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Experimental Attenuation of Rectangular Waveguides at Millimeter Wavelengths

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Abstract—**The experimental values of attenuation of commercially available rectangular waveguides were determined at frequencies between 25 and 200 GHz with emphasis on high accuracy. They were compared with the theoretical values computed from the dc conductivities, taking into consideration temperature effects, work hardening, size effects, surface roughness, and a room-temperature anomaly of the skin effect. A new way to express the excess attenuation due to these effects was formulated.**

Excess ratios of attenuation of coin-silver waveguides were found to be well below the values used in engineering in the past. They can satisfactorily be explained by surface roughness. The normalized excess attenuations of copper guides are higher than those of guides made of silver but lower than cited in the literature.

I. Introduction

SEARCHING for reliable data on the attenuation of rectangular waveguides for the millimeter-wave region frequently becomes a frustrating endeavor. One usually finds that the theoretical values listed in handbooks [1], [2] are considerably lower than those observed in practice. Also, these values are valid for pure silver whereas the commercially available waveguides are made primarily of coin silver (90-percent Ag, 10-percent Cu), which yields theoretical values of attenuation increased by a factor somewhere around 1.25. Catalogs of companies selling waveguides usually contain the same values [3], [4] or data reprinted from a book on plasma diagnostics [5]–[7] with experimental attenuation values increased by about a factor of 2 above the theoretical values. Results of rather thorough investigations were published by Benson [8] with emphasis on guide materials and surface preparations such as chemical polishing and annealing. His results confirm the previously observed increases of the attenuation and include data for the range of 20 to 140 GHz. The increases are due to excess losses, which the author attributes to surface roughness and minute surface irregularities. The data have an uncertainty of about ± 7 percent and some of them show variations of up to ± 20 percent. Some of Benson's results are in disagreement with those published earlier [9]. The review of these and other publications made it apparent that additional research to furnish more reliable data was highly desirable.

While studying the surface characteristics of metals, particularly copper, the author found [10] that a major contribution to the excess losses of copper at millimeter wavelengths is caused by an anomaly of the skin effect at room temperature. This, in turn, causes increased values of attenuation. The increases are larger than those caused by the effects of surface roughness and work hardening. In order to correlate the results of the original surface-resistance experiments with waveguide data and to generate reliable data, careful experiments were conducted. These experiments resulted in accurate values of the attenuation of standard rectangular waveguides in the millimeter-wave region. Subsequently, the obtained data were evaluated in great detail. The results of these efforts are presented in this paper.

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TABLE I
STANDARD RECTANGULAR WAVEGUIDES

Letter Prefix	EIA Notation	Recomm. Frequency Range	Dimensions (mm) Outside	Tol. (mm)	Dimensions (mm) Inside	Tol. (mm)	Cut off Freq. in GHz
K_a(R)	WR-28	26.5 - 40	9.144 x 5.588	±.05	7.112 x 3.556	±.04	21.0911
E	WR-12	60 - 90	5.131 x 3.581	±.05	3.099 x 1.550	±.02	48.4027
N(V)	WR-8	90 -140	4.064 x 3.048	±.04	2.032 x 1.016	±.01	73.8189
G	WR-5	140 -220	3.327 x 2.680	±.04	1.295 x .648	±.01	115.8301

II. Frequency Range and Types of Waveguides

The investigation concentrated on four sizes of typical, commercially available rectangular waveguides with the EIA notations WR-28, 12, 8, and 5. Specifications for these guides are listed in Table I. The frequency range covered by these guides is 26.5–220 GHz. The guides were made of coin silver (90-percent Ag, 10-percent Cu) and oxygen-free and high-conductivity (OFHC) copper. They came from several sources.

III. Experimental Procedures for the Determination of Attenuation

The attenuation values were found by measuring the insertion loss. First, the output signal of the measurement circuit was determined without the tested waveguide section being in the circuit, then, again after its insertion. After the insertion, two measurements were made, determining the loss first from the decrease of the output signal and then from the increase of the input signal by adjusting a precision attenuator in the input section until the original level of the output signal was reestablished. Directional couplers in the input guide were used to take reflections into consideration. The detector setup consisted of a detector mount (SWR = 3), an isolator (SWR = 1.4), and a 10-dB attenuator coupled in front of the isolator to keep the total SWR below 1.1. With the test section in place, the total SWR was below 1.12 in the 60–90-GHz range. In the 100–140-GHz range, the SWR was better than 1.3. At 140 and 180 GHz a bolometer, matched with an E–H tuner and a 6-dB attenuator in front, was used as the detection device. The measurements were made in the test laboratory of the Baytron Corporation. Additional high-accuracy measurements in the 26.5–40-GHz range and at 70 GHz were performed at North Carolina State University (NCSU). In these measurements, errors resulting from reflections were avoided by the use of phase shifters with carefully compensated discontinuities.[1]

The waveguide test sections at Baytron had a length of 60 and 72 in. At NCSU, their length was 32 and 36 in. Specially designed coupling elements were attached at the ends of the waveguide sections. The use of these coupling elements eliminates the aftereffects of heating on the

[1]Circuitry and measurement procedures will be described elsewhere.

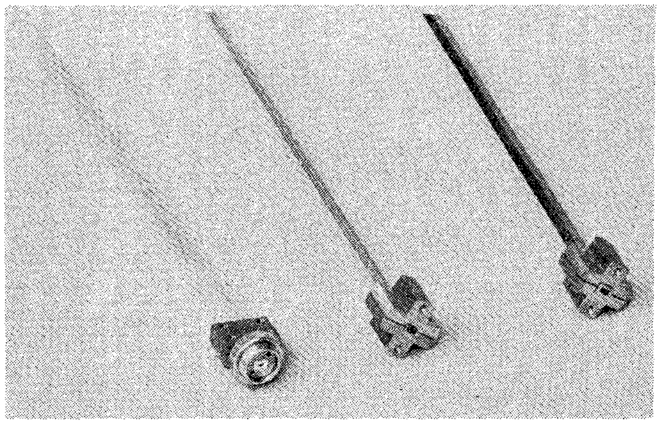

Fig. 1. Clamp-type coupling elements

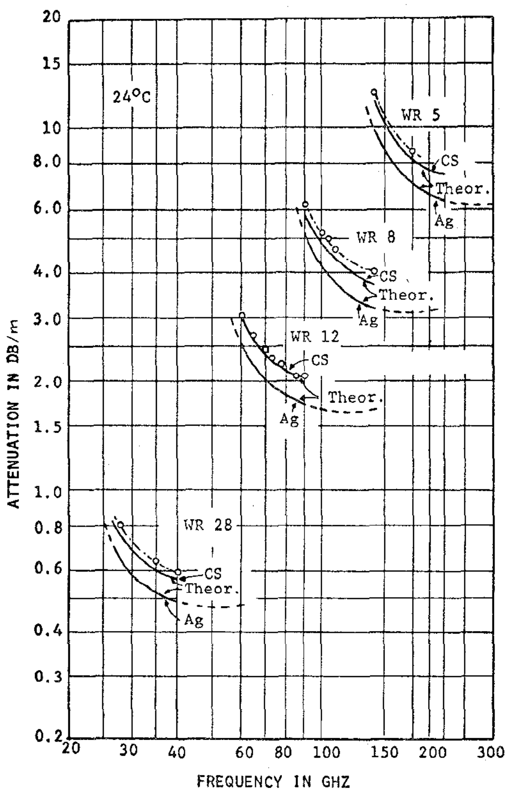

Fig. 2. Experimental attenuation of standard-size waveguides made of coin silver (CS).—, theoretical values computed from the dc conductivity of silver (Ag, $\sigma = 6.17 \times 10^7$ S/m) and of coin silver (see Fig. 4). O, experimental values. □, results of high-accuracy measurements (70 GHz).

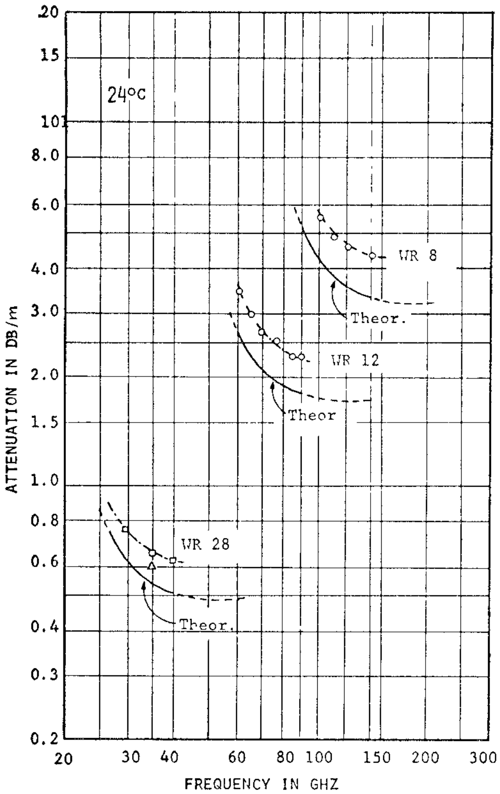

Fig. 3. Experimental attenuation of standard-size waveguides made of copper.—, theoretical values computed from the dc conductivity of high-conductivity copper ($\sigma = 5.8 \times 10^7$ S/m). □, values computed from measured Q-factors of polished cavities. △, value computed from the intrinsic surface resistance [10].

material properties and on the attenuation when regular flanges are being attached by soldering. Fig. 1 shows some of the coupling elements.

The results of these experiments are shown in Figs. 2 and 3 for waveguides made of coin silver and copper. The graphs show the experimental and theoretical values. The theoretical values are for pure silver, coin silver, and copper. In the case of copper, the experimental values for WR-28 were computed from measured Q-values of OFHC copper cavities at the indicated frequencies. The value indicated by the triangle in Fig. 3 was computed from the experimentally found intrinsic [10] value of surface resistance of copper. In this case, the increase of attenuation is solely due to the room-temperature anomaly of the skin effect.

IV. DC Values of Conductivity for Waveguide Materials

For comparing the experimental and theoretical values of attenuation, it was necessary to determine accurately the dc conductivities of the waveguide walls. From these conductivities the theoretical values of attenuation were computed. High accuracy of the attenuation experiments required taking into consideration the temperatures at the times when the attenuation and when the dc measurements were made. To correlate the data they were referenced to 20°C. In the past, when measurement errors were large, temperature effects were disregarded.

Parametric diagrams were developed in order to permit consideration of temperature effects. These diagrams show the dc conductivities at particular temperatures in terms of the conductivity referenced to 20°C. Temperatures between 20 and 30°C (68 and 86°F) are taken into account. The diagrams are based on the following equation describing the effect of temperature on the resistivity ρ of metals:

$$\rho_{T2} = \rho_{T1}[1 + c(T_2 - T_1)] \tag{1}$$

where ρ_{T2} and ρ_{T1} are the resistivities at the temperatures T_2 and T_1 and where c is the temperature coefficient. The values 0.0038 and 0.0039 were used as the coefficients for coin silver and copper, respectively. They were obtained from [11]. A temperature of 20°C was employed as a reference.

The diagrams are shown in Figs. 4–6. They contain the measured values of dc conductivities of material samples cut and machined from waveguides who's attenuation values were measured before. The waveguide sizes are shown by their WR numbers, and the various supplies or sources from which the waveguides were taken or purchased are indicated in the parentheses (B-Baytron, T-TRG/Alpha Industries, W-waveline). The circles (groups of three) represent averages of sets of repeated measurements. The maximum measurement error was about ±0.5 percent.

Fig. 4 shows the conductivities of material samples of waveguides made of coin silver. Their values differ considerably depending on guide sizes and origins. The differences were found to be caused by work hardening associated with the drawing processes during production. The manufacturers indicated that the sequences of repeated drawings and annealings differ for the various sizes, causing different degrees of work hardening present in the final product. The differences in work hardening, in turn, cause differences in the dc conductivities and in the values of attenuation. To confirm the validity of these assumptions, samples of waveguide materials were annealed. Fig. 5 shows how annealing affected the dc conductivities of the various samples. The annealing brought the different values for WR-12, 8, and 5 up to a common value of about 4.8×10^{-7} S/m. Differences of the conductivities of copper samples (Fig. 6) were less pronounced. They were near the typical value of conductivity for OFHC copper from which the guides were made. The figure also contains the conductivities of samples made of two kinds of copper, copper (I) and (II) available in our supplies. One of them, copper (II), was found to have a rather poor conductivity.

V. Effects of Size Deviations

There are various effects that contribute to the discrepancy between experimental and theoretical values of

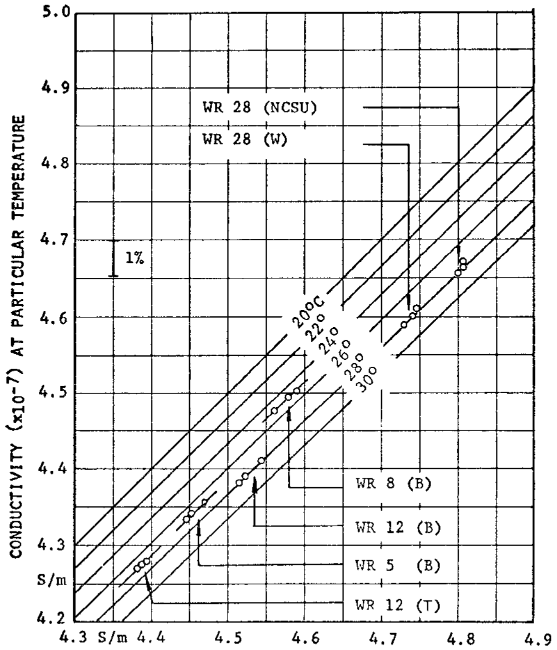

Fig. 4. Measured temperature-dependent dc conductivities of coin-silver samples of various waveguides. (Origins indicated in parentheses.)

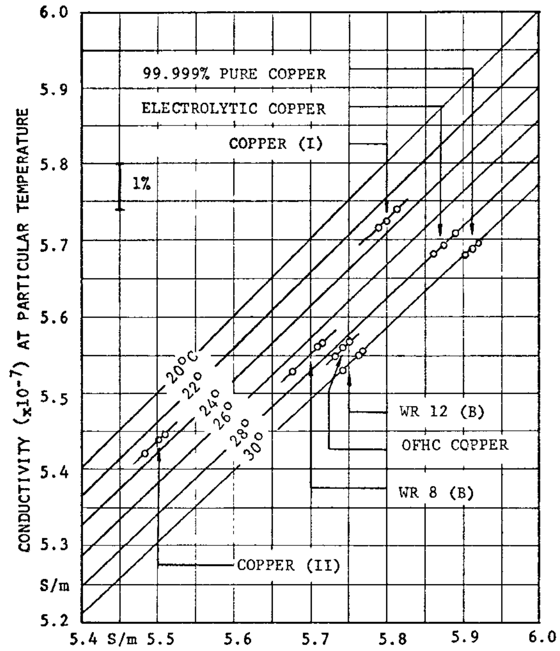

Fig. 6. Temperature dependent dc conductivities of copper samples of waveguides and cavities.

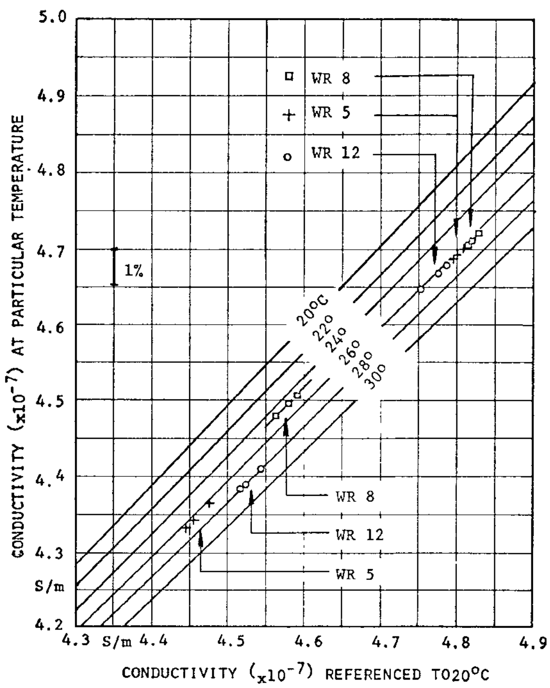

Fig. 5. Measured dc conductivities before (lower left) and after (upper right) annealing (30 min at 700°C in vacuum).

attenuation. One of these effects is caused by deviations of the inside dimensions of waveguides from the standardized values. Stated differently, this means that the theoretical values of attenuation should be determined for waveguides with inside dimensions equal to those of the tested sections. In order to apply this procedure, short sections of the three sizes of evaluated waveguides, WR 12, 8, and 5, were embedded in bakelite and the end surfaces polished according to procedures used in metallurgical photomicrography. Photographs of the cross sections and photomicrographic reproductions of corner regions and of sections of the lower flat boundaries were made. They are shown in Fig. 7 for silver and copper guides. The cross-sectional geometries are interesting since they differ considerably from the specified rectangular shapes. However, taking into account that the waveguides are fabricated by repeated drawing processes starting with circular cross sections, the manufacturers seem to have done an admirable job in getting the internal cross sections into shapes so close to rectangles, as shown in the figures.

The photographs were then used to find the actual internal dimensions of the tested waveguides. Attenuations and their deviations from those for standard dimensions were computed. The deviations were expressed by the ratios of the attenuation values, α/α_0, with α_0 representing the values for standard dimensions. The equation which yields this ratio is

$$\alpha/\alpha_0 = G/G_0 \qquad (2)$$

where G and G_0 are geometry factors appearing in the equation for the attenuation of waveguides [12]

$$\alpha = (R_s/Z_0)G$$
$$G = \left[1/b + (2/a)(\lambda_0/2a)^2\right]\left[1-(\lambda_0/2a)^2\right]^{-1/2}. \qquad (3)$$

The geometry factors G and G_0 are obtained from the measured inside dimensions, width a and height b, and the standardized values a_0 and b_0, respectively. The ratios R_s/Z_0 which contain the internal surface resistance R_s

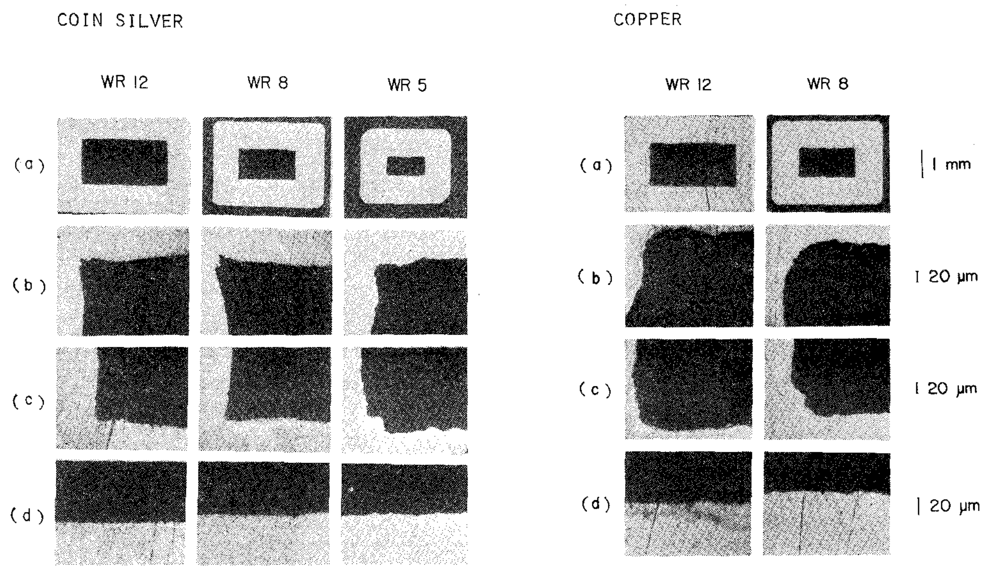

Fig. 7. Photographs of waveguide cross sections (a) embedded in bakelite (dark areas). Waveguides WR 12, 8, and 5 made of coin silver and copper. Photomicrographs of the left upper (b) and left lower (c) corner regions and of small sections of the lower wide walls (d). Scales of magnification are indicated on the right-hand side.

TABLE II
DIMENSIONS AND ATTENUATION RATIOS

Type of Guide	Standard Dimensions (mm) Inside	Tol. (mm)	Measured Dimensions (mm) Inside	Deviations (mm) Δa	Δb	Freq. (GHz)	$\frac{\alpha}{\alpha_0}$
WR-28 (Ag)	7.112 x 3.556	±.04	7.100 x 3.540	-.012	-.016	26.5 40	1.0077 1.0053
WR-12 (Ag)	3.099 x 1.550	±.02	3.141 x 1.577	+.042	+.027	60 90	.9508 .9726
WR-8 (Ag)	2.032 x 1.016	±.01	2.075 x 1.066	+.043	+.050	90 140	.9099 .9426
WR-5 (Ag)	1.295 x .648	±.01	1.346 x .662	+.051	+.014	140 220	.8750 .9463
WR-12 (Cu)	3.099 x 1.550	±.02	3.151 x 1.606	+.052	+.056	60 90	.9317 .9525
WR-8 (Cu)	2.032 x 1.016	±.01	2.075 x 1.071	+.043	+.055	90 140	.9073 .9392

and the free-space wave impedance Z_0 cancel each other in the ratio of the α values. The free-space wavelength λ_0 is a measure for the operational frequency f_0.

The cross-sectional dimensions of the tested guides and the attenuation ratios are listed in Table II. We observe that the deviations of the dimensions considerably exceed the specified tolerances and give deviations of the attenuation of up to about 13 percent. Based on the listed tolerances, these deviations would be maximally about ± 3.5 percent. The deviations are more pronounced at the lower ends of the transmission bands where the operational frequencies approach the cutoff frequencies.

VI. Consideration of the Various Effects

The preceding findings suggest that evaluation of the results of attenuation measurements should be made by formulating attenuation ratios for the effects caused by temperature and by size deviations. It is appropriate to use the attenuations of standard-size waveguides (Table I) with conductivities of 6.17×10^7 S/m for silver and 5.8×10^7 S/m for copper as references or normalizing values. The ratios are

$$\frac{\alpha_{CS}}{\alpha_{Ag}}=\sqrt{\frac{6.17\times10^7}{\sigma_{\exp CS}}}\qquad\frac{\alpha_{Cu\,\exp}}{\alpha_{Cu}}=\sqrt{\frac{5.8\times10^7}{\sigma_{\exp Cu}}}\tag{4}$$

for consideration of the dc conductivities, and

$$\frac{\alpha_{\text{real size}}}{\alpha_{\text{standard size}}}=\frac{G}{G_0}\tag{5}$$

for size effects. For some frequencies the latter ratios are listed in Table II. Diagrams for the various kinds of ratios are shown in Fig. 8. Included in the diagrams are the experimental values of attenuation shown in Figs. 3 and 4 normalized with regard to the above standard references α_{Ag} and α_{Cu}.

VII. Excess Attenuation

Next, the attenuation ratios are combined to yield a figure for the excess attenuation. It is described by the ratio of the experimentally found attenuation $\alpha_{\exp}$ and the

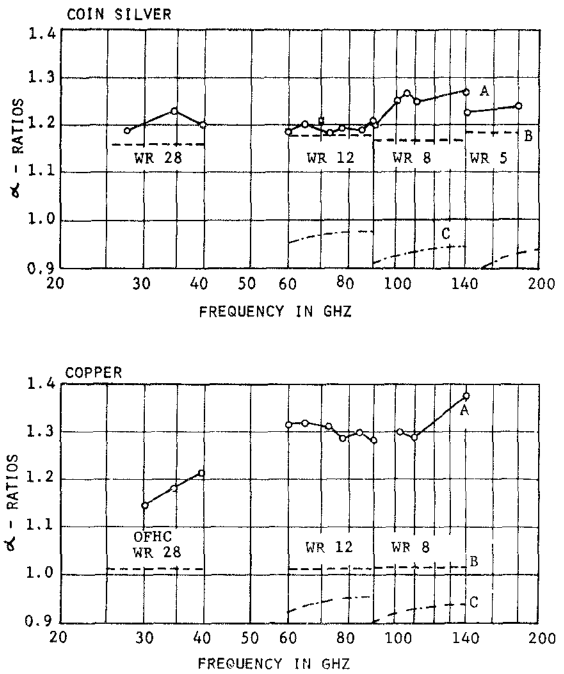

Fig. 8. Attenuation ratios with theoretical values for silver ($\alpha_{Ag}=6.17\times10^7$ S/m) and copper ($\sigma_{Cu}=5.8\times10^7$ S/m) as references. Standard dimensions at 24°C. ——*A*, $\alpha_{esp}/\alpha_{theor.}$; ----*B*, $\alpha_{CS^*}/\alpha_{Ag}$; $\alpha_{Cu}WG^{**}/\alpha_{Cu}$. ——–*C*, $\alpha_{real\ size}/\alpha_{standard\ size}=G/G_0$. * CS: Coin silver, ** Waveguide material.

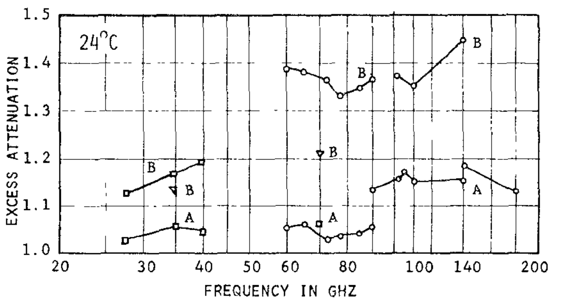

Fig. 9. Excess-attenuation ratios, $\alpha_{exp}/\alpha_{theor.\ corr.}$. *A*, coin silver. *B*, copper. □, results of precision measurements. ∇, increase due to anomalous skin effect.

theoretical value $\alpha_{theor.\ corr.}$. The latter is corrected for the measured dc conductivity at the temperature of the attenuation measurements and for the dimensional deviations from the standard figures. The corrected values are found to be

$$\alpha_{theor.\ corr.}=\alpha_{theor.\ Ag}\frac{\alpha_{CS}}{\alpha_{Ag}}\frac{\alpha_{real\ size}}{\alpha_{standard\ size}}. \qquad (6)$$

The resulting ratios $\alpha_{exp}/\alpha_{theor.\ corr.}$, as a function of frequency, are shown in Fig. 9. They represent a measure of the excess attenuation of waveguides at millimeter waves. The excess attenuation and excess losses are caused by surface roughness, corrosion (chemical reactions on the internal surfaces), and, in the case of copper, by a room-temperature anomaly of the skin effect. Work hardening associated with machining and surface processing is another source of increases in the surface losses. In the present case, however, this effect was taken into consideration by the measurement of the dc conductivity.

VIII. Attenuation, Surface Resistance, and Surface Properties

Since the attenuation is proportional to the surface resistance R_s according to (3), the ratio of the α values equals the ratio of the surface resistances R_s under corresponding conditions. We may write

$$\frac{R_{s\ exp}}{R_{s\ theor.}}=\frac{\alpha_{exp}}{\alpha_{theor.\ corr.}}. \qquad (7)$$

The surface resistance, commonly used in considerations of the skin effect, is the appropriate quantity for describing the electrical surface characteristics of metals at high frequencies [12]. At these frequencies, the electromagnetic phenomena occur in a thin layer ("skin layer") of the metal along the internal surfaces exposed to the electromagnetic waves. At 35 GHz, the equivalent depth of the skin layer is about 0.4 μm for copper and silver, and it decreases with $1/\sqrt{f}$ toward higher frequencies. The term $R_{s\ theor.}$ represents the surface resistance computed by customary skin-effect calculation for the material of the waveguide under ideal conditions. If the ratios of R_s and α are above the value 1, this indicates excess losses and excess attenuation above the theoretical values. These conditions were observed in the millimeter-wave region as indicated in the introduction.

The resulting diagrams for the excess attenuation and excess surface resistance shown in Fig. 9 are rather interesting. They show that the excess losses are comparatively small for coin-silver waveguides. The excess losses are in the order of magnitude typical for surface roughness. This result differs from previously published data which indicated increases of the attenuation of waveguides by a factor of 2. The excess losses of copper waveguides are considerably higher. It is assumed that the anomaly of the skin effect which causes an increase of about 14 percent at 35 GHz is the major cause of the increased attenuation.

IX. Surface Roughness

Measurements of the roughness of the internal surfaces of the tested waveguides were made to show the magnitude of the contribution to the excess losses. They were carried out with a profilometer [13]. The figures were corrected by using calibration graphs obtained by photomicrographic comparison. The surface roughness is nonisotropic, meaning that the roughness values differ in longitudinal and transverse directions on the inside surfaces of the waveguides. The nonisotropic character is caused by the drawing process at manufacturing the waveguides. The results are listed in Table III. Comparison with previous evaluations shows that the newly found increases of attenuation of the coin silver waveguides are typical for those solely caused by surface roughness.

TABLE III
INTERNAL SURFACE ROUGHNESS
(μm rms)

	Silver		Copper	
	Transverse	Longitudinal	Transverse	Longitudinal
WR 28	.50	.21	.26	.60
WR 12	.57	.31	.82	.73
WR 8	.36	.19	.71	.39
WR 5	.65	.39	—	—

X. CONCLUSIONS

Experiments were conducted to find the attenuation of commercially available rectangular waveguides for the millimeter-wavelength transmission bands. Emphasis was placed on highly accurate measurements and on a detailed evaluation of the results. The contributions to the discrepancy between experimental and theoretical values of attenuation were analyzed and taken into consideration by means of properly formulated equations.

The results show that waveguides made of coin silver have excess attenuations considerably below the values published in the past. They are about 5–15 percent above the theoretical values up to 200 GHz. This order of magnitude can be expected as a result of roughness. The excess attenuation of copper waveguides is considerably higher. The major contributions are caused by a room-temperature anomaly of the skin effect (14 and about 20 percent at 35 and 70 GHz, respectively), by surface roughness, and corrosion.

ACKNOWLEDGMENT

The cooperation of Baytron Company, Inc., T. Kozul, General Manager, where a large part of the attenuation experiments were made, and of the Metallurgical Department of the Engineering Research Support Division of NCSU for assisting with the metallurgical parts of the investigation is highly appreciated. The author wishes to thank Dr. F. Jalali for his assistance in many phases of the study.

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