SURFACE CHARACTERISTICS OF METALS AND WAVEGUIDE ATTENUATION AT MILLIMETER-WAVE FREQUENCIES BETWEEN 25 AND 180 GHz

Frederick J. Tischer
North Carolina State University at Raleigh, N. C.

Abstract

The discrepancies between theoretical and experimental values of the surface resistance of metals are analyzed. Experiments with carefully prepared plane and rough copper surfaces and precision measurements of waveguide losses are described and the results discussed.

Introduction

Strong efforts are presently under way to develop technology and equipment in the millimeter-wave region of the electromagnetic spectrum. The increased activity has several causes. The desire to provide new extremely wideband and fast operations in communications and the availability of solid state devices in this frequency range are the major reasons.

Data for describing the surface properties of metals at millimeter-wave frequencies are very important. They are directly related to the attenuation of waveguides, the Q-values of resonators, and the properties of circuits and filters. These figures, in turn, are necessary for the computation of the number of repeater stations required for communcation links, for finding the minimum detectable power in radio astro nomy, and for the design of millimeter-wave components and equipment.

Review of the literature and manufacturer's catalogs to find such reliable data, shows that they are nonexistent. A typical case is the attenuation of waveguides. Discrepancies exist not only between theoretical data obtained by customary calculations and the experimentally found values, but also between data measured and published by different investigators. The probable reason is that the experimental data were found many years ago, when measuring equipment was not yet as reliable and as good as it is today. Some of the then published data were republished repeatedly.

The discrepancies between theoretical and measured values of the attenuation of waveguides were originally observed in the upper frequency region of microwaves. They were investigated in primarily device-oriented studies. Since the effects under investigation and the measurement errors were in the same order of magnitude, no definite conclusion could be drawn from the result. Geometrical surface roughness was usually considered as the origin of the discrepancies. Similarly inconclusive were the recommendations of various authors with regard to the methods for achieving low surface losses. The discrepancies are more pronounced in the millimeter-wave region, but results and conclusions of different authors do not agree.[1,2]

The present paper describes efforts (1) to analyze the observed discrepancies and (2) to generate new meaningful and reliable data applicable to systems and component design. Emphasis in these efforts has been placed on two requisites: high accuracy of the electrical measurements was one, satisfactory definition and description of the surfaces under investigation was the other one. High accuracy permits determination and separation of the various effects contributing to excess losses and discrepancies. Accurate definition and description of the surface conditions make the results meaningful and practical. In addition, experimental conditions for the investigation were kept as simple as possible.

The investigation has had three parts. The purpose of one set of experiments was to separate the causes of the excess losses responsible for the discrepancies and to find, if possible, an intrinsic value of the surface resistance of conductors. The second part consisted of artificially creating surface roughness and then determining its effect on surface resistance. In the third part, highly accurate measurements and evaluations of commercially available waveguides were made. These measurements were made to assess the validity of the existing published figures and to establish relationships between the fundamental data of the other phases of the investigation and those encountered in practical engineering.

Anomalous Skin Effect of Single-Crystal Copper

Previous experiments analyzing effects of surface roughness carried out at 35 GHz indicated the existence of a minimum value of surface resistance. This value was noticeably above the theoretical figure and could not be reduced by improved polishing methods and special surface preparation. The results of these efforts led to an attempt to find an intrinsic surface resistance of copper at millimeter wavelengths at room temperature.

The basic approach in these efforts consisted of measuring the Q-factor of a rectangular cavity in which the plane surfaces to be investigated formed the side walls. After testing three types of cavities, the final experiments were carried out by use of a rectangular cavity with the cross section shown in Fig. 1. In this cavity, the side walls are formed by half-cylinders pressed against spacers attached to the end walls. The top and bottom walls are parts of the spacers. Holes in the end walls couple the cavity to input and output waveguides. The dimensions of the cavity were so optimized that the major contribution to the unloaded Q-factor of the cavity resulted from the side walls.

The optimization was carried out by evaluation of the equation for the Q-factor

$$1/Q_{cavity} = 1/Q_s + 1/Q_{t,b} + 1/Q_e,$$

where Q_s, $Q_{t,b}$, and Q_e are the Q-factors associated with the side walls, the top and bottom walls, and the end walls respectively. The cavity was optimized to give maximum contribution to the cavity losses by the side walls.[3] With the width of the cavity chosen to be 4.4 mm, the contribution by the side walls was about 90%.

The surfaces under evaluation were extremely carefully prepared and handled.[4] They were cut from single-crystal copper rods with a purity of 99.999%. Cutting was done by an acid saw and polishing by a chemical polishing wheel developed by the Oak Ridge National Laboratories. The side wall surfaces were of the (100) type of the copper crystal; they were subsequently electropolished, washed, dried, and annealed in hydrogen. They were also kept and transported in hydrogen and were mounted in an argon-filled glove box in the cavity. Argon was kept flowing through the cavity during transfer into the millimeter-wave circuitry and during measurements. The measurements gave the following results:

$$Q_{cavity,unloaded} = 4971; \; R_{s\ side\ walls} = 0.0554 \text{ ohms},$$

$$Q_{side\ walls} = 5579; \; R'_{s\ computed} = 0.0491 \text{ ohms}.$$

The error of the determination of Q_s, including disassembly and reassembly of the cavity, did not exceed ±1%. The value of R'_s was computed from the measured DC value of conductivity at 22°C, $\sigma_o = 5.73 \times 10^7$ S/m. The result indicates that the measured surface resistance of copper exceeds the computed value by a factor $r_x = R_s/R'_s = 1.129 \pm 0.02$ and that the skin effect is anomalous at millimeter wavelengths at room temperature. This anomaly, however, is not identical to that observed at low temperatures.

Effects of Surface Roughness

The basic concept of this part of the study was that roughness is just one of several effects contributing to excess losses which increases the surface resistance beyond the intrinsic value obtained for optimally flat and pure copper surfaces. Correspondingly, the walls of the cavities used in these experiments were artificially roughened and the Q-factors measured. The results gave values of the surface resistance for various degrees of roughness, which in turn were normalized with regard to the surface resistance of highly polished walls. The obtained ratios then were a measure for the effect of the roughness on the excess losses. Most recently the cavity shown in Fig. 1 was applied, and one-dimensional roughness was generated by grinding the side walls on specially designed grinders using carefully selected abrasive papers. The degree of roughness was determined by a stylus-type profilometer after calibration by photomicrography [6]. Additional tests were made by optical methods of roughness determination.

A representative example of the results of this part of the investigation is shown in the diagram of Fig. 2. It shows the resistance ratio for a copper surface vs. r.m.s. surface roughness for currents flowing across the grooves associated with the roughness at 35 GHz. The diagram indicates that the surface resistance of a rough surface with an r.m.s. of about 1 μm increases by about 30% of the value of a highly polished surface.

Waveguide Attenuation

The third part of the investigation involved determination of the attenuation of commercially available rectangular waveguides and evaluation of their non-electric surface characteristics. Its purpose was to evaluate the validity of previously published data and to find relationships between the experimental attenuation data and the more fundamental results of the other phases of the investigation.

Evaluation of the customary equation for the attenuation of rectangular waveguides shows that the attenuation is propostional to the surface resistance of the guide walls. The ratios of the measured attenuation values divided by the theoretical values hence directly yield the R_s ratios which are indications of the excess losses.

A review of published attenuation data reveals considerable discrepancies between results published[2,5] by different investigators,probably caused by measurement errors and by different measurement conditions. Measurement errors of about ±.2dB are not uncommon at 70 GHz. They correspond to an uncertainty of the R_s ratio between about 1.2 and 1.4. Very high measurement accuracies are thus required to give reliable data. In recognition of these requirements, very careful experiments were conducted to find the attenuation of a number of samples of waveguides of WR 28,12,8,and 5. Reflections were reduced by isolators and additional attenuators and their amounts continuously checked. The results were obtained as averages of repeated measurements. The results are shown in Figs. 3(a) and 3(b).

The results in general indicate that the attenuation of waveguides made of silver is considerably lower than suggested by previously published data. A trend is evident that the discrepancy between experimental and theoretical values of attenuation increases with increasing frequency. Chemical cleaning of a WR 12 section made of silver clearly reduced the surface resistance by about 5%.

Conclusions

Combining the results of the various parts of the investigation allows interesting conclusions. The experiments in the first part of the project indicate that an anomaly of the skin effect of copper exists at room temperature described by a R_s ratio of about 1.13. This anomaly represents one cause of the discrepancy between the experimental and the theoretical surface resistance, a discrepancy which probably cannot be reduced by any kind of surface preparation. Work hardening due to machining and surface processing increases the R_s ratio to about 1.18 for mechanically highly polished surfaces. Roughness then increases the ratio rapidly as can be observed by inspection of Fig.4. For rough surfaces, (one-dimensional roughness), when the peak-to-peak variation is large in comparison to the skin depth, the R_s ratio assumes a value corresponding to the area increase of the surface associated with the roughness. Chemical effects then additionally increase the surface resistance. These trends observed for the surface resistance of copper, obviously also apply to the ratios involving the attenuation of waveguides and the Q-factors of resonators. The recent experiments indicate that the basic effects are similar for silver surfaces. The investigation continues.

Acknowledgment

The cooperation of the U.S. Atomic Energy Commission and in particular of Dr. L. H. Jenkins of the Solid State Division of the Oak Ridge National Laboratories who furnished the measured single-crystal copper surfaces and of Baytron Company, Inc., Medford, Mass., Mr. Ted Kozul, General Manager, where most of the attenuation experiments were made, is highly appreciated. The author wishes to thank Dr. F. Jalali for the assistance. The work was supported by the National Science Foundation under Grant GH-34445.

References

1. T. S. Thorp, "R.F. Conductivity in copper at 8mm wavelength,"Proc. Inst. Elec. Eng., vol. 101, pt. 111, pp. 357-359, 1954.
2. F. A. Benson and D. H. Stevens, "Rectangular waveguide attenuation at millimeter wavelength, "Proc. Inst. Elec. Eng., vol. 110, -p. 1008-1014, 1967.
3. F. J. Tischer and F. Jalali, "Resonant cavities for the measurement of the surface resistance of conductors at millimeter wavelength," Rev. Sci. Instrum., vol. 46, pp. 11-14, 1974.
4. F. J. Tischer, "Anomalous skin effect of single-crystal copper in the millimeter-wave region at room temperature," Physics Letters, vol. 47A, pp. 231, 233, 1974.
5. M. A. Heald and C. B. Wharton," Plasma diagnostics with microwaves," John Wiley & Sons, Inc., New York, N.Y. 1965.

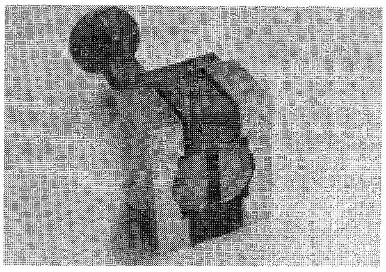

Fig. 1. Cross-sectional structure of cavity resonator.

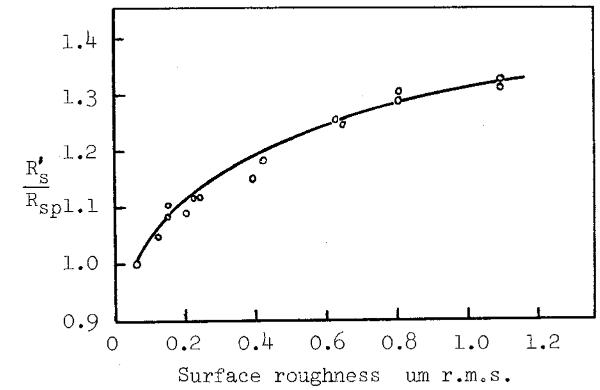

Fig. 2. Surface resistance ratio R'_s/R_{sp} vs surface roughness.

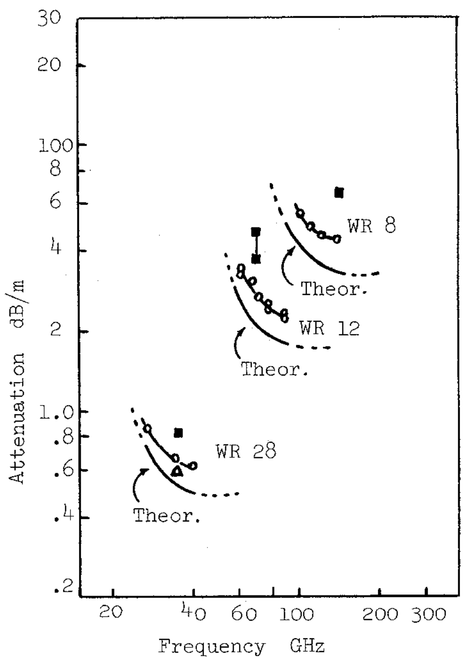

Fig.3. Measured attenuation of standard-size waveguides made of copper.
■ Benson[2]; o Tischer; □ values calculated from measured surface resistance of polished copper; Δ Tischer[4], value calculated from measured intrinsic surface resistance.

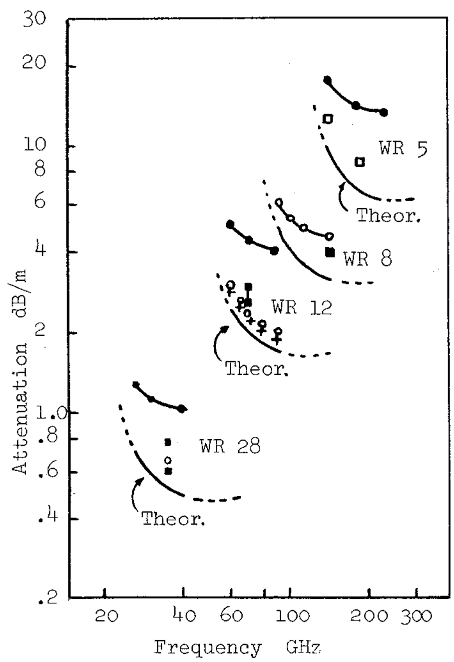

Fig.4. Measured attenuation of standard-size waveguides made of coin silver.
● Wharton[5]; ■ Benson[2]; o Tischer;
+ Tischer, chemically cleaned waveguide;
□ Tischer, accuracy not assured.