Determining Attenuation of Waveguide from Electrical Measurements on Short Samples

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Summary—**An improved method for accurately determining the attenuation of waveguide from measurements on very short samples is presented. First, two samples are measured separately and then in tandem. When the measurements are properly made, the sum of the attenuations when the samples are measured separately agrees with the attenuation when measured in tandem at each frequency of measurement. Second, the average effective resistivity is found over a band of frequencies. Using the average effective resistivity, the attenuation at any frequency in the band can be determined. Results for WR159 copper waveguide are shown.**

INTRODUCTION

THIS PAPER presents an improved method for accurately determining the attenuation of waveguide, using two samples only a few feet long. Other methods have the disadvantages of: 1) using more total length of waveguide, 2) of requiring very precisely machined cavities, or 3) of lacking the required accuracy. This improved method consists of two parts. The first part is the insertion of a length of waveguide between a microwave measuring setup and a movable short and the measuring of the voltage standing-wave ratios (vswr) before and after the insertion. The two samples are inserted separately, then in tandem. An attenuation value, associated with the inserted waveguide is obtained from the vswr readings at each frequency of measurement. To prove-in the particular measuring equipment being used, the sum of the attenuations of the two samples measured separately, must agree with the attenuation of the two samples measured in tandem. The second part is finding an average effective resistivity over a band of frequencies. This may be done either by computations or by plotting the attenuation values found above, at each frequency, on computed attenuation-vs-effective-resistivity characteristics. The intersections of the average effective resistivity with the computed attenuation characteristics give accurate values of attenuation for the waveguide being measured. For the WR159 copper waveguide measured, the effective resistivity is 2.1×10^{-6} ohm-centimeter, and the attenuations are 0.0130 db per foot at 6,425 mc, 0.0135 db per foot at 6,175 mc, and 0.0138 db per foot at 5,925 mc. The samples were $3\frac{1}{2}$ feet long.

FACTORS AFFECTING ATTENUATION

The two principal factors which affect the attenuation of waveguide are the internal dimensions of the waveguide, and the effective resistivity of the conducting surfaces. The internal dimensions of the waveguide are principally controlled by the drawing plug used in manufacture. The effective resistivity depends on the roughness of the conducting surfaces, the direct-current (dc) resistivity of the metal, and the extent and nature of the metal in the conducting surfaces. The roughness of the conducting surfaces is important because of the increased path length due to the roughness, since current at microwave frequencies travels essentially on the surface. The dc resistivity can be computed from dc and dimensional measurements or by making a chemical analysis and comparing the analysis with others for which the dc resistivities have already been determined [26]. The dc resistivity places a lower limit on the value of the attenuation that may be expected. In the samples tested, corrosion is not thought to be important.

PREVIOUS METHODS OF MEASUREMENT

Attenuation of waveguide has been measured by many methods. Five of the most commonly used methods are the following:

1) A length of waveguide is inserted in a microwave measuring setup and the loss is measured by comparing attenuator settings, before and after the insertion. The comparison attenuator may be in the microwave path or in an intermediate-frequency path if a double- or triple-detection measuring set is used. The result is the average attenuation for the total length. A long run (several hundred feet) of waveguide is required for accurate determination. Reflections from waveguide flanges may cause an error due to the interaction factor [28].

2) A length of waveguide is inserted between a microwave measuring setup and a short and the power returned from the short is measured by comparing attenuator settings before and after the insertion. The same comments apply to this method as to method 1) except that the length of waveguide under test needs to be only half as long. In addition, voltages reflected from waveguide flanges may cause small errors by adding vectorially to the voltage reflected from the short.

3) A length of waveguide is made into a cavity by shorting the section at both ends. The frequency at which maximum power is absorbed in the cavity formed by the shorts and the sample of waveguide, is determined, as is the frequency interval between the lesser and greater frequencies at which the power absorbed is half as much. The attenuation calculated from the readings is the average attenuation for a few inches of waveguide.

4) A length of waveguide is inserted between a slotted section and a short, and the vswr is measured. The attenuation due to the length of waveguide is determined

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by subtracting the computed attenuation of the slotted section between the movable probe and the short from the attenuation calculated from the vswr reading. The result is the average attenuation for the total length. Great reliance is placed on computed values of attenuation in the slotted section and in the short. A run of waveguide 10 to 60 feet long is required. Reflections from waveguide flanges can cause large errors.

5) A length of waveguide is inserted between a slotted section and a short and the vswr is measured before and after the insertion. The attenuation calculated from the readings is the average attenuation for the total length. As in method 4), 10 to 60 feet of waveguide can be measured. Reflections from waveguide flanges can cause large errors.

THEORY OF MEASUREMENT FOR THE IMPROVED METHOD

If a microwave frequency is applied to the near end of a waveguide section that is shorted at the far end, a standing wave is set up. Voltage standing-wave ratio, vswr, the ratio of the value of the maximum voltage to the value of the minimum voltage, is infinite for the quarter-wave length section nearest the short, if the short is lossless, because the minimum voltage is zero. For quarter-wave length sections nearer the generator, both the maximum and minimum values of voltage increase. Since the minimum value is increasing faster than the maixmum value, the vswr decreases. The higher the loss per unit length in the waveguide, the faster the vswr decreases. Reflections from waveguide flanges can cause large errors. The sources of error are discussed later.

In order to obtain good accuracy in the measurement of very large vswr's, the 3 db method of evaluation of vswr is used. In this method, two distances are measured. The first distance is that between successive minimums, P and P', on the standing-wave characteristic shown in Fig. 1. This distance is exactly one-half wavelength in waveguide, $\lambda_G/2$. The ordinate of the standing-wave characteristic in Fig. 1 is $|V/A|^2$, where V is the voltage at a distance x from the short, and A is a constant.

The second distance, y in Fig. 2, is that between points O and Q at which the power is twice the power W at point P. The measurements of power at O, P, and Q must not be affected appreciably by noise. Let S be the letter symbol for vswr. Then

$$S = \frac{\lambda_G}{\pi y}. \tag{1}$$

A derivation of this equation by E. M. Purcell is shown on page 505 of reference [18].

For large vswr's, the distance y is very small. In the measurements reported herein, this distance varies between 0.008 and 0.017 inch. Because it is difficult to obtain accurate measurements of this sort using a slotted section, E. G. Morton of the Bell Telephone Laboratories, Inc., suggested in 1945, the use of a movable short and a fixed sampling orifice. In this method, the movable short moves the standing wave past a sampling orifice which acts as a probe. The slotted-section method, described in the section on "Previous Methods of Measurement (5)," moves a probe along a slotted waveguide to sample the standing wave.

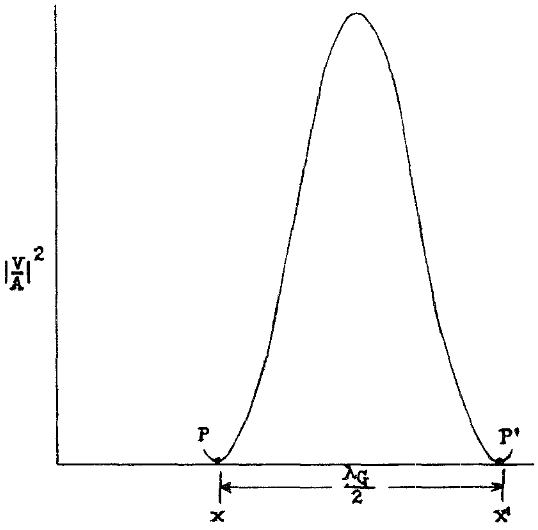

Fig. 1—Determining a half wavelength.

$$\left|\frac{V}{A}\right|^2 = \frac{\cosh 2\alpha x}{2} - \frac{\cos 2\beta x}{2}$$

V = Voltage at distance x from short
A = Constant
α = Attenuation per unit length
x = Length from the short
β = Radians per wavelength

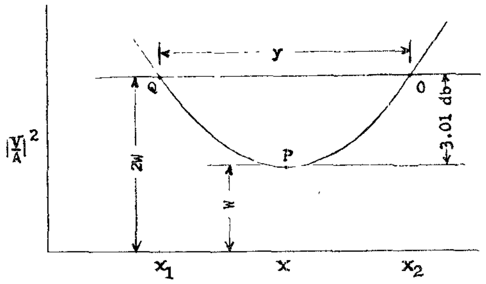

Fig. 2—Determining the displacement y between 3 db points. (Portion of Fig. 1 expanded around point P.)

Attenuation is obtained by substituting the value of S obtained from (1) into (2).

$$\alpha x = 10 \log_{10} \frac{S+1}{S-1}, \tag{2}$$

where

α = attenuation per unit length in db,

and

x = distance from the short.

A derivation of this equation by E. Weber is shown on page 818 of reference [18].

One source of error which should be noted here is the effect of noise in measuring at or near a voltage minimum. A common method of minimizing this error is to increase the length of the waveguide between the orifice and the short. Another way proposed by J. H. Vogelman [5] is to use a lossy short. Still a third way, using a lossy shunt, is described by J. M. Altschuler and A. A. Oliner [2]. The method described herein uses a pad attached to the front of a movable short. The loss in the pad takes the place of the equivalent loss in a length of waveguide and raises the voltage minimums out of the noise, so that accurate 3 db changes can be measured. The choice of a value for the pad is considered later in the sections "Noise," and "Difference Between Numbers" under "Discussion of Errors." The value does not have to be known.

The attenuation calculated from (2) includes the loss in the short, if any, and in all connected waveguide from the short to the sampling orifice.

In order to eliminate the extraneous losses that are measured along with the loss of the sample, it would appear that only two sets of readings are required at each frequency. The first set of readings would be made to determine the attenuation of the waveguide parts located between the orifice of the voltage-sampling orifice and a movable short. The second set would be made with the sample of waveguide inserted between the orifice and the movable short. The difference should be the attenuation of the sample of waveguide.

Unfortunately, there are many sources of error that may affect the accuracy of the above measurements. In order to prove-in the particular measuring equipment being used, at each frequency, two additional sets of readings, 2) and 3), are required as follows:

1) A measurement, made with one test sample inserted;
2) A measurement, made with another test sample inserted; and
3) A measurement, made with both test samples inserted in tandem.

The sum of the attenuations of the two test samples measured separately, and in tandem, should be the same, within reasonable limits. If this criterion is not met, the measuring equipment, or technique, or both, need to be improved. The possible sources of error will be considered later under "Discussion of Errors." The average of the sum of the attenuations of the two samples measured separately and the attenuation of the two samples measured in tandem will be called the "measured attenuation."

The surface roughness factor might be defined as the ratio of the length of a profile path over a rough surface to the length of a path over an ideal surface. The surface roughness factor has been measured by the use of microphotography by F. A. Benson [7]. The correlation with microwave determinations has been good.

For the $TE_{10}^{\square}$ mode, Benson has found cases in which the factor was as great as 1.4 for current paths transverse to the axis of transmission. It is generally much less. He found that the factor was about unity for the path in line with the axis of transmission. For the purposes of this paper, it is assumed that an average surface roughness factor can be used and that it can be combined with the dc resistivity to give a resultant "effective resistivity."

Suppose now that the attenuations of hollow conducting waveguides are computed using (3) and (4) in the Appendix. The resultant attenuation, at any one frequency, varies as the square root of the effective resistivity. Using frequency as a parameter, it is possible to plot attenuation-vs-effective-resistivity characteristics for as many frequencies as is desired. These characteristics are straight lines on log-log paper. Usually three frequencies in each band will suffice. Such characteristics are shown in Fig. 3.

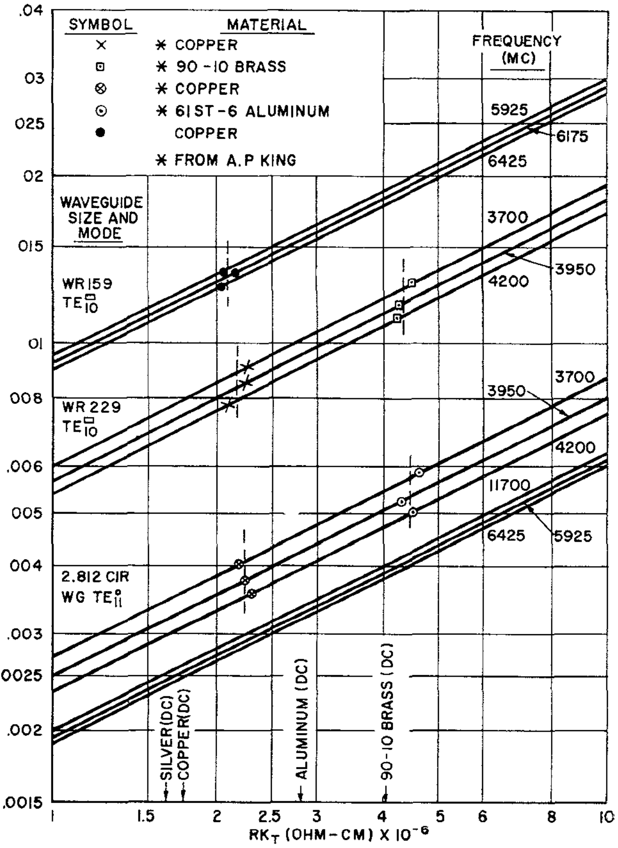

Fig. 3—Measured attenuation plotted on calculated attenuation (α)-vs-effective resistivity (R) characteristics.

The "measured attenuations" as found above can be plotted, frequency by frequency, on the characteristics as shown in Fig. 3. In general, they will not fall on a common abscissa. The causes may be inherent in the measuring equipment.

It might be expected that the effect of surface roughness would be greater at the higher microwave frequencies than at the lower microwave frequencies. However, this effect would not ordinarily vary much over a small band of frequencies. For the purposes of this discussion, it is assumed that there is no change in this effect over the small band of frequencies of interest. Consequently, an attempt can be made to increase the accuracy by finding an arithmetic-average effective resistivity that best represents the "measured attenuation" data.

The intersections of the average effective resistivity and the attenuation characteristics will determine the attenuation of the sample waveguide, for as many frequencies as there are plotted characteristics.

The differences between this improved method and previous methods using a slotted section and a short can be summarized as follows:

1) An orifice is used as a voltage sampler.
2) A movable short is used to move the standing wave past the orifice.
3) A pad is used instead of a long length of waveguide or a lossy short, to prevent noise from affecting the accuracy of the measurements.
4) The particular measuring equipment used is proved-in by measuring the attenuation of two samples separately, then measuring the two samples in tandem.
5) Accurate attenuation per foot at any frequency is determined by using the value of an arithmetic-average effective resistivity that best represents the data.

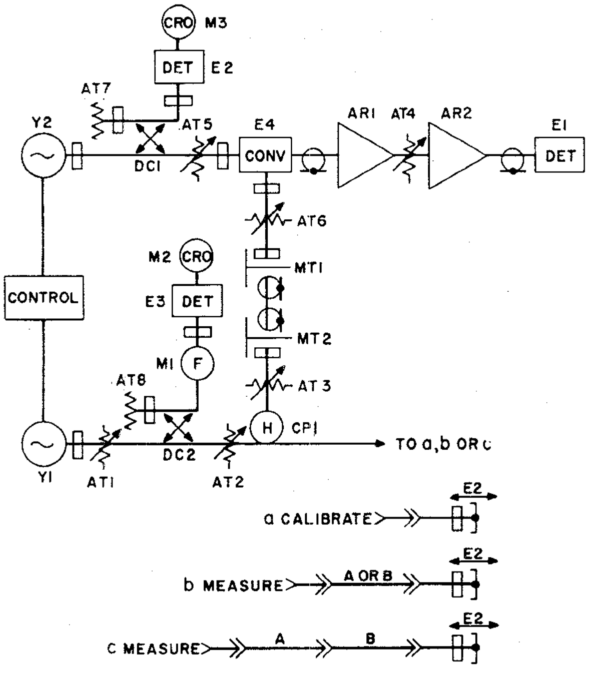

Fig. 4—Schematic drawing of test setup for measurement of attenuation.

Description of Measuring Equipment

The circuit schematic of the equipment used in making these measurements is shown in Fig. 4. The physical layout is shown in Fig. 5. The setup consists of waveguide parts and an associated heterodyne measuring set. The signal and beat-frequency oscillators *Y*1 and *Y*2, mounted in shielded containers, are shown at the extreme left end of the waveguide setup. A klystron power supply and control panel for the oscillators is located in the bottom of the cabinet shown at the extreme left in Fig. 5. Attenuators AT1 and AT2 are used to pad the signal oscillator Y1 in order to prevent pulling. A directional coupler DC2 is used to connect equipment which continuously monitors the frequency of Y1. The sampling orifice CP1 consists of an 18-inch length of WR159 waveguide with a hole on one side as shown in Fig. 6. The waveguide test samples A and B consist of 42-inch sections of WR159 waveguide. A movable short E2 and associated pad are mounted on a carriage, as shown in Fig. 7. The carriage holds the short in the same relative position with respect to the sides of the waveguide as the carriage is moved. The pad, mounted on the face of the movable short E2, consists of a small, triangular piece of lossy Synthane. A dial indicator measures the distance y between 3 db points. A closeup of the dial indicator, as mounted to measure the y distance, is shown in Fig. 8. A close-up of the micrometer, as mounted to measure the distance between half-wavelength points, is shown in Fig. 9. A battery and meter are used to indicate that the micrometer spindle is just touching. Connected to the sam-

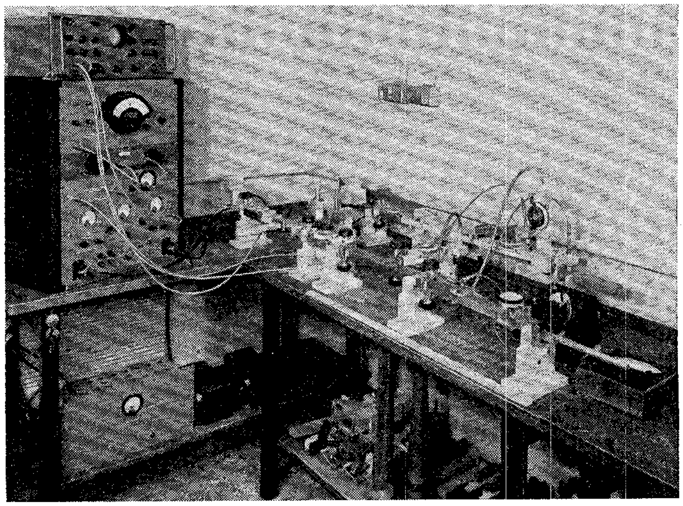

Fig. 5—Test setup for "calibrate" measurement.

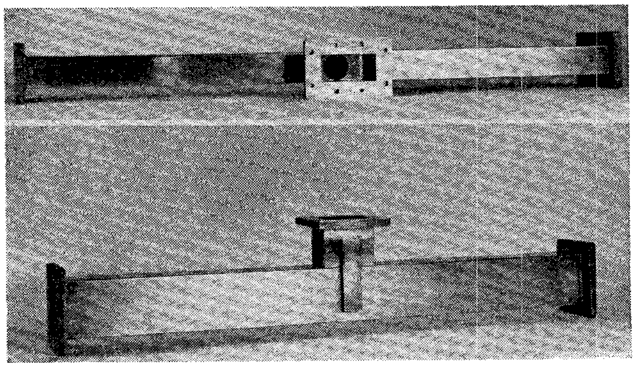

Fig. 6—Two views of the assembly containing the voltage-coupling orifice.

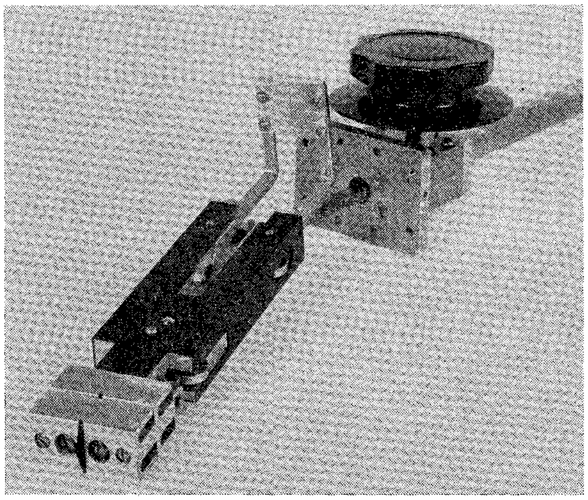

Fig. 7—Movable shorting piston and pad.

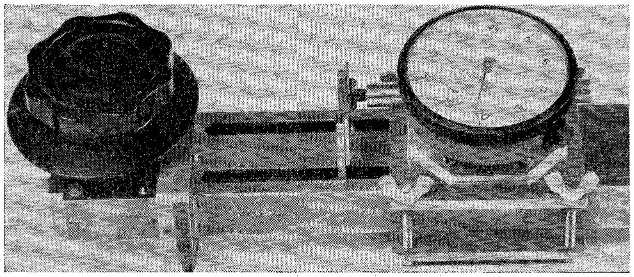

Fig. 8—Dial indicator mounted to measure the distance y.

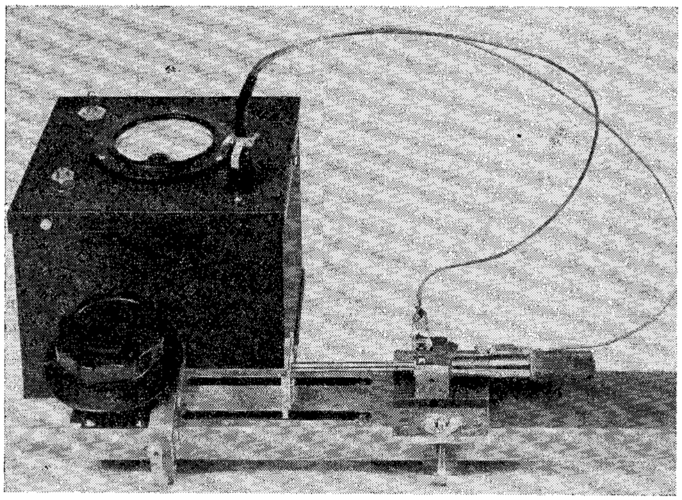

Fig. 9—Micrometer mounted to measure a half wavelength.

pling orifice are the pads AT3 and AT6 and a converter E4, which consists of a hybrid junction and a crystal detector. A coaxial cable connects the converter to the 70 mc equipment, consisting of a preamplifier AR1 and an amplifier-detector (AR2 and E1) shown on the extreme left-hand side of Fig. 5. The power supply for the 70 mc equipment is shown on the bottom of the bench. AT4 is the 70 mc precision attenuator used to measure accurately a change of 3 db.

Preparation of Waveguide Assemblies

Flanges on the two test samples, on the section of waveguide in which the movable short is located, and on the section of waveguide in which the sampling orifice is drilled, are finished so that the waveguide assemblies meet a 45 db return-loss requirement. The return loss is measured over the 500 mc band of frequencies between precision "standard" flanges that have a 60 db return loss, or better, when measured as a pair.

Attenuations Obtained From Measurements

In determining the attenuation of WR159 waveguide, four sets of data were recorded at each frequency (5,925, 6,175, and 6,425 mc): 1) data with no waveguide test sample inserted between the orifice and the section in which the movable short is mounted, the setup for which is shown in Fig. 4 and 5; 2) data with test sample A inserted between the orifice and the section in which the movable short is mounted; 3) data with test sample B; and 4) data with test samples A and B in tandem. The data recorded for each set consists of distances between 3 db points and the distances between adjacent minimums. The distances between 3 db points ranged from 0.025 centimeter to 0.043 centimeter. The vswr's corresponding to these values ranged from 88 to 42. The attenuations obtained from the above vswr's ranged from 0.099 to 0.205 db and are shown in Table I.

TABLE I

Attenuation of WR159 Waveguide

		Attenuation (db)		
Row	Frequency (mc)	5925	6175	6425
1	Section A (42.0 inches long)	0.0488	0.0483	0.0462
2	Section B(42.0 inches long)	0.0471	0.0466	0.0444
3	Sections A and B in tandem	0.0955	0.0952	0.0901
4	Sum of sections A and B Row 1+Row 2	0.0959	0.0949	0.0906
5	Average of Row 3 and Row 4	0.0957	0.09505	0.09035
6	Per cent difference between Row 3 and Row 4	0.4	0.3	0.6

Finding Average Effective Resistivity and Determining Attenuation Values

The second part of this improved method is finding the average effective resistivity over a band of frequencies. One way is to use the results from the previous section, and to find the calculated effective resistivity (RK_T) at each frequency by using (3) of the Appendix. An easier way is to plot in Fig. 3 the values of attenuation per foot shown in Row 1 of Table II, then to determine the average effective resistivity as shown by the dashed line. The intersections of this dashed line with the attenuation characteristics lead to values of 0.0138 db per foot at 5,925 mc, 0.0135 db per foot at 6,175 mc, and 0.0131 db per foot at 6,425 mc. These are the accurate answers sought.

TABLE II

ATTENUATION OF WR159 WAVEGUIDE DETERMINED FROM AVERAGE EFFECTIVE RESISTIVITY

Row	Frequency (mc)	Attenuation (db per foot)		
		5925	6175	6425
1	Calculated attenuation from Row 5, Table I	0.01367	0.01358	0.01291
2	Effective resistivity from Fig. 3 for values in Row 1 ($\times 10^{-6}$ ohm-cm)	2.06	2.17	2.03
3	Determined attenuation from Fig. 3 using average effective resistivity (dashed line)	0.0138	0.0135	0.0131
4	Per cent difference between Row 1 and Row 3	1.1	0.9	1.5

Data from A. P. King[1] of the Bell Telephone Laboratories, Inc., has been similarly plotted on the proper attenuation characteristics and dashed lines drawn to show average effective resistivity values. These data are included to show that measurements made by other methods also show about the same spread in effective resistivity values.

SURFACE ROUGHNESS FACTORS

If we know the dc resistivity and the average effective resistivity, division of the second by the first leads to the surface roughness factor. H. T. Wilhelm[1] of the Bell Telephone Laboratories, Inc., reports that the dc volume resistivity of the material in the WR159 waveguide measured had a value of 1.756×10^{-6} ohm-centimeter at 25°C (equivalent to 1.703×10^{-6} ohm-centimeter at 20°C). The values of dc resistivities of silver, copper, aluminum, and 90-10 brass are also indicated in Fig. 3.

As shown in Table III, the effective resistivities derived for the copper waveguides in Fig. 3 lead to surface roughness factors of: 1.32 for the 2.812 circular waveguide, 1.29 for the WR229 waveguide, and 1.23 for the WR159 waveguide.

TABLE III

SURFACE ROUGHNESS FACTORS

Row	Waveguide	WR159	WR229	2.812 CIR
1	DC resistivity for copper ($\times 10^{-6}$ ohm-cm)	1.703	1.703	1.703
2	Effective resistivity from Fig. 3 ($\times 10^{-6}$ ohm-cm)	2.1	2.2	2.26
3	Surface roughness factor K_T	1.23	1.29	1.32

In order to compute factors for the 2.812 circular waveguide and the WR229 rectangular waveguide, it is assumed that the copper in these waveguides has the same dc resistivity as that in the WR159 waveguide.

A. P. King[1] measured waveguide runs with lengths of 150 to 200 feet in order to determine the attenuations of WR229 and 2.812 circular waveguide, plotted in Fig. 3.

Benson [7] reports factors that average 1.11 for a 60-foot length of WR90, drawn to loose tolerances, and 1.034 for a 15-foot length of WR90, drawn to tight tolerances. A comparison of (5) with (3) shows that the factors reported by Benson must be squared to compare with the surface roughness factors derived in this paper, as the factor given herein is under the radical and his is not. Squaring the Benson factor leads to the following results: 1.23 for WR90 waveguide (loose tolerances) [7] 1.07 for WR90 waveguide (tight tolerances) [7].

DISCUSSION OF ERRORS

Nine of the major factors affecting the accuracy of the determinations are discussed below.

Dimensions of the Waveguide

Table IV shows the effect of a 0.001-inch change in both wide and narrow dimensions of a waveguide on the attenuation. This effect is computed to be 0.2 per cent. The WR159 waveguide from which the samples described in this paper were made was within the specification tolerances of $1.590 \pm 0.002 \times 0.795 \pm 0.002$ inches.

TABLE IV

EFFECT OF WAVEGUIDE TOLERANCE ON ATTENUATION OF WR159 WAVEGUIDE AT A FREQUENCY OF 5925 MC [CALCULATED USING (3) IN THE APPENDIX]

Wide Dimension (inches)	Narrow Dimension (inches)	R (ohm-cm)	Attenuation (db per foot)
1.590	0.795	2.1×10^{-6}	0.013756
1.589	0.794	2.1×10^{-6}	0.013782

Impedance Mismatch

Impedance mismatches at the waveguide flanges [9] have been made very small by careful preparation of the waveguide assemblies.

Purcell [18] states that the error due to orifice susceptance is very small for this method of measurement.

The error due to change in impedance presented by the pad and the short has been made very small by a mechanical design that assures that the impedance presented will be the same for all positions axially in the waveguide. Over the years, many types of supports for movable shorts have been tried. The design of the carriage used in these tests was chosen after trials had shown that previous designs would not meet the stringent requirements for change of impedance vs movement axially in the waveguide. The change in impedance is checked by measuring y, the distance between the 3 db readings, at two or three minimums and checking that the values of y do not differ by more than

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[1] Unpublished work.

2 per cent for the calibrate measurements, or by more than 1 per cent for the remaining measurements.

The effect of the leakage of the short has been minimized by using two choke-type shorts in tandem, and fastening lossy Synthane to the sides and top of the supporting carriage. This reduces the behind-the-carriage resonance effects to a negligible value.

Distance Measurements

The determination of the 3 db change is done by using a calibrated 70 mc attenuator, making use of the calibration corrections to 0.01 db, and interpolating to 0.005 db on the 1.5-inch-per-db output meter. The distance y between the 3 db points is measured by a sensitive dial indicator.

Half wavelength in waveguide is determined accurately by using a long micrometer spindle, with battery and meter to indicate when the spindle is just touching the bracket as shown in Fig. 9.

Noise

Two checks are made to avoid errors due to noise. First, the input-output characteristic of the converter-preamplifier is checked for linearity. Input signals must be kept in the linear range, since the IF attenuator is connected after the preamplifier. Second, the loss of the pad attached to the movable short is chosen to lift the voltage, at a minimum, out of the noise by about 20 db in order to have 0.1 db accuracy in attenuator readings.

Difference Between Numbers

Since the method depends upon subtracting a "calibrate" attenuation from a "measure" attenuation, the smaller the value of the "claibrate" attenuation, the better the accuracy, in general. This means keeping the value of the pad attached to the movable short as small as possible.

Frequency Drift

Frequency drift of the signal oscillator is minimized by making the measurements in a temperature-controlled room. The sort of measuring setup used is essentially a very sensitive frequency meter [19] and care must be taken to minimize errors due to drifts of the oscillator frequency and to changes in length of the waveguide due to temperature changes.

Two or More Signal Frequencies

On occasions, a klystron produces more than one signal frequency. An error introduced by more than one signal frequency being detected at the same time will make the calculated attenuation for that reading too small.

If the signal oscillator produces sufficient power in harmonics, an error will be introduced that will make successive distances between the 3 db points different.

Crosstalk

In a heterodyne-type measuring set, such as the one used, crosstalk between the signal oscillator and the converter will cause errors in the measurements. This was the reason for the complete shielding of both the signal- and beat-frequency oscillator mounts and the power leads to them.

Approximate Formulas

Computations, carried out to 5 significant figures show no appreciable error due to the use of the approximation in (1).

CONCLUSIONS

The method reported in this paper leads to a precise determination of the attenuation of waveguide in short or long samples equipped with flanges, without destroying the commercial value of the samples.

It avoids the use of a precise slotted section, substituting instead a precise movable short which, in the opinion of the authors, is much easier to build.

It incorporates a check on the effect of noise on the accuracy of measurement. The check is accomplished by measuring the samples separately, then in tandem.

This method takes account of small inaccuracies in measurements, shown by scattering, by finding an average effective resistivity, then uses this resistivity in order to determine the accurate attenuations.

APPENDIX

FORMULAS FOR CALCULATION OF ATTENUATION

Rectangular Waveguide ($TE_{10}{}^{\square}$)

$$\alpha = \frac{5.963\left[\frac{RK_T}{\lambda}\right]^{1/2}\left[\frac{1}{b}+\frac{\lambda^2}{2a^3}\right]}{\sqrt{1-\frac{\lambda^2}{4a^2}}}. \tag{3}$$

Circular Waveguide ($TE_{11}{}^{\circ}$)

$$\alpha = \frac{11.932}{d}\left[\frac{RK_T}{\lambda}\right]^{1/2} \cdot\left[\frac{1.419}{\sqrt{1-\left[\frac{\lambda}{1.71d}\right]^2}} - \sqrt{1-\left[\frac{\lambda}{1.71d}\right]^2}\,\right]. \tag{4}$$

α = attenuation in db per foot.
R = dc resistivity of conducting surface in ohm-centimeters.
a = wide dimension of waveguide in inches.
b = narrow dimension of waveguide in inches.
λ = free-space wavelength in inches.
d = diameter of waveguide in inches.
K_T = surface roughness factor.
RK_T = effective resistivity of conducting surface in ohm-centimeters.

Rectangular Waveguide ($TE_{10}^{\square}$)

Taking Account of Surface Roughnesses: A formula derived by Benson [3] from Kuhn [21] for the $TE_{10}^{\square}$ mode is:

$$\alpha = \frac{\lambda_G}{b(\lambda_e)^{3/2}}\left[\frac{c}{\sigma}\,\frac{\mu_1}{\mu}\left[\frac{\epsilon}{\mu}\right]^{1/2}\right]^{1/2} \cdot\left[\left(K_{T2}+\frac{a}{2b}K_{T1}\right)\frac{\lambda_e^2}{\lambda_c^2}+Kp\frac{a}{2b}\left(1-\frac{\lambda_e^2}{\lambda_c^2}\right)\right] \qquad (5)$$

where

α = attenuation produced by wall metal
a = wide dimension of waveguide
b = narrow dimension of waveguide
c = velocity of light = 2.99776×10^{10} centimeters per second
σ = conductivity of wall metal
μ_1 = permeability of wall metal
λ_G = guide wavelength
λ_e = wavelength in unbounded dielectric
λ_c = critical guide wavelength
ϵ = dielectric constant of dielectric
μ = permeability of dielectric
K_{T1} = ratio of length of actual surface to that of an ideal surface for wide face of waveguide transverse to tube axis
K_{T2} = corresponding factor for narrow face
Kp = factor for longitudinal direction.

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