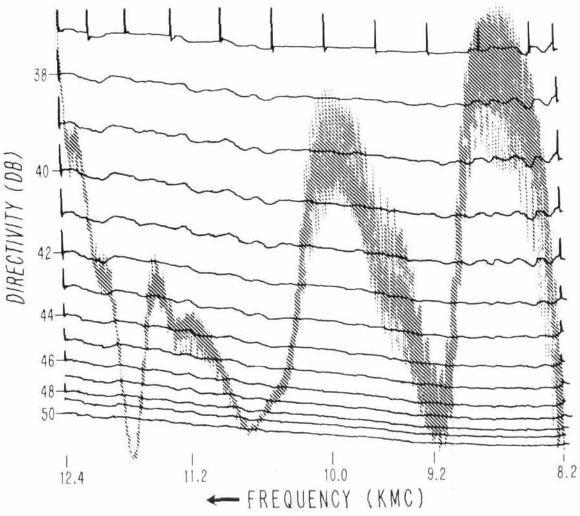


Fig. 9. *Swept-frequency directivity measurement made of non-hp- manufactured directional coupler using reflection set-up shown in Fig. 1.*

The set-up used for directivity measurement is the one previously described for reflection measurement and shown in Fig. 1. The second directional coupler in this diagram is now the coupler under test and the load used on the end of the system is a standard sliding load whose reflection coefficient has been measured accurately at many frequencies by the technique of Fig. 4. The system is calibrated first with a short on the load end. Several sweeps are made with different settings on the standard attenuator to obtain a grid of calibration lines. Each line is labelled with the standard attenuator db setting used, and also the corresponding relative signal level value which is 1/(antilog db/20). The short is now replaced with a sliding load and a swept record is made on a new sheet of transparent paper on top of the calibration grid. For this test record, the standard attenuator is set at zero and the load is moved back and forth rapidly during the sweep. Several sweeps may be necessary to be sure that all possible load phases are experienced.

The test record appears as a series of oscillations with an average value which varies with frequency. The oscillations are caused by the beating of the fixed-phase directivity signal and the variable-phase load reflection. The average

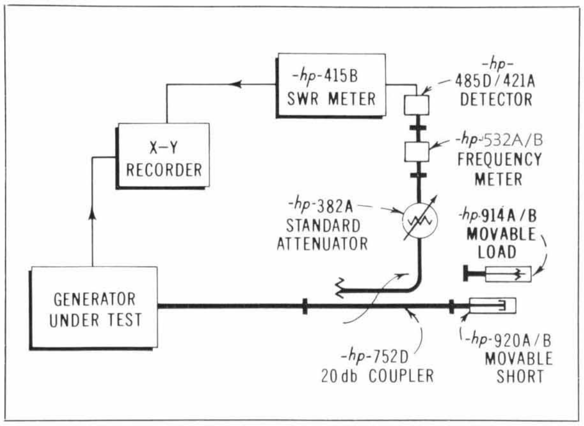


Fig. 10. *Set-up for making swept-frequency measurement of reflection coefficient of a signal generator.*

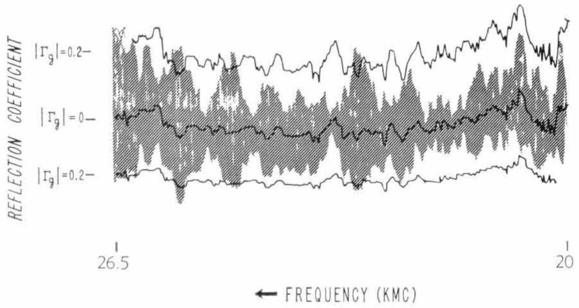


Fig. 11. *Swept-frequency measurement of source reflection coefficient of an* -hp- *Model 938A harmonic doubler over 20 - 26.5 kmc range.*

value of the test data is the larger of the two signals, and the peak value of the oscillation (above the average) is the smaller of the two. Since the load reflection coefficient is known, the coupler directivity can be determined either from the average or the peak value as read from the calibration grid on which the test data is superimposed. This value expressed in db is actually the directivity minus the main line transmission loss, so that the transmission loss must be added to obtain the true directivity. This loss is $20 \log 1/S_{21}$ or $20 \log 1/(1-|S_{31}|^2)^{1/2}$. (For a 3 db coupler it is 3 db and for a 10 db coupler it is .46 db, and so on).

Fig. 9 shows data taken on an X-band directional coupler. In this case a very good load with return loss in excess of 50 db was used so that the oscillations are relatively small and the directivity specified at 40 db is the average value of the plot. The coupler tested is one purchased from another manufacturer.

An alternative method of reducing the data can be used where the original calibration grid is modified to obtain a new grid which represents the loci of the peak values of the total signal for various directivity values. The directivity of the test coupler can be read directly over the new grid by following only the peaks of the test data. The new grid is obtained from the original one by first adding the coupler transmission loss in db to the db value labelled on the plot, and then adding the reflection coefficient of the load to the relative signal level value labelled on the plot at each one of several frequencies.

The tests just described can be applied as well to the measurement of the reflection coefficient of a sliding load. In this case a directional coupler of known directivity is used and the same procedure is followed. To obtain the alternative calibration grid, the main line transmission loss (in db) is subtracted from the coupler directivity, and the resultant value expressed as a relative signal level is added to the original grid lines which are labelled for various load reflection coefficients. The load reflection can then be read by following the peaks of the test data.

MEASUREMENT OF THE REFLECTION COEFFICIENT OF A SIGNAL GENERATOR

The technique used to measure the source mismatch or reflection coefficient of a signal generator is shown schematically in Fig. 10. In this method the main generated signal is combined at the detector with the signal that is multiply reflected between a terminating short and the generator. Thus, the net signal level at the detector is $1/(1-\Gamma_g)$ multiplied by the signal level which would appear if the system were terminated in a matched load, Γ_g being the generator reflection coefficient. At some fixed frequency, if the short is moved, the phase of the secondary signal re-reflected by the generator changes through all values. The maximum and minimum signal levels at the detector are then $1/(1-|\Gamma_g|)$ and $1/(1+|\Gamma_g|)$, respectively, multiplied by the matched load signal level, and their ratio can be read directly as generator SWR on the SWR meter within the limits of error of the system.[5]

To obtain swept frequency data on the generator reflection coefficient, a calibration grid must first be plotted. The system is terminated first with a well-matched load in place of the short and the standard attenuator is set at 6 db. A swept record is obtained on the recorder and is labelled as $|\Gamma_g|=0$. Two lines are now plotted, one above and one below this line for a given specified value of $|\Gamma_g|$, by setting the attenuator at a value

$$20 \log 2(1-|\Gamma_g|)$$

for the upper swept plot and $20 \log 2(1+|\Gamma_g|)$ for the lower swept plot. The load is now replaced by the sliding short and the attenuator is again set at 6 db. The generator is now swept through the frequency band several times and the short is moved to a different position for each sweep. The resulting plot is a series of oscillations about the original 6 db calibration line. The loci of upper and lower peaks are signal level values of $1/(1-|\Gamma_g|)$ and $1/(1+|\Gamma_g|)$, respectively, multiplied by the original signal level when the system was terminated in a matched load. Since the calibration grid lines were labelled accordingly, the generator reflection coefficient can be read from the grid at all frequencies by following the peaks.[6]

The directivity and attenuator mismatch errors involved in this measurement are similar to those described earlier in connection with the measurement of a load reflection. However,

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[5] This method is also useful in tuning a generator reflection to a negligibly low value. A tuner placed between the generator and coupler can be tuned until no variation of meter reading takes place as the short is moved. Such a technique is very useful in making accurate attenuation measurements.

[6] Note that the uppermost calibration line which can be drawn is for $|\Gamma_g|=0.5$ corresponding to zero attenuation in the calibration attenuator. However, swept calibration lines for all values of $|\Gamma_g|$ can be plotted below the original 6 db line. For $|\Gamma_g|=1$ the lowest line would be plotted with an attenuation of 12 db.

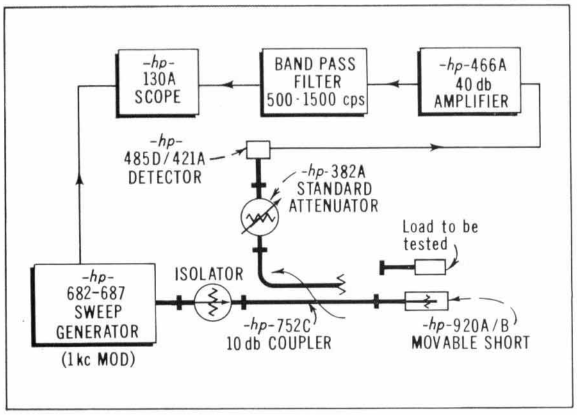

Fig. 12. (at left) *Set-up for rapidly measuring the reflection from a load on a broad band basis using an oscilloscope.*

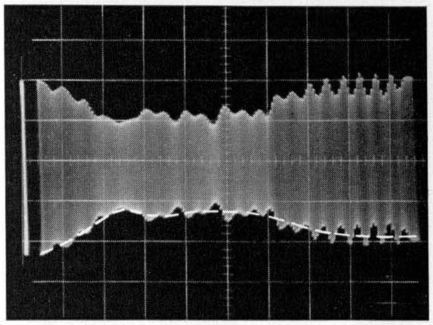

Fig. 13. *A typical calibration obtained with set-up of Fig. 12 for a load reflection coefficient of 0.1. Fast ripples are from multiple system reflections and should be averaged out on both upper and lower edges of trace. For clarity typical averaging is shown only along lower edge of trace by white dashed line.*

the major portion of the mismatch error in this case is not a fixed percentage of the reflection coefficient being measured but is rather a fixed value, like the directivity error. For a practical waveguide system this error should not exceed a value of .02. Plus and minus limits of error can be plotted above and below each calibration line if desired.

The error value is $[1/(\text{antilog } D/20) + .02 + |\Gamma_g| (.01 + 1/(\text{antilog } D/20))]$ where D is the coupler directivity.

Fig. 11 shows typical test data taken on a harmonic doubler generator (*-hp-* 938A). Here the calibration lines are for a value $|\Gamma_g| = 0.2$ and the generator sweep frequency range is 26.5 to 20 Kmc.

FAST MEASUREMENTS WITH OSCILLOSCOPE

In measurement systems which use a ratio meter or SWR meter, the sweep speeds used are too slow for oscilloscope presentation. An amplifier of broader bandwidth is required if faster sweeping is to be used. This of course means an increase in the noise level and a decrease in the dynamic range of the measurement. However, with the system shown in Fig. 12 a dynamic range of 35 to 40 db is still possible with sweep speeds fast enough for scope presentation.

A standard broadband 40 db amplifier (*-hp-* 466A) is used to amplify the 1 Kc square wave from the detector. A band-pass filter following the amplifier passes only the 1 Kc fundamental component. The bandwidth of this filter allows amplitude variations at rates up to 500 cycles which is adequate for retaining the fine structure of the measurement information at reasonable sweep rates. This system is used for load reflection measurement and is calibrated as in previously described systems with the standard attenuator and a terminating short. The picture on the oscilloscope is a 1 Kc signal whose amplitude varies as the generator frequency and horizontal deflection are swept. It is necessary, then, to read the peak-to-peak value. The calibration grid, which can be drawn with grease pencil, contains two lines for each calibration signal level. A typical calibration is shown in Fig. 13. This is an X-band system swept from 12.4 to 8.2 Kmc at a rate of 32 Kmc per sec. The calibration attenuator is set at 20 db while the system is terminated with a sliding short. Thus the calibration is for a load reflection coefficient of 0.1. The fast ripples on the signal amplitude are caused chiefly by multiple reflection between the terminating short and the isolator. This is one disadvantage of the method over those using a ratio meter where this multiple reflection is monitored by both channels and does not appear in the meter reading. The calibration lines on the scope face can be drawn with grease pencil as shown in Fig. 13 and should average out the fast ripples but should follow any generator output variation. To distinguish one effect from the other, the terminating short can be moved. The multiple reflection ripples will move as the short is moved, while the generator output variations will remain unchanged.

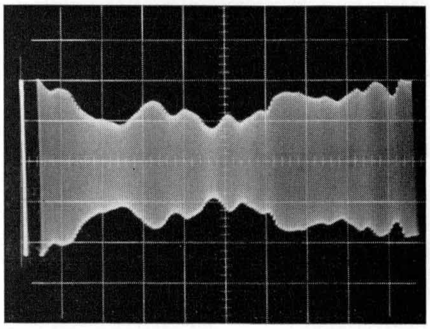

Fig. 14. *Measurement made of standard 0.1 reflection to compare typical measurement with calibration in Fig. 13.*

Fig. 14 shows a scope picture obtained with a 10% standard reflection (*-hp-* X916C) terminating the system with the standard attenuator set at zero. It can be seen that the system measures this load within certain error limits. The error shown by the deviation of the data from the 10% calibration lines is due chiefly to the coupler directivity signal which can be as high as 10% of the load reflection being measured in this case.

The fast sweeping system is very useful when adjustments must be made on a component under test to bring it within certain specified limits over a broad frequency band. The method is less accurate and has less dynamic range than previously described methods which use a ratio meter. However, with the future possibilities of automatic signal levelling, which maintains not only the generator signal level constant but provides also a very good source match, accuracy should be improved. Dynamic range can be increased by using a 1 watt travelling wave amplifier.

—*J. K. Hunton and Elmer Lorence*