A Shunt Technique for Microwave Measurements

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Summary—**A new method of measuring low-loss quantities at microwave frequencies, which employs a lossy shunt structure, is described. The additional loss introduced thereby reduces the excessively high VSWR's to values lying in the measurable range. The relevant information is abstracted from the data in a precision manner independent of the parameters of the shunt structure itself. Applications are made to the measurement of low-loss dielectric constants, structures with shunt representations such as certain bolometer elements, attenuation constants, and VSWR's of slightly lossy variable short circuits. Physical realizations of such shunt structures are discussed.**

I. Introduction

In the measurement of the properties of low-loss microwave structures one normally encounters difficulties in measuring the associated high values of VSWR or their equivalent. One often attempts to overcome these difficulties by the use of physically large samples, where this is possible, or to go to special instrumentation more suited to the measurement of very high VSWR. When, for some reason, these alternatives are both impractical, it becomes suggestive to introduce dissipation into the measurement system by artificial means in order to reduce the values of VSWR to be measured. The analysis of the data must then be carried out in such a manner that the desired result is separable from the artificially introduced loss. A method of introducing such loss is furnished by the shunt technique described herein, which employs a lossy shunt structure in conjunction with otherwise standard laboratory equipment.[1] These shunt structures are realizable in a simple manner and may be of relatively arbitrary value and shape. In addition to the advantage of measuring in the lower VSWR ranges, where noise and instability are not so critical, and to the ensuing simplification in instrumentation, the techniques presented here incorporate averaging procedures which serve to reduce certain errors and which permit an estimate of the remaining errors. It must, of course, be assumed that the lower values of VSWR can be measured accurately by the use of one of the various schemes commonly employed to do this.

The principles underlying this technique are given below, followed by examples of their application to the measurement of low-loss dielectric constants, attenuation constants of waveguide, VSWR's of slightly lossy variable short circuits and input admittances of low-loss shunt structures. Some representative experimental data are given and the detailed physical realizations of some lossy shunt structures are discussed. Since the shunt technique involves the use of a circular locus in the reflection coefficient plane, an appendix describing a method for obtaining the circle parameters in a precision manner has been included. This method is applicable not only in connection with the shunt technique, but wherever the exact parameters of a circle arbitrarily located in a polar system are to be found.

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[1] J. H. Vogelman has independently employed the deliberate introduction of loss into a variable short circuit for the measurement of small waveguide attenuations; his procedure, which is quite different from the one described here, appears in "Precision measurement of waveguide attenuation," *Electronics*, vol. 26, pp. 196–199; December, 1953.

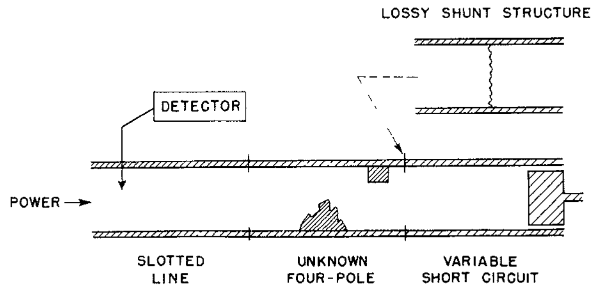

Fig. 1—Experimental set-up for four-pole measurements.

II. Underlying Principle

A commonly used experimental set-up for measuring four-pole parameters includes, except for the lossy shunt structure, the apparatus shown in outline in Fig. 1. Each such (or similar) set-up, regardless of how elaborate it may be, and quite apart from the losses in the measuring system, has associated with it an upper limit of VSWR, assuming some given accuracy, beyond which no measurements can be made. This upper value can be expressed in the Γ, or voltage reflection coefficient, plane as the "limit circle," as in Fig. 2 (facing), outside of which VSWR measurements cannot be carried out. It is well known that as the variable short circuit is moved through all possible positions the input data forms a circle in the Γ-plane.

If the loss in the unknown four-pole is so small that the data would fall outside the limit circle, the insertion of a lossy shunt structure between the four-pole and the shorting plunger (see Fig. 1) will in general cause the input reflection coefficients corresponding to the various plunger positions to be reduced to measurable values. Typical data before and after the insertion of the lossy shunt structure are indicated in Fig. 2 by the crossed and circled points, respectively. The knowledge of a sufficient number of isolated points (at least three) on such a circular locus suffices to specify all points on the locus. One of these points is of special interest here: the point corresponding to that position of the plunger which effectively shorts out the shunt element, i.e., the plunger position $n\lambda_g/2$ away from the shunt element. (λ_g is guide wavelength; $n=0, 1, 2, \cdots$.) It is apparent that the input reflection coefficient associated with this position of the short circuit is unaltered by the insertion of the shunt structure. Therefore, by the measurement of the positions of the minima and the values of VSWR which have been reduced by the insertion of a lossy shunt structure, one can draw a circle which includes a datum point independent of the shunt circuit parameters and lying outside the normal measurement range. This point may be chosen deliberately by placing the shunt element in a special known position with respect to the four-pole. Although an arbitrary number of such datum points can be measured in this fashion so that the data defining a low-loss reciprocal four-pole might be obtained, it is felt that this procedure is most suitable for finding quantities derivable from a single datum point.

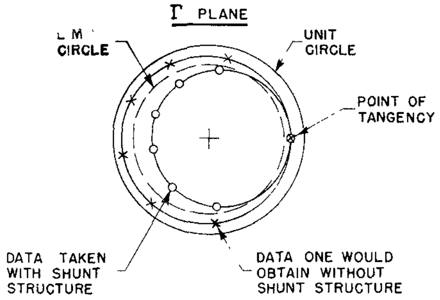

Fig. 2—Loci in the Γ-plane with and without shunt structure.

The shunt element under discussion is a lossy microwave structure in uniform waveguide which can be represented by a single complex shunt admittance at appropriate terminal planes. Although the detailed physical realizations of such elements are discussed later, it is appropriate to mention here that thin lossy films mounted in the transverse plane of the guide are useful for this purpose. Such films have a shunt representation at a single plane (i.e., input and output terminal planes coincide with the geometrical plane of the film), and the discussion below is limited to them for the sake of clarity. Extension of this material to shunt structures with representations at two noncoincident terminal planes, where this is applicable, will be self-evident.

A shunt film in conjunction with a variable short circuit [see Fig. 3(a)] takes on the network form shown in Fig. 3(b), where B' is the susceptance of the shorted (variable) length of transmission line as viewed from the plane T_{s+} (just to the right of T_s). As the plunger is varied through all positions the locus of the input admittance as seen from T_{s+} is the line $G=0$, i.e., the imaginary axis of the admittance plane, while the locus seen from T_{s-} (just to the left of T_s) is the line $G=G_s$. These loci have in common only the point at infinity, i.e., the point at which the plunger effectively shorts out the shunt film.

When this combination of circuit components is used to terminate a passive four-pole (see Fig. 4), the locus of Γ at T_1 (see circled points in Fig. 2) corresponding to the output admittance locus $G=G_s$ must be circular in view of the bilinear transformation from the output admittance plane to the input Γ plane. The circle obtained at T_1 in the absence of the shunt film (represented by the crossed points in Fig. 2) is the transformation of the line $G=0$ through the same four-pole. Since the two loci $G=0$ and $G=G_s$ have one point in common, the corresponding transformed loci in the input Γ plane likewise must have one, and only one, point in common and are consequently tangent to each other. This property of tangency minimizes the possibility of error associated with the use of the shunt film since tangency implies that, for practical purposes, the circles coincide along a small arc in the neighborhood of the tangent point; the circle modified by the shunt structure therefore reproduces to a very good approximation the unmodified circle near the tangent point.

In summary, by placing the shunt structure at some point between the four-pole and the short circuit, taking input data for various positions of the short circuit, plotting these in the input Γ plane and completing a circle through the points, one has determined a circle on which that point corresponding to a short circuit at the plane T_s (or $n\lambda_g/2$ away) is identically the datum point which would have been obtained if the shunt structure had not been present.

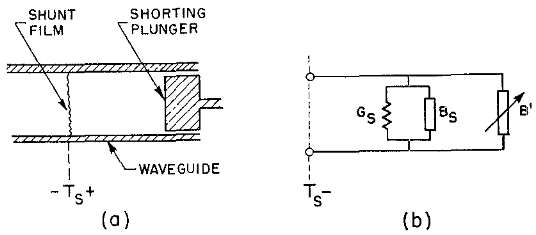

Fig. 3—Shunt film combined with variable short circuit. (a) Combination of a variable short circuit and a lossy shunt film, (b) representation of the same combination at T_s-.

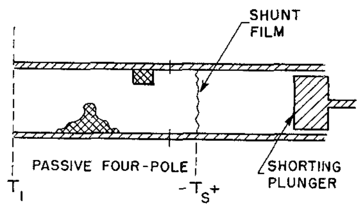

Fig. 4—Actual termination being measured.

III. Applications to Specific Measurements

1. Low-Loss Dielectric Constant

The principle outlined above is especially applicable to the Roberts and von Hippel method of dielectric constant measurements[2] in that the latter requires only the

[2] S. Roberts and A. von Hippel, " A new method for measuring dielectric constants and loss in the range of centimeter waves," *Jour. Appl. Phys.*, vol. 17, pp. 610–617; July, 1946.

knowledge of the input reflection coefficient corresponding to a short circuit located exactly at the output end of the dielectric sample. The usual procedure is modified as follows: A short circuit is placed immediately behind and touching the dielectric sample, and the position D of the voltage minimum in the slotted line is measured. (Presumably, the VSWR cannot be measured accurately enough with the equipment on hand.) The short circuit is then replaced by a shunt film (which can be realized by painting the end of the sample itself with Aquadag) and by a variable short circuit, as shown in Fig. 5.

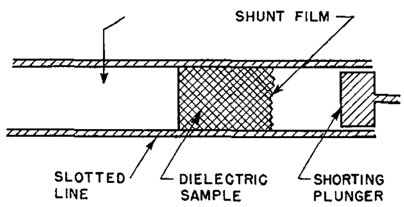

Fig. 5—Measurement of dielectric sample.

Input datum points are taken and plotted in the Γ plane as discussed in the preceding section. The desired short circuit point is then the point of intersection between the circle drawn through the plotted points and the radial line in the Γ plane corresponding to the minimum position D measured earlier. From this point, which is the input reflection coefficient of the shorted sample, the dielectric constant is computed in the usual transcendental manner. A typical set of data for a dielectric sample[3] measured with and without a shunt film is shown in Fig. 6. By drawing the best circle through

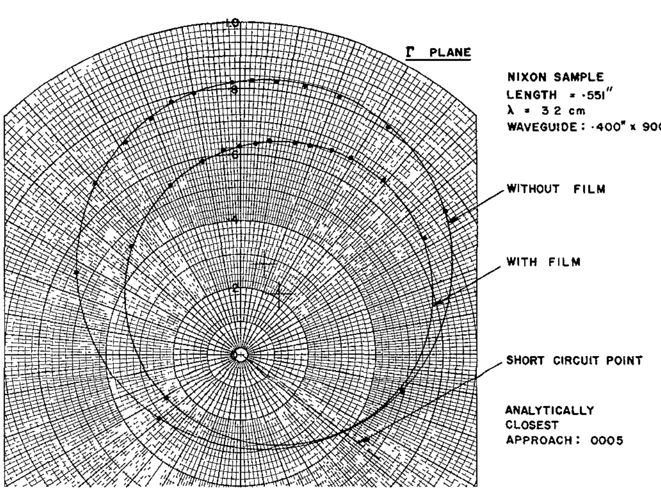

Fig. 6—Dielectric constant measurement data.

the points by analytical means (see Appendix), it was found that the circles were tangent to each other to within .0005 times the radius of the unit circle. It is understood that appropriate corrections for the dissipation in the variable short circuit and the associated waveguide must be made when this loss is of significance.

2. Admittance of Low-Loss Structures with Shunt Representations

The low-loss structures under consideration now (for example, certain bolometers) are those representable by shunt networks. The admittance of such a shunt structure is given simply by its input admittance when it is terminated by an open circuit. When the conductive part cannot be measured directly by the equipment on hand, the complex admittance can be successfully determined by the use of an "auxiliary"[4] shunt film.

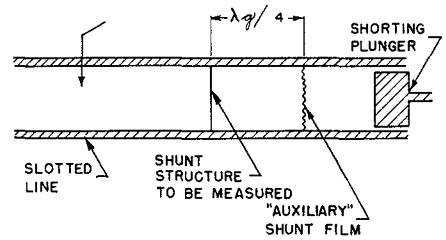

Fig. 7—Measurement of a low-loss shunt structure.

The measurement procedure is indicated in Fig. 7. The "auxiliary" shunt film is placed $\lambda_g/4$ behind the shunt structure to be measured, and the appropriate data are taken and then plotted in the manner indicated earlier. That point on the circle corresponding to the position of the variable short circuit when it effectively shorts out the "auxiliary" shunt film is the input reflection coefficient from which the desired admittance is computed. In certain situations it may be more convenient to choose some distance L between the shunt elements other than $\lambda_g/4$. The procedure above must then be modified to account for the terminating admittance which now corresponds to the input admittance of a short-circuited line of length L rather than to an open circuit. Of course, the usual corrections for guide wall losses must be made when these become comparable to the dissipation in the measured shunt structure.

In order to indicate the order of magnitude of the quantities involved and the accuracy to which they can be measured, the results of a measurement on a certain bolometer element are given here. After accounting for dissipation in the guide walls, the bolometer was found to have an input reflection factor of $(0.968 \pm .002)$ exp $[j(2.123 \pm .008)]$, which results in an admittance of

$$\left(0.068 \begin{matrix} + .003 \\ - .006 \end{matrix}\right) - j\left(1.789 \begin{matrix} - .019 \\ + .047 \end{matrix}\right).$$

It is worth noting that the values of VSWR actually measured did not exceed 20, although the reflection

[3] In order to demonstrate the tangency of the two circles experimentally, we have employed a sample (Nixon) with a higher loss tangent than those for which this method is actually intended.

[4] The term "auxiliary" is used in connection with this application to differentiate between the shunt structure to be measured and the lossy film introduced to bring the data within the measurable range.

factor of interest corresponds to a

$$\text{VSWR of } 61.5 \begin{matrix} +4.3 \\ -3.7 \end{matrix}.$$

Maximum errors are indicated.

3. *Attenuation Constant of Waveguide*

Whereas knowledge of the location of the shunt film relative to the structure being measured was essential in the preceding two applications, the film may be located arbitrarily along the direction of propagation in the measurement of α, the attenuation constant of waveguide. Actually, two measurements are made as indicated in Fig. 8(a) and (b). The first measurement, (a), is for calibration purposes, and must therefore include the same apparatus as that used in the measurement of the sample described by Fig. 8(b).

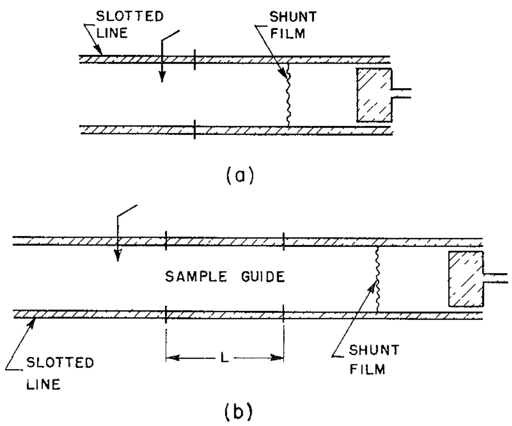

Fig. 8—Measurement of attenuation.

The variable short circuit and the waveguide connecting it to the shunt film are assumed to have the usual small metal losses so that when the variable short circuit is placed $n\lambda_g/2$ away from the shunt film, a very small resistance effectively "shorts" out the shunt film (which is assumed to have a much higher resistance of its own). With the short circuit in this position [in both Fig. 8(a) and (b)], the slotted line sees all the loss associated with the setup except for the dissipation in the shunt film The loss seen is then at a minimum and consequently the corresponding input reflection coefficient is given by that point (on the circle drawn through the plotted datum points) which is closest to the unit circle. The attenuation constant follows as

$$\alpha = \frac{1}{2L} \ln \frac{|\Gamma_a|}{|\Gamma_b|} \text{ nepers/unit length,} \tag{1}$$

where $|\Gamma_a|$ and $|\Gamma_b|$ are the maximum reflection coefficient magnitudes on the circles resulting from the measurements indicated in Fig. 8 (a) and (b), respectively. When both $|\Gamma_a|$ and $|\Gamma_b|$ are almost equal to unity, as they usually are in these measurements, one can approximate α by

$$\alpha = \frac{|\Gamma_a| - |\Gamma_b|}{2L} \text{ nepers/unit length.} \tag{2}$$

Since, in effect, the results of two measurements have been subtracted from each other to yield α, accuracy is increased when both measurements are carried out under conditions as closely identical as possible. It is advisable, for example, to use sample guides $n\lambda_g/2$ long so that the same regions of the slotted line are used in both measurements.

The measurement of α in this manner generally permits the use of shorter sample guides than the usual procedure involving the direct measurement of input VSWR, although sample guides here should not be shorter than about $2\lambda_g$. When relatively long guides are measured, the procedure outlined here is sensitive to errors from frequency and temperature fluctuations.

Measurements of the attenuation constant of various sample lengths of brass rectangular guide were carried out at $f = 9{,}375$ mc. The calibration measurement (a) was performed once, while measurement (b) was repeated for 3-inch, 6-inch, 9-inch, and 18-inch lengths. The reflection coefficients obtained by analytical means from this data[5] yield the results exhibited in Fig. 9, where the definition $\delta_{a,b} = 1 - |\Gamma_{a,b}|$ has been adopted since all values of $|\Gamma_{a,b}|$ involved are almost unity. In these terms, one can write

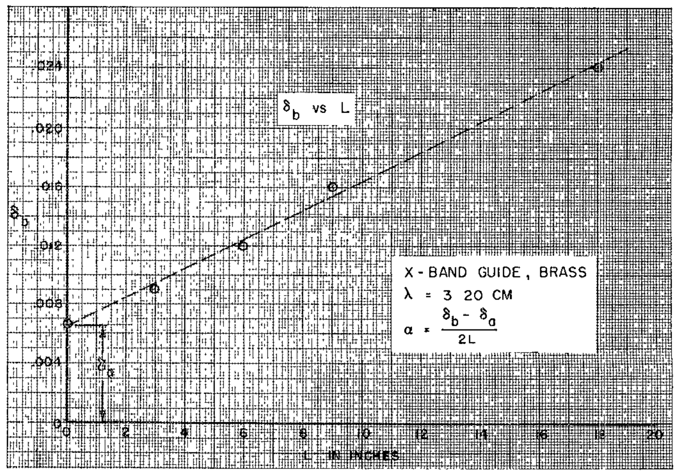

Fig. 9—Experimental results of attenuation constant measurements.

$$\alpha = \frac{\delta_b - \delta_a}{2L} \quad \text{or} \quad \delta_b = (2\alpha)L + \delta_a, \tag{3}$$

the equation of a straight line which intercepts the δ_b axis at δ_a, the value associated with calibration measurement (a). The various values of δ obtained experimentally are indicated in Fig. 9, together with a line defined by the last equation drawn through the average of these points. The small experimental scatter shows the sensitivity of this method to change in reflection factor caused by insertion of short, almost lossless guide.

[5] See Appendix; $|\Gamma_{a,b}| = (r_0' + \rho')_{a,b}$.

4. *VSWR of a Slightly Lossy Variable Short Circuit*

Variable short circuits, especially when they are designed for broadband use, often have associated with them small losses which, at any one frequency, can be expressed as the $(VSWR)_s$ of the short circuit. A series of input datum points taken with a slotted line terminated *only* in the lossy short circuit would yield for the associated reflection coefficient locus a circle of radius $|\Gamma_s|$ with center at the origin as shown in Fig. 10. If this circle lies outside the "limit circle," the insertion of the shunt film produces a measurable locus tangent to it, as indicated in Fig. 10, which yields the value of $|\Gamma_s|$, the reflection coefficient associated with $(VSWR)_s$.

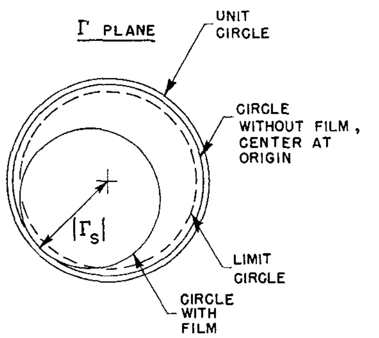

Fig. 10—Circles, with and without film, due to lossy short circuit.

If the loss in the variable short is known to be large compared to that in the associated lengths of line, the measurement just outlined furnishes a good approximation to $(VSWR)_s$. It is to be noted that the measurement of $|\Gamma_s|$ has in essence already been described above as measurement (a) in connection with the determination of α. The resulting value $|\Gamma_a|$, however, is representative of the total loss associated with the slotted line, the variable short circuit and with whatever connecting guides, if any, may be located between the slotted line and the short circuit. $|\Gamma_s|$ may be abstracted from $|\Gamma_a|$ if the guide losses in the slotted line itself and in the connecting guide are known. The attenuation constant of a connecting guide, α_g, and of the slotted line, α_{ss}, may be measured with an additional slotted line as described above, although it is usually sufficient to calculate these values theoretically. $|\Gamma_s|$ may be computed from

$$|\Gamma_s| = |\Gamma_a|(1 + 2\alpha_g l_g + 2\alpha_{ss} l_{ss}), \tag{4}$$

where l_g is the length of the connecting guide and l_{ss} the distance from the probe to the end of the slotted line. It can be shown that it is an excellent approximation to take the position of the voltage minimum associated with $|\Gamma_a|$ on the circle as the position of the probe used to define l_{ss}.

IV. Physical Realizations of Shunt Structures

As has been indicated in the second section, shunt structures which are representable at a single terminal plane may be realized by thin lossy films located in the transverse plane of the waveguide. Both Nichrome (NiCr) and Aquadag have been used by us for this purpose. NiCr films are relatively stable and as such are suitable for use in measurements extending over longer periods of time. These elements have been made successfully by evaporating a 500 ohms/square NiCr film onto a 5 mil thick plate of coverglass stock cut in the shape of the guide cross section. Although the shape of the film determines the susceptance of the shunt element, its exact shape and resistance are not of importance. It is preferable to prevent the film from touching the edge of the glass plate in order to avoid any dubious contacts between the film and the guide walls. With the use of a small amount of cement, such as Duco, the element is mounted carefully in the transverse plane of the guide. A well-machined jig has been found to be helpful in positioning the element exactly in the transverse plane. The element may be mounted either in a separate section of waveguide or in the same waveguide in which the short circuiting plunger moves. In order to keep small losses behind the shunt film at a minimum, the film should be placed as near to the short circuit as possible, provided that the separation between it and the plunger is always such as to avoid higher mode interaction. While in applications 3. and 4. the presence of the glass is of no consequence, it must be accounted for in 2. where the electrical position of the short circuit with respect to the film must be known for the one relevant plunger position.

In spite of their instability, Aquadag films were used in conjunction with the measurement of low loss dielectric constants primarily because of the ease with which such films can be painted on the surface of the samples. Solutions were made from commercially available Aquadag (22 per cent solid) and distilled water. A single application of a solution of one part Aquadag and three to four parts water by weight produced usable films. Even after the film appears to be dry to the eye its characteristics continue to change exponentially for a longer period of time (as determined by dc resistance measurements) so that about two hours should elapse between painting and the actual measurement. It was found that the rate of stabilization of the film could not be altered by the use of either an air blower or low temperature infrared baking. Even after the two-hour drying period these films continue to change in resistivity at a very slow rate, apparently in response to temperature and humidity conditions, so that the data associated with a single circle should be taken as quickly as possible. However, some dielectric constant measurements have been extended over a three hour period, and the effect of these small resistance changes was not reflected in the data. When it was found that certain dielectric materials could hardly be wetted with the Aquadag solution, the surface in question had to be "primed" with extremely small amounts of adhesive agents before the solution could be painted on.

In addition to their realization as thin transverse films, shunt networks may also be constructed in the form of a variety of resistively terminated or radiating thick slots and Tee structures. A simple example is a thick symmetric (H-plane) slot cut in the narrow side of rectangular waveguide, subject to the requirement that the wall thickness is greater than the slot width. The parameters of the corresponding shunt network may be adjusted somewhat, without changing the slot size, by altering the slot's termination. It can be shown that such a slot may be rigorously represented by a shunt admittance whose terminal planes are symmetrically disposed with respect to the slot symmetry plane, and are coincident with it only for extremely narrow slots. Once these terminal planes are located,[6] the measurement procedures outlined in the preceding section may be used after the appropriate slight modifications are made regarding the noncoincident terminal planes. Since in applications 3. and 4. the location of the terminal planes need not be known, no changes whatsoever are required.

Any symmetrical H-plane Tee with its stub arm either radiating or terminated in a dissipative load, may also serve as a lossy shunt structure. A coax Tee, for example, falls into this category. An appropriately terminated symmetrical E-plane Tee, or a thick symmetrical (E-plane) slot cut in the broad face of rectangular waveguide, is normally represented by a purely *series* network at appropriate reference planes; by a quarter-wavelength shift of both of these planes, however, the representation takes on the shunt form of interest here.

Appendix

Precision Determination of Circle Parameters

Let the parameters which uniquely define a circle in the polar system of the Γ plane be r_0 and θ_0, the coordinates of its center, and ρ its radius, where the coordinates of an arbitrary point[7] in the plane are $(|\Gamma|, \theta)$ as shown in Fig. 11. Then, given a set of datum points $(|\Gamma|, \theta)$, which according to theory must fall on a circle, one can plot these points, draw a circle C through them by eye and abstract the parameters r_0, θ_0, and ρ. The resultant parameter values are good approximations to the "true" values, i.e., to those values which define that circle, according to some criterion, which fits the data most closely. The approximate and "true" values are related by the small corrections Δr_0, $\Delta\theta_0$ and $\Delta\rho$ according to the equations

$$r_0' = r_0 + \Delta r_0, \quad \theta_0' = \theta_0 + \Delta\theta_0, \quad \rho' = \rho + \Delta\rho. \quad (5)$$

The analytical determination of these corrections is based upon a plot of Δd vs Φ, where Δd is the distance from the circumference of the approximate circle C to the individual data point $|\Gamma|$, θ, taken along a radial line of circle C. Φ is the angular co-ordinate of the datum point with respect to the same center measured in a clockwise direction from the line $\Phi = 0$ joining the center of C to the origin of the plane. Both of these quantities are shown in Fig. 11. Although the angles Φ may be obtained analytically, it is easier and quite sufficient to measure them with a protractor. Δd is computed from

$$\Delta d = \left[|\Gamma|^2 + r_0^2 - 2|\Gamma| r_0 \cos(\theta - \theta_0)\right]^{1/2} - \rho. \quad (6)$$

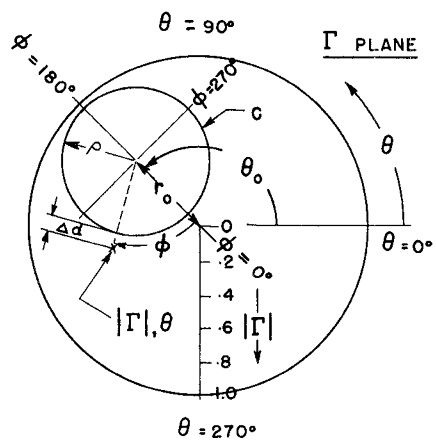

Fig. 11—Definition of geometric quantities in the Γ-plane.

Once a plot of Δd vs Φ has been obtained, a sine curve of the form $\Delta d = k_1 + k_2 \sin(\Phi - k_3)$ must be drawn through the plotted points in a manner conforming to the points as much as possible, but otherwise unrestricted except for periodicity. The drawing of the curve is facilitated if a set of "universal" sine curves of

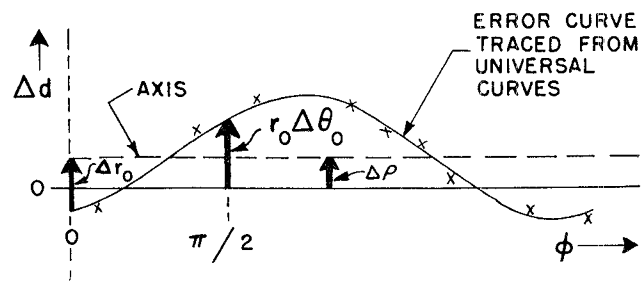

Fig. 12—Error curve.

equal period but differing in amplitude is drawn on transparent paper to the same scale as that used for the Δd vs Φ plots. The "universal" curves are placed under the Δd vs Φ plot and one of them (the error curve) is selected and traced onto the plot. During this process it is convenient to place a light source under the universal curves. The corrections Δr_0, $\Delta\theta_0$ and $\Delta\rho$ are defined in terms of the error curve in the manner indicated in Fig. 12. Here, Δr_0 is the distance from the

[6] These planes are given directly as the positions of the variable short circuit and the voltage null in the slotted section corresponding to zero radiation from the slot.

[7] $|\Gamma| = (\text{VSWR}-1)/(\text{VSWR}+1)$; $\theta = (720D/\lambda_g + 180)$ degrees, where D is the distance to the voltage minimum from the plane at which the reflection coefficient is defined.

error curve to its axis at $\Phi=0$; $r_0\Delta\theta_0$ is the distance from the axis to the curve at $\Phi=\pi/2$; $\Delta\rho$ is the distance from the line $\Delta d=0$ to the axis. These quantities are positive and negative, respectively, when the arrow points up and down. It may happen that no correction is indicated or possible, as occurs when the plotted points scatter about the line $\Delta d=0$, or when errors in the data cause such a disposition of the plotted points that they will not accommodate a sine curve of the required periodicity.

Although it is hardly ever necessary, the correction procedure can be repeated by treating the corrected parameters as approximate and finding a second correction. Much time can be saved in doing this if the second error curve is deduced from the first by taking the Δd's for the second curve as the vertical distance from the first error curve to the plotted points. This distance is positive or negative, respectively, when the plotted point in question lies above or below the first error curve. The values of Φ obtained for the first error curve may be used without alteration for the second error curve.

The magnitude of the scatter of the points about the last error curve drawn is indicative of the limits of experimental precision. From this scatter one can deduce tolerances to be put on corrected values r_0', θ_0' and ρ'.

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A Rotary Joint for Two Microwave Transmission Channels of the Same Frequency Band

H. P. RAABE†

Summary—**This paper describes a rotary joint for two microwave transmission channels of the same frequency band. It consists of two pairs of rectangular waveguide terminals, a circular waveguide which transmits both channels, and coupling elements between the rectangular waveguide terminals and the circular waveguide which convert the rectangular H_{10} mode into the circular H_{01} and E_{01} modes. If pure H_{01} and E_{01} modes can be excited, perfect separation of the channels as well as constant amplitudes and phases can be obtained when the joint rotates. While the conversion into the circular E_{01} mode is performed by a conventional method, a new method had to be developed for the conversion of the rectangular H_{10} into the circular H_{01} mode.**

INTRODUCTION

ROTARY JOINTS for microwave transmission channels have wide application in the field of radar as a link between the stationary transmitter-receiver apparatus and the rotating antenna. Since transmitted and received power is generally guided through the same channel, only single rotary joints are required. However, complex radar systems may require double transmission and receiving channels. For such systems double rotary joints must be devised.

In this report a new type of double rotary joint (DRJ) is described which represents the class of multiple mode rotary joints. The basic idea is this: If the diameter of a circular waveguide is large enough to allow transmission of more than one circularly symmetrical mode, and if it is possible to excite any of these modes individually, there will be no crosstalk between the channels when simultaneously transmitted.

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PART I: DESIGN PRINCIPLE OF THE DOUBLE ROTARY JOINT

Choice of Circular Modes

That circularly symmetrical mode which requires the smallest diameter of a cylindrical waveguide is the E_{01} mode. Therefore, it is the preferable mode for single rotary joints. If the diameter of the cylinder is increased the next circularly symmetrical mode which can be transmitted will be the H_{01} mode. The E_{01} and the H_{01} modes are the most advantageous for the design of a DRJ.

Since the E modes will produce a longitudinal current a contact problem exists for the circular waveguide in the plane of rotation. As space around the waveguide is available, a choke joint can easily be provided.

The Undesired Circular Modes

The next and most essential problem is the design of coupling elements between standard rectangular waveguides and the circular waveguide. Coupling elements usually radiate a large number of modes. However, only