EXPERIMENTAL ATTENUATION OF RECTANGULAR WAVEGUIDES AT MILLIMETER-WAVELENGTHS

F. J. Tischer
North Carolina State University
Raleigh, NC 27607

Abstract

Experimental values of attenuation between 25 and 200 GHz, DC values of conductivity, temperature effects, size effects, and surface roughness were measured and carefully evaluated.

Excess ratios of attenuation due to the above effects were formulated and determined.

Introduction

Effort expended in finding reliable data on the attenuation of rectangular waveguides for the millimeter-wave region frequently becomes a frustrating experience. In handbooks and catalogs of companies selling waveguides, one usually finds the theoretical values listed which are considerably below those expected in practice. Also, they are valid for pure silver while the commercially available waveguides are made primarily of coin silver which have attenuations increased by a factor somewhere around 1.25. Occasionally data are reprinted from a book on plasma diagnostics[1] with attenuation values increased by about a factor 2 above the theoretical values. Results of experiments were published by Benson[2] with emphasis on guide materials, chemical polishing, and annealing. His results confirm the previously observed discrepancies between theoretical and experimental values of attenuation and include data for the region of 20 to 140 GHz. The increases are due to excess losses which the author attributes to surface roughness and minute surface irregularities. The uncertainty of the listed data ranges from ±7% up to ±20%. Some of the results are in disagreement with those published earlier.

In a recent study of the surface characteristics of metals, in particular copper, by the author[3], it was found 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 becomes one of the major causes of the increased attenuation besides surface roughness and work hardening. In order to correlate these results with waveguide data and to generate reliable data, careful experiments were conducted for determining the attenuation of standard rectangular waveguides in the transmission bands of the millimeter-wave region for TE_{10} waves. The results of these efforts are presented in this paper.

Frequency Range and Types of Waveguides

The investigation concentrated on four sizes of waveguides, 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 to 220 GHz. The guides were made of coin silver (90% Ag, 10% Cu) and OFHC (oxygen-free and high-conductivity) copper. They came from several sources.

Experimental Procedures for the Determination of Attenuation

The attenuation values were found by carefully measuring the insertion loss. The detector setups consisted of detector mounts (SWR=3), isolators (SWR=1.4), and 10 dB attenuators coupled in front of the isolators to keep the total SWR below 1.1. High accuracy measurements in the 26.5 to 40 GHz region and at 70 GHz were carried out at N. C. State University under elimination of errors caused by reflections using matched phase shifters.

Specially designed coupling elements were attached at the ends of the waveguide sections for eliminating effects of heating when flanges were attached by soldering.

The results of some of the experiments are shown in Fig. 1 for waveguides made of coin silver. The graphs also show the theoretical values for pure silver and coin silver (CS).

DC Values of Conductivity for Waveguide Materials

The high accuracy (±.5%) of some of our measurements of Q-factors and attenuation values required a corresponding accurate determination of the DC conductivities. This required considering the temperature at the time of measurement and distinguishing between the conductivities of the materials of different guide sizes and different origins.

The temperature effects were taken into consideration by parametric diagrams. An example is illustrated in Fig. 2 which shows the conductivities of material samples cut from waveguides made of coin silver. Their values differ considerably depending on guide sizes and origins. The differences were found to be due to work hardening associated with the drawing processes at the fabrication. By heat treatment, the different values for WR-12, 8, and 5 can be brought up to a common value.

Effects of Size Deviations

Additional contributions to discrepancies between experimental and theoretical values of attenuation are caused by deviations of the inside dimensions of waveguides from the standardized values. Photographs of the actual cross sections and photomicrographic reproductions of corner regions and of sections of the flat boundaries are shown in Fig. 3. The cross-sectional geometries differ considerably from the specified rectangular shapes.

The photographs were used to find the internal dimensions and the deviations of the attenuations from those for standard dimensions. The deviations of the dimensions considerably exceed the specified tolerances and give deviations of the attenuation of up to about 13%. With the specified tolerances, these deviations would be maximally about ±3.5%.

Consideration of the Various Effects and Excess Attenuation

The experimental findings were evaluated by formulating attenuation ratios for the various effects, such as temperature in combination with the actual DC values of conductivity and the size effects. As references or normalizing values, 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 were used. The attenuation ratios were next combined to yield a figure for the excess attenuation described by the ratio of the experimentally found attenuation α_{exp}, and the 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 resulting ratios are shown in Fig. 4 as a function of frequency. This ratio may be considered as a measure of the excess attenuation of waveguides at millimeter waves. The excess attenuation and excess losses are caused by surface roughness and corrosion. Work hardening which is another source of increases of the surface losses was taken into consideration by the measurement of the DC conductivity.

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. The measured values were corrected by using calibration graphs obtained by photomicrographic comparison. Comparison with previous evaluations shows that the increases of attenuation of the coin silver waveguides have magnitude typical for the roughness effects.

References

1. M. A. Heald and C. B. Wharton, "Plasma Diagnostics with Microwaves," John Wiley & Sons, Inc., New York, N. Y., p. 308, 1965.

2. F. A. Benson and D. H. Stevens, "Rectangular waveguide attenuation at millimeter wavelength," Proc. Inst. Elec. Eng., vol. 110, pp. 1008-1014, 1967.

3. F. J. Tischer, "Anomalous skin effect of single crystal copper in the millimeter-wave region at room temperature," Physics Letters, Vol. 47A, pp. 231-232, 1974.

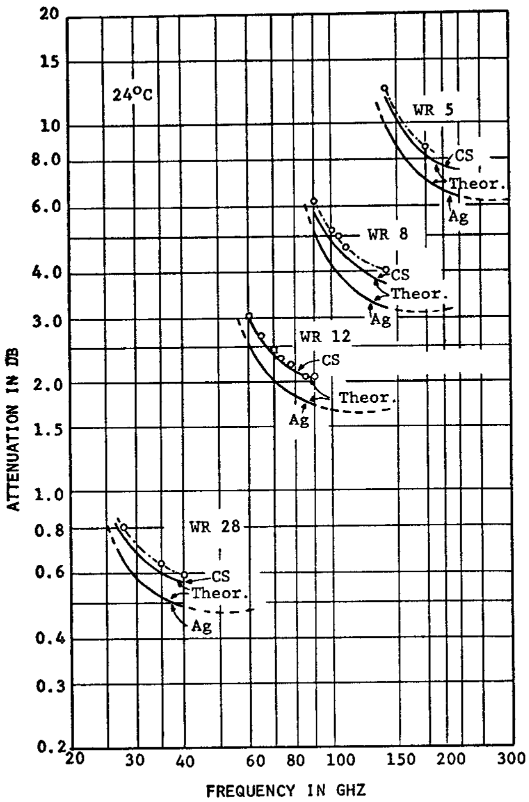

Figure 1. Experimental attenuation of standard-size waveguides made of coin silver.
— Theoretical values computed from the DC conductivity of silver (Ag, $\sigma = 6.17 \times 10^7$ S/m) and of coin silver (CS, see Fig. 4).
○ Experimental values; □ results of high accuracy measurements (70 GHz).

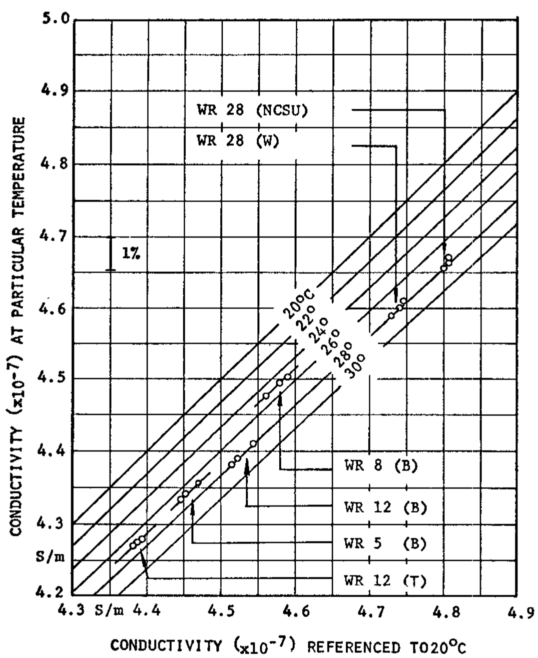

Figure 2. Measured temperature-dependent DC conductivities of coin-silver samples of various waveguides. (Origins indicated in parentheses.)

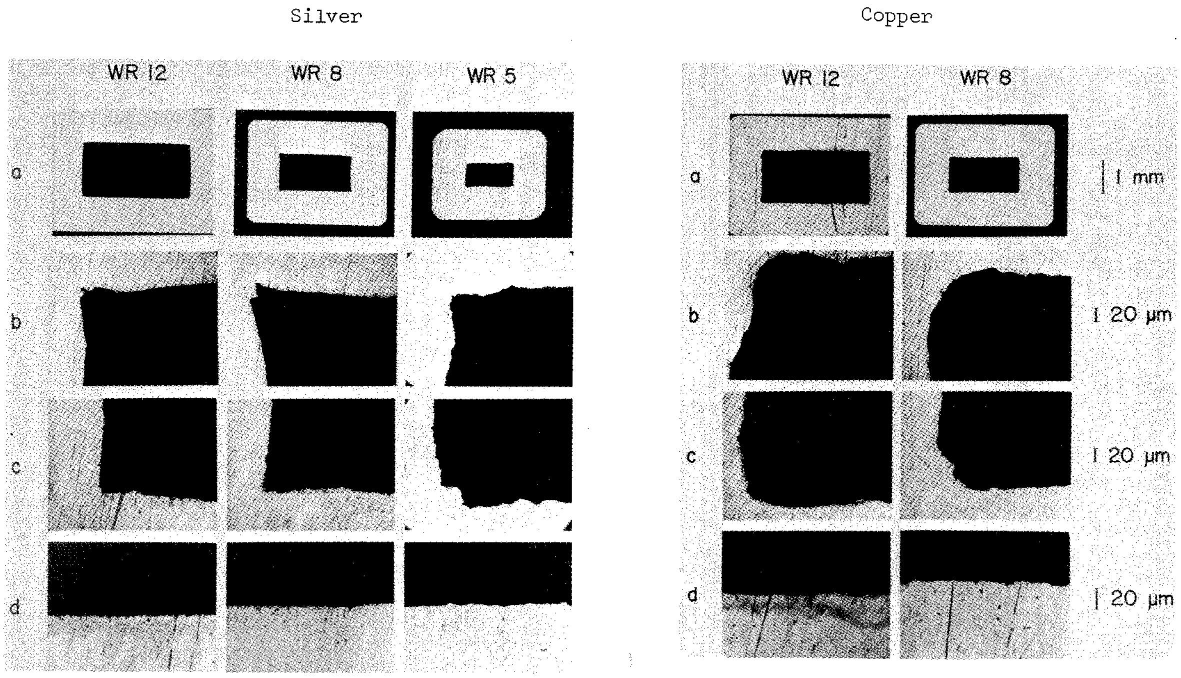

Figure 3. Photographs of waveguide cross sections (a) and photomicrographs of corner regions (b,c) and wide walls (d) of rectangular waveguides made of coin silver and copper.

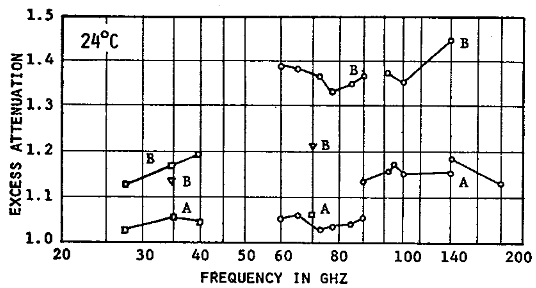

Figure 4. Excess-attenuation ratios, $\alpha_{exp}/\alpha_{theor.\ corr.}$

A: **Coin silver**
B: Copper
□ Results of precision measurements
▽ Increase due to anomalous skin effect.

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