diode terminals is no longer equal to G_0, the value established in the previous step.

Suppose now that with the susceptance in place the line section L_2 is varied in length, say, by a line stretcher. Since this section sees a match at its output terminals t-t' (the tuner is unaltered), it follows that the admittance presented to the LO does not change in this operation; that is, the LO excitation at the diode terminals is independent of L_2. On the other hand, the admittance looking back from the diode terminals does vary with L_2 and, in fact, traces the circle shown in Fig. 3, as is well known from transmission line theory.[5]

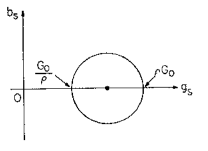

Fig. 3—Locus of the admittance y_s.

Using the equation for this circle one may eliminate the term b_s^2 in (1). The real part G_{out} of the resulting expression takes the form

$$G_{out} = g_0' - \frac{2g_1^2(g_0'+g_s-g_2)}{(g_0'^2-g_2^2-G_0^2)+g_s[2g_0'+G_0(\rho+1/\rho^{-1})]}. \quad (4)$$

This expression applies to any setting of the line stretcher. Since G_{out} is an increasing function of g_s, it follows that as the line stretcher is varied, the highest and lowest values of G_{out} measured by the bridge, which we denote by g_h and g_l, correspond to the highest and lowest values of g_s, namely, ρG_0 and G_0/ρ, respectively. It also is evident that G_{out} measured in the previous matched condition, which we denote by g_m, corresponds to $g_s = G_0$, $\rho = 1$.

Applying these three sets of conditions to (4) and using the identity for G_0 given by (2), we obtain three simultaneous equations which we can then solve for the mixer conductances. We obtain

$$\begin{aligned} g_0 &= g_0' - G_s & \text{(a)} \\ g_1^2 &= g_0'(g_0' - g_m) & \text{(b)} \\ g_2 &= \frac{1-k}{1+k}\left(\frac{\rho+1}{\rho-1}\right)g_0', & \text{(c)} \end{aligned} \quad (5)$$

where

$$k = \frac{g_m - g_l}{g_h - g_m} \quad \text{and} \quad g_0' = g_h + \frac{g_h - g_l}{\rho k - 1}.$$

It is unnecessary to resolve the algebraic sign of g_1, since only $|g_1|$ or g_1^2 appear in equations pertaining to mixers.[2,6] Thus the desired mixer conductances can be calculated using four easily measured quantities.

Several precautions should be observed using Dicke's method. For example, an attenuator should be inserted between the LO and the standing-wave indicator to isolate the line from any admittance fluctuations of the LO. The attenuator can also be used to vary the oscillator output. It might be mentioned at this point that the tuner need not be connected directly to the diode terminals but can be any multiple of a half wavelength away from the diode reference plane. The audio bridge signal amplitude should be no greater than about 5 mv p-p to insure linear operation at the IF terminals.

A schematic diagram of a possible mixer test jig is shown in Fig. 4. The blocking capacitor C_b isolates the bias supply from the LO circuit. A path for direct current must exist in the bridge circuit, however.

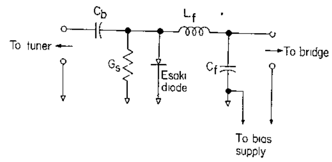

Fig. 4—A possible mixer test circuit for the Dicke method.

The choke L_f and capacitor C_f decouple the bridge from the LO circuit. The reactance of L_f and the susceptance of C_f should be large at the LO frequency but small at the bridge frequency. If C_f is too large, one must reduce the measured output capacitance by the value of C_f to obtain the true diode capacitance C.

In closing it should be mentioned that if the diode series impedance is not negligible or if the diode capacitance is voltage dependent, the more general but less convenient form of Dicke's method must be employed.[1]

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[5] W. C. Johnson, "Transmission Lines and Networks," McGraw-Hill Book Co., Inc., New York, N. Y.; 1950.

[6] C. S. Kim and J. E. Sparks, "Tunnel Diode Converters," *Proc. Natl. Electronics Conf.*, vol. 16, pp. 791–800, 1960.

A Versatile Phase Measurement Method for Transmission-Line Networks*

Current phase-measurement methods[1] for transmission-line circuits fall into two general categories. The first is the comparison method, where the path under measurement is compared with another calibrated, variable one. The phase shift through the variable path is adjusted to equal that of the unknown path, and this condition is shown by a null detector. Null indication by both phase and amplitude adjustment is usually required; however, null indication by phase adjustment alone[2] can be effected. The second category of phase measurements includes those measurements which provide voltage or meter output indication of phase angle. This category includes direct high frequency phase-detector circuits of limited frequency range or frequency-conversion methods where analog or digital circuits measure phase at a converted lower frequency.

The new method to be described here is an extension of the second category, which is the meter or voltage indication of phase. It is capable of direct measurement over a broad frequency range. Fig. 1 shows the arrangement of the phase meter equipment. The RF signal source for the phase measurement is amplitude modulated (sine wave or square wave). This modulation signal is carried as a sync to the synchronous detector. The RF signal is split, with one path going directly to one end of the slotted line as a reference phase signal and the other path going through the network under measurement. The output of the latter network feeds the other end of the slotted line as the unknown phase signal.

Fig. 2 develops the relations between the two RF field vectors, the individual square detector probe outputs, and the differential output of the two probes constituting the phase detector. The independent variable is the relative phase angle θ of the two RF signals for a fixed position X in the slotted line or the converse, variable position with fixed phase angle.

The vector diagram shows the resultant field vector E_t vs the RF phase angle θ. With a square law detector, the cosine law of triangles shows the output to be a constant term $(E_1^2+E_2^2)$ plus one varying with the cosine of phase angle θ. This relation is plotted for equal and unequal reference and unknown vectors E_1 and E_2.

The differential output $(V_a - V_b)$ of a pair of spaced probes is proportional to the sine of the phase angle. This allows the use of calibrated scales on the meter. The positive and negative output is provided by using a modulated RF test signal and a synchronous detector at the output of the amplifier. The meter and voltage output is calibrated by moving the phase detector successively to positions for the maximum positive and negative outputs. The amplifier gain and a balance control are adjusted so that these two outputs are fixed meter currents labelled $+90°$ and $-90°$. After calibration, the phase detector is positioned at the exact center of the slotted line to read the absolute phase difference of the two input signals referred to slotted line input terminals. The meter indication covers a 180° sector; to determine which of the two possible sectors the phase lies in, the phase detector is moved toward the unknown input. If meter motion is positive, the meter indication is correct. If a negative motion is obtained, the phase lies in the 90° to 270° sector and the actual angle is 180° minus the angle indicated on the meter.

High resolution is obtained by operating the phase meter near a zero and increasing the gain by definite amounts corresponding to meter scales; typical ranges are $\pm 90°$, $\pm 20°$, $\pm 6°$, $\pm 2°$, etc. In this mode of operation the distance of the phase detector from the center of the line is converted to a phase

* Received by the PGMTT, June 6, 1961.

[1] F. E. Terman and J. M. Pettit, "Electronic Measurements," McGraw-Hill Book Co. Inc., New York, N. Y., p. 267; 1952.

[2] S. D. Robertson, "A method of measuring phase at microwave frequencies," *Bell Sys. Tech. J.*, vol. 28, pp. 99–103, 1949.

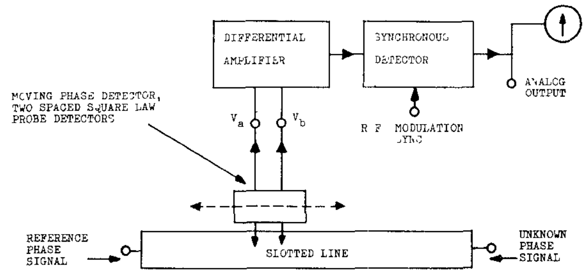

Fig. 1—Direct-reading microwave phase meter (using double square-law probe phase detector on slotted line).

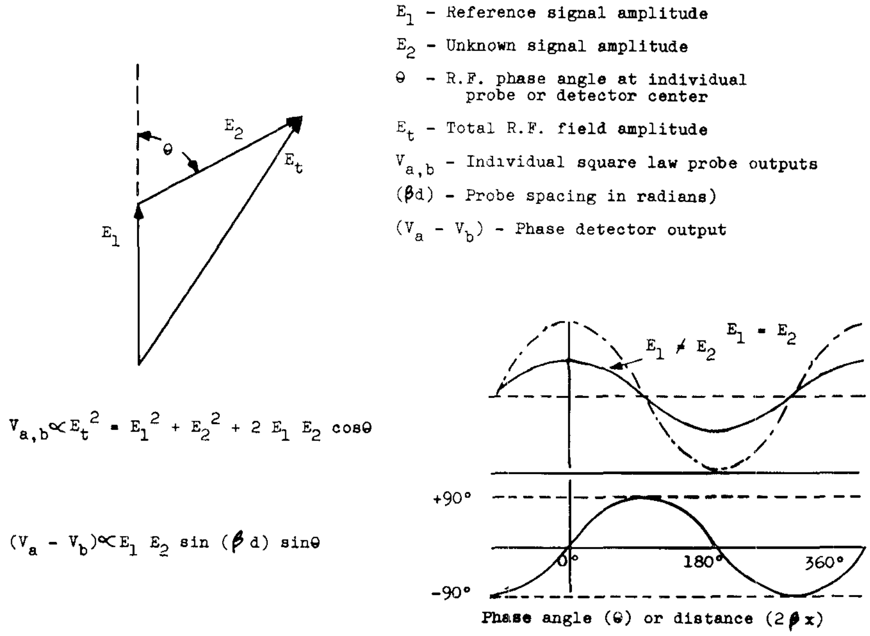

Fig. 2—Individual probe and phase detector output relations.

angle ($2\beta x$) and this angle is added to the meter indication.

The spacing of the two probes determines only the sensitivity of the phase detector. For broad frequency use, the spacing can be a quarter wavelength at the center frequency.

Phase measurement accuracy in transmission systems is frequently limited by reflections. The moving-probe type of phase detector provides inherently low reflection measurement apparatus. Equality of reference and unknown signal amplitudes is not required for operation; however, it is desirable in order that errors due to reflections of the strong signal in the weak signal channel may be kept to a minimum value.

This phase meter method has been used from 300 Mc through X band with 10:1 frequency range for a fixed spacing of the two probes.

For power levels of 1 to 10 mw for the reference and unknown signals, a sensitivity of 0.1° has been obtained with 1-kc modulation.

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A VHF High-Power *Y*-Circulator*

A number of articles [1] on the theory, design and application of three-port circulators may be found in the literature. Specific devices of this kind are commercially available for low signal power levels. In this letter a high-power version of a three-port or Y-circulator is presented. The characteristics measured at high power are compared with measurements performed at low power.

A strip-line structure was chosen for the junction configuration. To obtain a required $\pm 2\frac{1}{2}$ per cent bandwidth at the center frequency of 220 Mc, with a constant applied magnetic field, the junction geometry of the center conductor was chosen in the form of a clover leaf. A MnMg aluminate ferrite (such as Trans-Tech 414)[1] with a low saturation magnetization was selected to obtain the desired performance at these low frequencies. The rather unfavorable temperature characteristics of this material, however, necessitated forced cooling. The ferrite disks above and below the strip-line junction are placed in a pillbox enclosure. The space between the edge of the circulator ferrite disks and the inner wall of the circular enclosure is filled with a coolant of low loss, high dielectric strength fluid such as Freon 113 (Trichloro-trifluoroethane).[2]

In the high power environment, care has to be taken to avoid discontinuities in dielectrics to prevent electrical breakdown. On the design being presented, electrical breakdown was observed with dc above 15 kv. The attenuation introduced by the dielectric loss of the coolant is insignificant in the 200-Mc region.

The circulator element was designed with the following geometric parameters. A ferrite disk of 5-in diameter is used. The enclosure diameter was chosen to be 7 in. Fluid inlets and outlets are distributed around the periphery of the circular enclosure and located in the three electrically-neutral regions (60° off each port). A thermocouple consisting of a Chromel-Alumel wire pair is attached to the top ferrite disk so as not to interfere with the circulating coolant. Two holes are situated at the top and bottom ground plate to facilitate the escape of air during the filling process. Fig. 1 shows an exploded view of the circulator element.

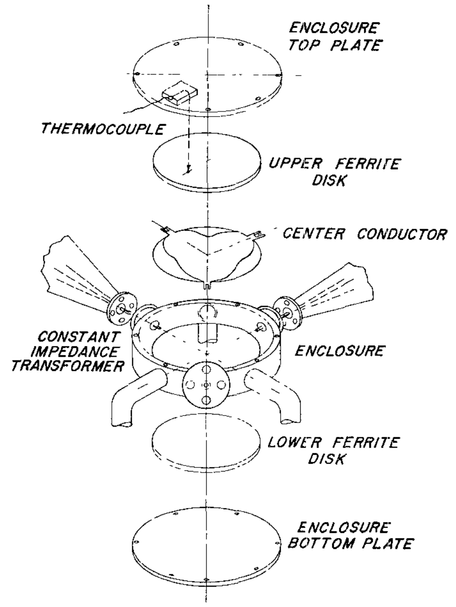

Fig. 1—Exploded view of the Y-circulator element.

To enable the investigation of the circulator over an appreciable bandwidth a broadband transformer design was selected for the three ports. For a limited frequency band of operation, a compensated transformer of reduced length is desirable to reduce the overall size and weight of the circulator.

A coolant such as Freon 113 was selected primarily for electrical reasons. The ferrite disk temperature has to be kept at approximately 24°C at a maximum of 2 kw average transmitted RF power. The dissipated power is then of the order of 200 w. The cooling volume of the circulator is in the order of 120

* Received by the PGMTT, July 25, 1961, revised manuscript received, August 31, 1961.

[1] TT414 is a product of Trans-Tech., Inc., Gaithersburg, Md.

[2] Freon 113 is a product of the Du Pont Co., Wilmington, Del.