and ultimately, for $\kappa z \gg 1$, approaches an equilibrium value. That is,

$$U(z) \to \frac{a_0^2 \omega_1}{4W_0} \tag{28}$$

as $z \to \infty$. The first maximum, where the pulse energy overshoots the equilibrium value by almost 50 per cent, occurs at the smallest value of κz for which

$$J_0(2\kappa z) = 0; \tag{29}$$

that is, at

$$\kappa z = 1.202. \tag{30}$$

The position of the first maximum could be used as a basis for measurement of the coupling coefficient in a coupled-mode system.

Thus, as the pulse on Mode 2 propagates along the transmission system, the pulse length grows without bound and the shape of the pulse envelope continues to change, but the energy of the pulse approaches an equilibrium value that is directly proportional to the magnitude of the coupling coefficient.

III. Comments

Coupled-mode systems are customarily characterized by their frequency-domain response. We have presented here a derivation of the time-domain response of an important class of coupled-mode systems; we hope that this derivation will provide new insights into the behavior of these systems.

The principal assumptions that we have made are 1) that the coupling coefficient between modes is independent of frequency, and 2) that the $\omega - \beta$ characteristics of the two modes are straight lines. Note that the assumption of a linear $\omega - \beta$ characteristic is not the same as an assumption of zero dispersion. It is clear from (14) and (15) that for weak coupling, most of the energy transfer between modes occurs in the frequency range $\omega_0 - \omega_1$ to $\omega_0 + \omega_1$. Thus, if the $\omega - \beta$ characteristics are straight *in this frequency range*, and the coupling coefficient is constant *in this frequency range*, then the results that we have derived here should be approximately correct. If the $\omega - \beta$ characteristics deviate from linearity outside of the frequency range $\omega_0 - \omega_1$ to $\omega_0 + \omega_1$, the resulting effect would probably be a rounding of the sharp edges of the pulse on Mode 2.

A Precise and Sensitive X-Band Reflecto"meter" Providing Automatic Full-Band Display of Reflection Coefficient

F. C. DE RONDE

Abstract—A simple waveguide system has been made for the instantaneous measurement of the magnitude of the reflection coefficient as a function of frequency for the 8.2–12.4 Gc band.

Reflection coefficients in the range 1 to 0.001 can be measured on linear scales; above 0.01 the error is less than ±3 per cent, below 0.01 it is estimated to be in the order of ±5 per cent.

By using a long line between the unknown impedance and the two wall-current detectors, which act as measuring probes, an audio-frequency voltage has been obtained which is linearly proportional to the amplitude of the unknown reflection coefficient.

A third wall-current detector is used as a leveler.

The principle is quite simple and can easily be applied for other frequencies or transmission lines.

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I. Introduction

REFLECTO"METERS" using directional couplers and a ratiometer are commonly used for swept-frequency display. Although they work much faster than standing-wave indicators their accuracy is considerably lower. A great improvement over the usual method of two couplers together with broadband detectors can be obtained if one directional coupler with built-in wall-current detectors [1], [2] is used. However, the finite directivity of the directional coupler and its variation with frequency limits the accuracy especially at very low values of the reflection coefficient, while reflection of the coupler limits it at very high values.

The ratiometer, however, although usually more accurate than the waveguide components, is a rather complicated and expensive apparatus. If the detector of the incident wave is used to level the oscillator output, the detector of the reflected wave now gives a direct indication of the reflection coefficient. Amplitude modulation is no longer necessary and a much faster visual display is possible.

Even if ideal directional couplers existed, a disadvantage is that the scale would be square-law.

The greatest *precision* can be obtained if both the incident and the reflected wave are not disturbed. The simplest way to achieve this is to obtain the necessary information from the standing-wave pattern, and until now this could not be done with greater precision than with a slotted line. However, this instrument is not suitable for swept-frequency measurements. Instead of moving a probe along the line, the standing-wave pattern can also be moved past a fixed probe, and this occurs automatically when the frequency is swept. The best result can be obtained if a long line is used between the unknown impedance and the measuring probe. If wall-current detectors are used as measuring probe and leveler, a high accuracy can be obtained since they can easily be made identical and their effect on the standing-wave pattern is negligible.

A high *sensitivity* can also be expected, because the incident wave can be regarded as the local oscillator and a much smaller reflected wave as the signal of a mixing system.

In the present paper the reflecto"meter",[1] a measuring system based on the preceding principles, will be described. It gives the magnitude of the voltage reflection coefficient as a function of frequency over the 8.2–12.4 Gc waveguide band on a linear scale on an oscilloscope. Moreover, the dependence of the reflection and also of the transmission characteristic of devices on parameters such as dc bias, magnetic field, etc., can be displayed instantaneously.

II. Description of the Circuit

The principle of the reflecto"meter" is given in Fig. 1. The output of the sweep oscillator passes the detector 1 which acts as a leveler to provide a frequency-independent incident power, as seen by the detectors 2 and 3, which are the measuring probes. An external AF amplifier is necessary if the sweep oscillator is not already suitable for external leveling. Otherwise, the output of the leveller detector can be applied directly to the Automatic Level Control (A.L.C.) input.

In order to decouple the leveler from the measuring detectors a broadband isolator[2] is inserted. A pad would have given a much lower sensitivity.

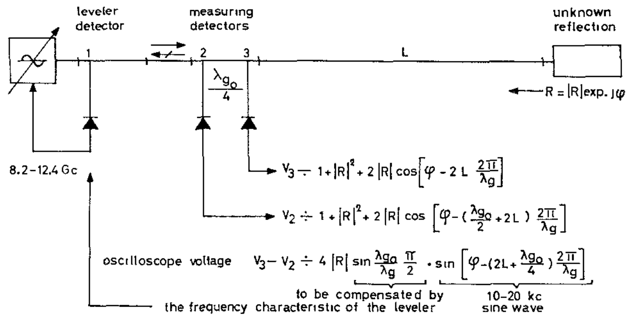

Fig. 1. Principle of the reflecto"meter".

The unknown impedance Z is separated from the measuring detectors by the long line of length L.

A. Measuring Detectors

The reflection $|R|$ to be measured is caused by the impedance Z, having a complex voltage reflection coefficient $R=|R|\exp j\phi$. For simplicity the isolator is here assumed to be perfect over the waveguide band. For square-law detection the output signals of detector 2 and 3 are proportional to

$$V_2 \propto 1 + |R|^2 + 2|R| \cos\left[\phi - \left(\frac{\lambda_{g_0}}{2} + 2L\right)\frac{2\pi}{\lambda_g}\right]$$

$$V_3 \propto 1 + |R|^2 + 2|R| \cos\left[\phi - 2L\frac{2\pi}{\lambda_g}\right]$$

The difference of these voltages (after adjustment for equal sensitivities) is proportional to

$$V_3 - V_2 \propto 4|R| \sin\frac{\lambda_{g_0}}{\lambda_g}\frac{\pi}{2} \cdot \sin\left[\phi - \left(2L + \frac{\lambda_{g_0}}{4}\right)\frac{2\pi}{\lambda_g}\right] \qquad (1)$$

$\lambda_{g_0}/4$ being the distance between the detectors. From (1) it follows that $4|R|\sin(\lambda_{g_0}/\lambda_g)(\pi/2)$ is the amplitude of an audio signal of which the frequency is determined by the length L and the sweep rate. The factor $\sin(\lambda_{g_0}/\lambda_g)(\pi/2)$ is caused by the quarter-wavelength separation of the detectors 2 and 3 and can easily be compensated by the leveler as will be discussed later on. If this is done the difference voltage of the detectors as indicated by the oscilloscope[3] is *linearly* proportional to $|R|$.

The frequency of the AF signal, although not constant, can easily be calculated to be about 15 kc for $L=4$ m and a full-band sweep with a sweep frequency of 100 cycles.

Full advantage of the long line can be taken if a high-pass filter is inserted between each measuring detector and the oscilloscope (see Fig. 2). Unwanted signals of lower frequencies, not caused by the reflection to be

[1] As the measuring system gives a direct display on an oscilloscope, it would have been better if the word "meter" could be substituted by scope. However "Reflektoskop" proved to be a registered Trade Mark already.

[2] Unidirectional transmission line would be better. However, Uniline is a registered Trade Mark.

[3] Luckily this is not a registered Trade Mark.

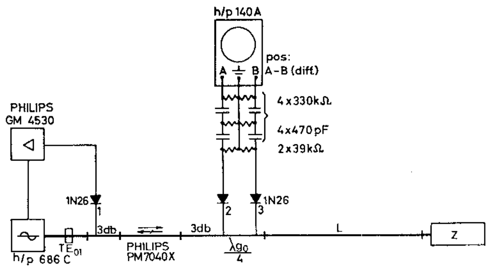

Fig. 2. Actual reflecto"meter" circuit.

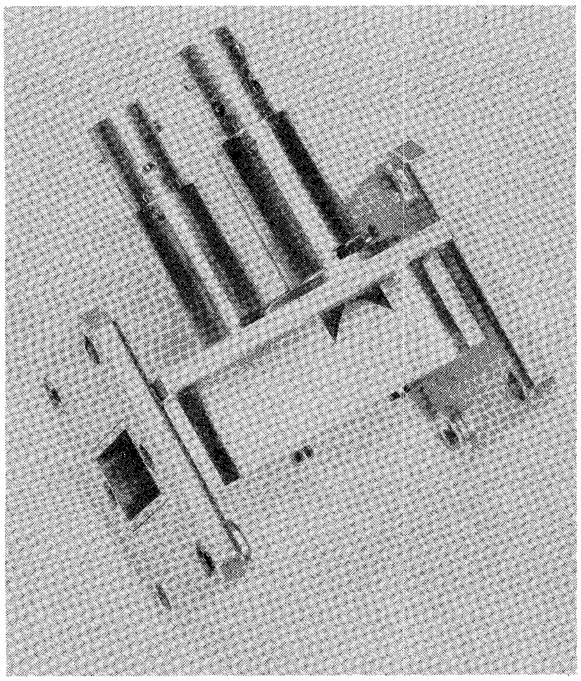

Fig. 3. Quarter-wavelength detector unit.

measured, are then greatly reduced. This is especially important for the measurement of very small reflections, which will be discussed in Section III.

It seems desirable to have the detector signals rectified in order to display only the envelope of the AF signal. This however complicates the system, and some information can easily be lost, especially in the case of highly dispersive phenomena, e.g., spurious resonances. Screening the lower half of the picture by a mask on the graticule is a simple way to improve the display.

The advantage of using two detectors instead of one is that the wanted signal level is twice as high while the unwanted signal, which is proportional to $1+|R|^2$, is eliminated. Moreover, sensitivity changes due to detector law variations tend to cancel each other if the detectors are a quarter-wavelength apart. In order to get the best linearity over the whole range $0<|R|<1$ detector loads of about 50 kΩ proved to be good values for a level not exceeding 10 mW. Any oscilloscope with an ac differential input and a maximum sensitivity of about 0.1 mV/cm can be used. To obtain maximum linearity and to display transmission at the same time a dual-*trace* oscilloscope is preferable.

The disadvantage of using two detectors instead of one is that the amplitude of the audio-frequency signal is not proportional to $|R|$ but to $|R|\sin(\lambda_{g_0}/(\lambda_g)(\pi/2)$. For constant reflection the amplitude varies according to $\sin(\lambda_{g_0}/\lambda_g)(\pi/2)$. It can easily be calculated that minimum deviation from flatness occurs for the value $\lambda_{g_0}/4=9.6$ mm, and although the maximum deviation that occurs at 8.2 and 12.4 Gc does not exceed 15 per cent, it is far too much for precision measurements. However, this can easily be compensated by the leveler.

A photograph of the quarter-wavelength detector unit containing improved wall-current detectors [2] can be seen in Fig. 3.

B. The Leveler

In order that the differential voltage of the measuring detectors is a direct indication of the reflection coefficient, the output of the sweep oscillator has to be constant over the whole band. This can be achieved by using another wall-current detector of the improved type [2] as a leveler. In this way the output as seen by the measuring detectors can be made flat within ± 0.1 dB for the whole X band.

The characteristic of the leveler detector can be given about the same $\sin(\lambda_{g_0}/\lambda_g)(\pi/2)$ dependence by placing some lossy material[4] in the corner of the diode circuit outside the waveguide. In this way the influence of the quarter-wavelength displacement on the measuring signal can be compensated to a certain extent. The remainder can be eliminated with a series of small screws behind the leveler, at the same time allowing compensation for not too frequency-dependent influences such as insertion loss of the isolator, identity of the wall-current detectors, etc. If the screws are adjusted when the unknown is replaced by a standard reflection, a higher accuracy can be obtained than seems possible at first sight.

For optimum accuracy the isolator must present a good match seen from the side of the leveler as well as from the measuring detectors. Since no matched isolator is available yet, it is flanked by low-reflection broadband pads. In order not to loose too much sensitivity, the isolator has first been improved with the aid of our reflecto"meter." The remaining reflection (a few per cent) has been reduced to about one per cent by using 3-dB broadband pads, each having a reflection less than a few per mil.

With the sweep rate used, the variations in the output of the sweep oscillator and those due to the frequency characteristic of the leveler detector are of an audio-frequency character, and a simple AF amplifier can be used in the leveler circuit. The leveler signal is amplified several thousand times before it is fed to the external AM input of the sweep oscillator. The external AF

[4] Eccosorb MF 117, manufactured by Emerson and Cuming, Inc., Canton, Mass.

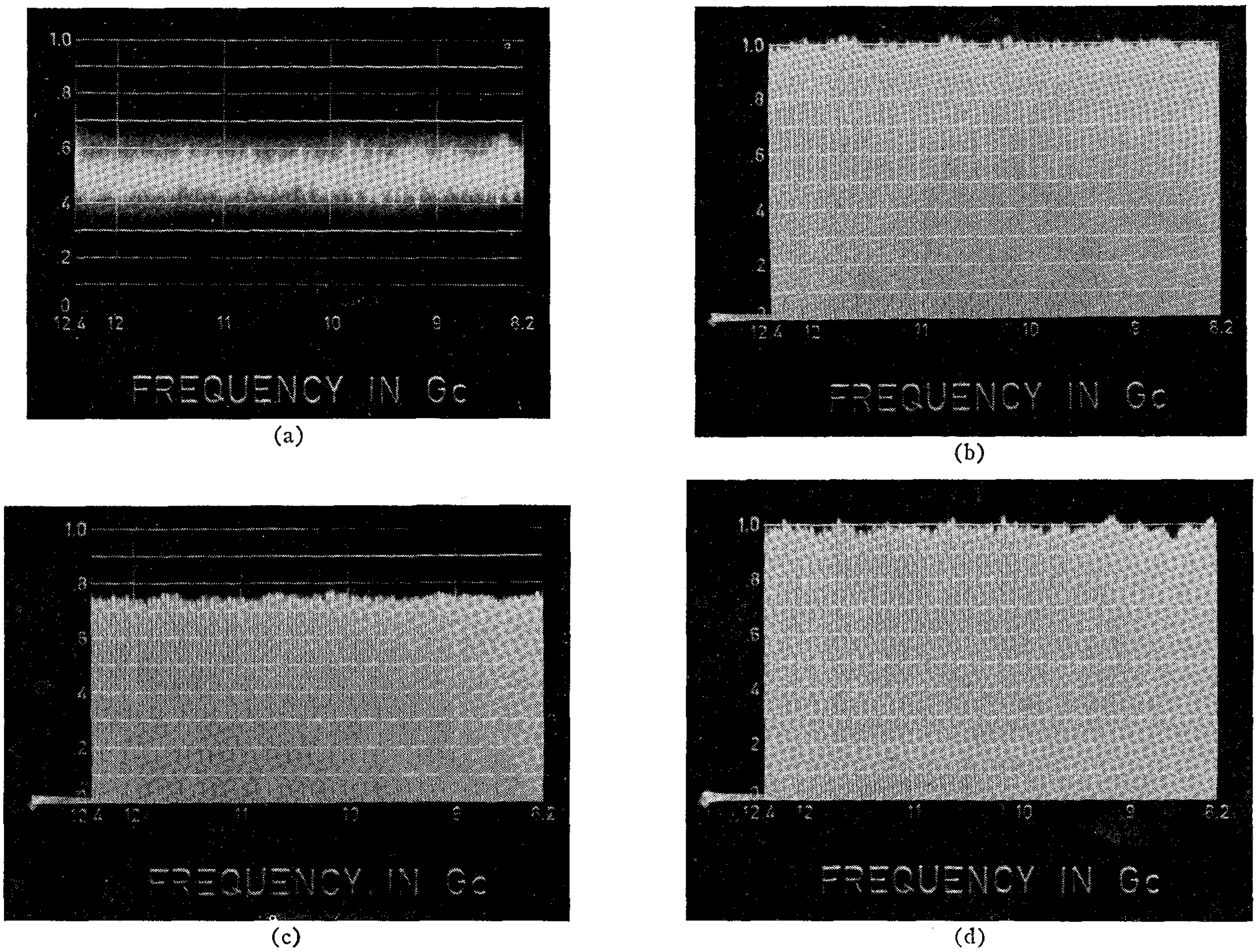

Fig. 4. X-band reflecto"meter" display of "standard" reflections. (a) $|R_{st}| \leq 0.001$ fs $|R| = 0.01$. Scope sensitivity 0.1 mV/cm. Display shifted vertically for better observation. (b) $|R_{st}| = 0.1$ flat within 0.004. $D = 3.75$ mm, $d = 0$. fs $|R| = 0.1$. (c) $|R_{st}| = 0.3$ flat within 0.006. $D = 6.05$ mm, $d = 1.87$ mm. (d) $|R_{st}| \geq 0.995$, fs $|R| = 1$.

amplifier can be omitted if the sweep oscillator is provided with an A.L.C. input (e.g. the Hewlett-Packard 694 A).

III. Standard Reflections

When a reflection characteristic, i.e., the reflection coefficient as a function of frequency, of any impedance is measured it is necessary to know the range and the precision of the reflecto"meter". These can easily be checked with frequency-independent standard reflections.

The simplest standard reflections are 0 and 1. An almost perfect load $|R_{st}| \leq 0.001$ was placed directly in the long line L in order to eliminate the reflection due to a discontinuity at the position of the flanges, which can soon reach a value of 0.005 even though precision waveguide is used throughout. The display can be seen in Fig. 4(a). For a standard reflection equal to unity, a quarter-wavelength short—$|R_{st}| \geq 0.995$—was used, and the resultant display is given in Fig. 4(d).

Between these extremes, very simple "standard" reflections of $|R| = 0.1$, 0.2, and 0.3 were made [3] by placing a dielectric tube of $\epsilon \approx 2.5$ and outer diameter D in front of the forementioned movable load. The tube was filled with a metal rod of diameter d, and with the right combination[5] of D and d values a nearly constant reflection over the waveguide band was obtained. The reflection coefficient due to the discontinuity at the position of the flanges can hardly be made less than a few per mils. So it is evident that it is very difficult and practically meaningless to speak about accuracies of a few per cent for a standard reflection of, e.g., 0.1. Although the "standard" reflections have been measured with a precision slotted line, reflection from the discontinuity can more easily be measured with the reflecto"meter." The discontinuity disappears when the nearly perfect load is placed directly in the long line.

IV. Sources of Error

In view of the precision to be achieved with swept-frequency measurement, some general sources of error can be distinguished. As perfect components do not exist, the frequency and even the power of the

[5] In [3] this had not been done because the purpose of the investigation was different.

e.m. wave may influence their behavior. The best solution is to try to use the simplest circuit, i.e., the circuit with the fewest and the best components possible. The frequency dependence appears in the reflection and transmission of the components, whereas the power influence, i.e., the nonlinear behavior, occurs at the nonlinear parts of the circuit, here the diodes.

In order to eliminate the effect of *power variation with frequency*, the sweep oscillator output must be leveled. The best results are obtained if the leveler and the measuring detectors are identical. For this reason diodes of the same type (1N26) and from the same firm are used in wall-current detectors of the improved version [2], which are checked and adjusted before measurements. If one wall-current detector is used as a leveler, the output of the sweep oscillator as seen by the others can be made flat within ± 0.1 dB for the whole X band.

Even if the perfect leveling were possible, the measuring detectors can cause errors due to variations in the crystal law which occur when the standing-wave pattern moves past the detectors. As these are situated a quarter-wavelength apart, this influence is more or less eliminated.

Another important source of error in swept-frequency measurement is the *reflection and the frequency-dependent transmission* of the components. Although frequency-dependent reflection is more severe, even frequency-independent reflection can cause errors. Usually the most complicated component gives the greatest difficulties, here the broadband isolator. Reflection at the input spoils the frequency characteristic of the leveler, giving an error independent of $|R|$. Reflection at the output causes multiple reflections between the isolator and the reflection to be measured, giving an error dependent on $|R|$. A reflection of one per cent gives an error of $\pm|R|$ per cent. In order to take full advantage of the low reflection of the pads flanking the isolator, flanges have been omitted between each pad and detector.

Although the insertion-loss of the isolator is rather low, it varies continuously and increases towards the ends of the waveguide band. This variation could be compensated by the screws behind the leveler.

Other reflections worth discussion are those of the wall-current detectors themselves and those of the long line L. As the reflection of one wall-current detector is not greater than one per cent [2], the reflection of two detectors at a quarter-wavelength distance does not exceed this value over the X band. As the reflection of the leveler is automatically eliminated, the reflection of the measuring detectors remains. It can easily be calculated that this reflection does cause two types of error. One is automatically eliminated by using the high-pass filters, the other by an adjustment for the range of reflection of interest.

Physically the most convenient long line seems to be a loop of waveguide. However, the smallest reflection and therefore the greatest accuracy, and at the same time the cheapest solution, has been obtained by taking a straight piece of unfinished precision waveguide provided with flat flanges. As this straight piece hardly gives any reflection, even the smallest broadband reflection, e.g., a movable load with $|R| \leq 0.001$, can be seen nicely [see Fig. 4(a)]. The influence of the losses of the long line and of their variation with frequency is automatically compensated when the reflecto"meter" is adjusted for a certain range.

To reduce the reflection at the flanges, which soon amounts to a half per cent, their number is minimized and flat flanges are used throughout. However, it is these errors that reduce even the accuracy of standard reflections, and the precision of a measurement is thereby limited.

Errors due to the electronic part of the circuit occur at the high-pass filters and probably in the oscilloscope. Switching transients influence the amplitude of the reflection at the starting point (12.4 Gc) of the sweep oscillator. This can be reduced by a small change of the starting frequency. Deviations of the linearity of the scope can be neglected for the type used.

V. Performance

The performance of the reflecto"meter" largely depends on the adjustment of the leveler and measuring detectors. Besides being accurate, the reflecto"meter" is also sensitive. Reflections as small as 0.001 can be measured, an especially for these it is evident that detector identity has a great influence on the accuracy. If, for reflections which are very close to 1, a high accuracy is needed, profit can be taken from resonance measurements, which can be performed, e.g., by a plotter as described elsewhere [4].

Standard reflections have been used to compare the reflecto"meter" with a precision slotted line. The highest precision is obtained if the system is adjusted for maximum flatness and maximum deflection for the range to be used. So for measurements in the range $|R| \leq 0.1$, adjustment has been made such that 1 on the scale of the graticule corresponds to $|R| = 0.1$, etc. The results are given in Fig. 4. The values for flatness have been obtained from precision slotted-line measurements at 10 frequencies equally distributed over the X band. As the accuracy of the slotted line was estimated to be ± 1 per cent, expressed in reflection coefficient, an insight into the accuracy of the reflecto"meter" can be obtained.

Although the reflecto"meter" has been especially developed for full-band display, even the most frequency sensitive reflections such as spurious resonances can be detected, as shown in Fig. 5, where the reflection of a wavemeter with a Q of about 5000 is clearly visible. The greater the length of the long line, the better the resolution. If rectification had been used in order to display only the envelope, probably the pip would have disappeared. At this type of reflection, usually the phase also varies very rapidly with the frequency. Then a narrow-band display of both amplitude and phase is sufficient

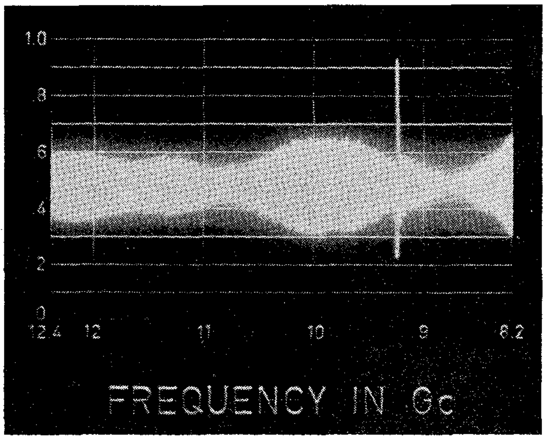

Fig. 5. Display of H/P X-532 frequency meter, terminated by a matched load. Display shifted vertically for better observation. fs $|R|=0.1$.

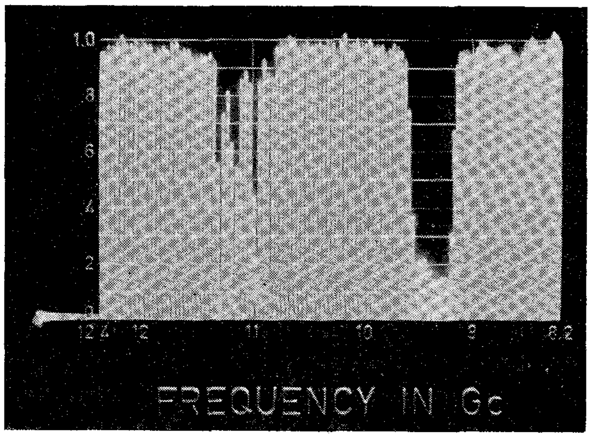

Fig. 6. Reflection characteristic of a rejection filter for 9200–9600 Mc. fs $|R|=1$.

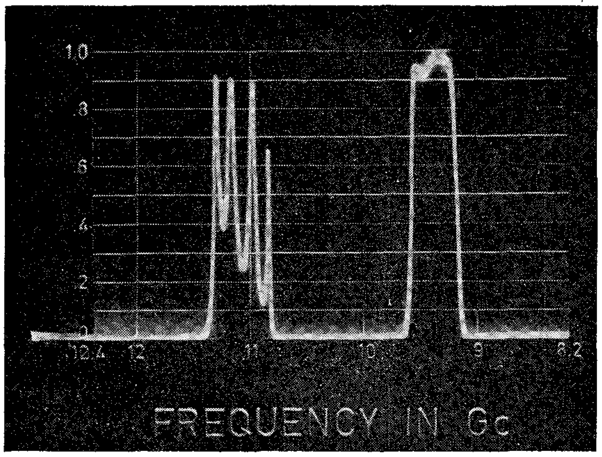

Fig. 7. Transmission characteristic of the same filter.

over 10 per cent maximum of the center frequency, for which a plotter [4] can be used under swept-frequency conditions. As an example, Figs. 6 and 7 show the behavior of a rejection filter.

VI. Conclusion

With the reflecto"meter", automatic precision measurement of reflection or transmission coefficients as a function of frequency at microwaves is made possible. Not only is much time saved in research and development, but also a better understanding of microwave phenomena is achieved; therefore, the reflecto"meter" could be very useful for teaching purposes. The principle of the reflecto"meter" can be applied for other wavelengths or transmission lines, provided identical detectors and preferably reflectionless components are available for these. If a quarter-wavelength detector unit is used with sum, or difference detectors [1], analogously transmission measurements can be done, i.e., with the same accuracy, sensitivity, and linear scale for the magnitude of the transmission coefficient.

The reflecto"meter" can be seen as the counterpart of the time domain reflectometer (TDR) [5] and may be called frequency domain reflectometer (FDR). Because of dispersion the TDR cannot be used so easily for waveguides. Both systems have their own use. The reflecto"meter" is less costly and easier to make for higher frequencies.

Acknowledgment

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