Dr. J. W. Waters [10] in this area to their attention and for furnishing data obtained from Dr. Waters.

REFERENCES

[1] S. A. Zhevakin and A. P. Naumov, "The absorption coefficient of water vapor for electromagnetic waves in the range 2 cm–10 μm," *Radiophys. Quantum Electron.*, vol. 6, p. 675, 1963.

[2] J. H. Van Vleck and V. F. Weisskopf, "On the shape of collision-broadened lines," *Rev. Mod. Phys.*, vol. 17, pp. 227–236, Apr.–July 1945.

[3] G. W. King, R. M. Hainer, and P. C. Cross, "Expected microwave absorption coefficients of water and related molecules," *Phys. Rev.*, vol. 71, pp. 433–443, Apr. 1947.

[4] J. H. Van Vleck, "The absorption of microwaves by uncondensed water vapor," *Phys. Rev.*, vol. 71, pp. 425–433, Apr. 1947.

[5] C. H. Townes and A. L. Schawlow, *Microwave Spectroscopy*. New York: McGraw-Hill, 1955, p. 104.

[6] E. P. Gross, "Shape of collision-broadened spectral lines," *Phys. Rev.*, vol. 97, pp. 395–403, Jan. 1955.

[7] D. L. Croom, "Stratospheric thermal emission and absorption near the 22.235 Gc/s (1.35 cm) rotational line of water-vapor," *J. Atmos. Terrest. Phys.*, vol. 27, pp. 217–233, 1965.

[8] ——, "Stratospheric thermal emission and absorption near the 183.311 Gc/s (1.64 mm) rotational line of water-vapor," *J. Atmos. Terrest. Phys.*, vol. 27, pp. 235–243, 1965.

[9] A. H. Barrett and V. K. Chung, "A method for the determination of high-altitude water-vapor abundance from ground-based microwave observations," *J. Geophys. Res.*, vol. 67, pp. 4259–4266, Oct. 1962.

[10] J. W. Waters in *Methods of Experimental Physics*, vol. 12, part B, M. L. Meeks, Ed. New York: Academic, 1976, pp. 142–176.

The Measurement of the Surface Resistivity of Evaporated Gold at 890 GHz

R. J. BATT, G. D. JONES, AND D. J. HARRIS

***Abstract*—A modified pyroelectric detector is used to measure the surface resistivity of evaporated gold at 890 GHz. The value of 0.65 Ω square yields a ratio of measured-to-theoretical surface resistivity of approximately 2.2.**

I. INTRODUCTION

THE ATTENUATION of a metal waveguide or the reflectivity of a mirror is determined by the surface resistivity of the wall of the guide or the mirror surface. To calculate the attenuation or reflectivity, the effective value of the surface resistivity is required at the operating frequency.

The attenuation for the fundamental TE_{10} transmission mode of a rectangular waveguide is given by [1]

$$\alpha(f)N/m = \frac{R_s}{120\, b\pi \left[1 - \left(\frac{f_c}{f}\right)^2\right]^{1/2}} \left[1 + \frac{2b}{a}\left(\frac{f_c}{f}\right)^2\right] \quad (1)$$

where R_s is the surface resistivity. The theoretical value of R_s is related to the bulk resistivity ρ by the expression

$$R_s = (\pi f \mu_r \mu_0 \rho)^{1/2} \quad (2)$$

all the symbols having their usual meaning. The theoretical waveguide loss predictions using surface resistivity figures which are derived from dc values of bulk resistivity using (2) seriously underestimate the actual waveguide losses for frequencies greater than about 10 GHz. This apparent anomaly in surface resistivity has been investigated by many workers [2], [3] for various waveguide materials such as copper, silver, and brass in the microwave region up to frequencies of about 200 GHz. The reported ratios of measured-to-theoretical loss of up to 2.5 imply similar variations of effective-to-theoretical surface resistivity.

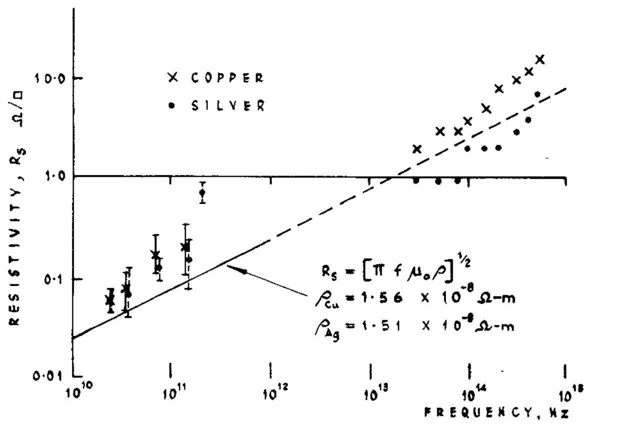

Fig. 1. Variation of surface resistivity of copper and silver with frequency.

Fig. 1 summarizes some surface resistivity values for copper and silver deduced from the measured waveguide attenuations [2], [3] in the region 10–200 GHz. The theoretical variation with frequency is shown (solid line) assuming the bulk resistivities of copper and silver which are equal to within 3.5 percent. ($\rho_{Cu} = 1.56 \times 10^{-8}\Omega \cdot$ m, $\rho_{Ag} = 1.51 \times 10^{-8}\ \Omega \cdot$ m.)

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The effective surface resistivity can be deduced also from reflectivity measurements. The power density P_a absorbed in a metal surface reflecting an incident electromagnetic wave results from the induced current, and is given by $4H^2R_s$, while the incident power density P_i is given by the relationship $P_i = 120\pi H^2$. For low-loss reflection, the ratio of absorbed-to-incident powers is given by

$$\frac{P_a}{P_i} = \frac{R_s}{30\pi}. \quad (3)$$

Hence a value for the surface resistivity for a metal surface may be deduced by direct measurement of the absorbed and incident powers.

Apparent surface resistivity values obtained from infrared reflectivity measurements [4], assuming that (3) is still valid in this region, are included in Fig. 1 and can be compared with the extended theoretical frequency variation. The surface resistivity is greater than that which would be theoretically predicted in the microwave region and may be dependent on a number of factors besides frequency; for example, surface roughness. Fig. 1 also shows the absence of experimental data in the region 300 GHz–30 THz.

The reported loss measurements determine absorbed power and hence surface resistivity by indirect methods. These methods require correction for other system losses, e.g., coupling factor losses in cavity measurements, or rely on the small difference between two relatively large measured quantities, e.g., in low-loss transmission and reflection methods. A more direct method avoiding these limitations is preferable.

II. The Measurement Technique

The direct measurement of the absorbed power in evaporated gold films when HCN-laser radiation is incident on the films is reported here.

The measurement of effective surface resistivity involves independent determinations of the incident radiation power P_i and the absorbed power P_a in the surface of the gold film. The incident HCN (337-μm) laser radiation power was measured using a disk thermopile, the absolute sensitivity of which had been determined by the National Physical Laboratory [5], [6]. The absorbed power was determined using a modified pyroelectric detector having a reflecting surface film of the material under investigation. The radiation power dissipated in the metal film is determined by substitution of an equivalent low-frequency power also dissipated in the film. In this experiment the incident radiation-power level was typically 1 mW and the power absorption of the order of 5 μW.

A. The Modified Pyroelectric Detector

The gold film to be measured was evaporated on to the front surface of a pyroelectric-detector element, the normal thin front coating of Nichrome (750 Ω/square) being overlaid with the gold film to a thickness larger than the skin depth at 890 GHz ($\delta_{890} \simeq 8 \times 10^{-2}$ μm, $t \simeq 1$ μm). Nonhygroscopic PZT was chosen for the pyroelectric element which has surface dimensions of 4 × 2 mm, the modified detector being constructed by the Plessey Allan Clark Research Centre. A number of electrical contacts (gold) were made along each short edge, as shown in Fig. 2. A single contact was made to the backface and connected to an FET input amplifier.

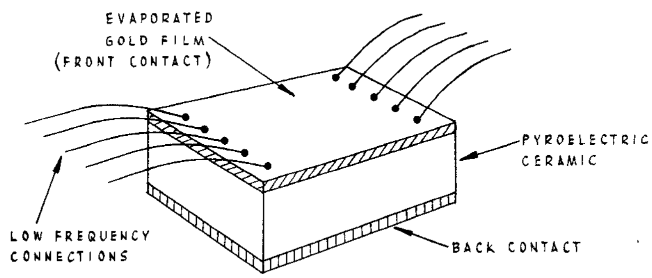

Fig. 2. Modified pyroelectric detector element showing front contact connections.

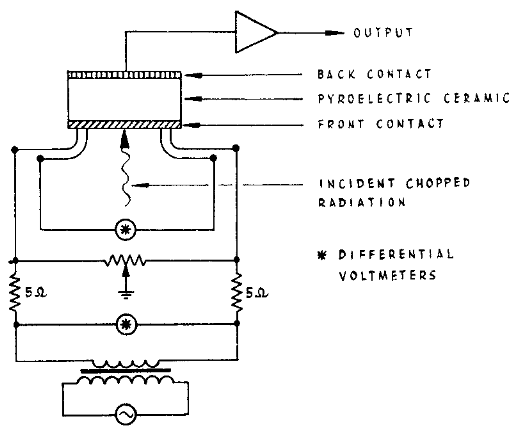

Fig. 3. Circuit for low-frequency heating of the evaporated gold film.

The front-face contacts allow a low-frequency current to be passed through the film and the power delivered to the film is measured as shown in Fig. 3. The voltage drop across the film and the current through the film were determined using differential voltmeters. The low-frequency heating circuit is arranged to provide a virtual earth in the center of the film to balance the capacitively coupled voltages at the applied frequency. This ideally leaves only the pyroelectrically generated EMF at twice the applied frequency to be amplified.

The modified pyroelectric detector was then used in the normal way to produce a pyroelectric voltage proportional to the absorbed power resulting from the chopped incident radiation. The radiation was removed and a detector output of equivalent magnitude was obtained by heating the gold film with a low-frequency current at half the chopping frequency. The absorbed power is determined in terms of the low-frequency current and voltage measurements and is *independent* of the sensitivity of the pyroelectric element.

B. Experimental Arrangement

The modified pyroelectric detector and the disk thermopile were mounted on a Perspex disk in a chamber which can be evacuated. The Perspex disk can be rotated to place

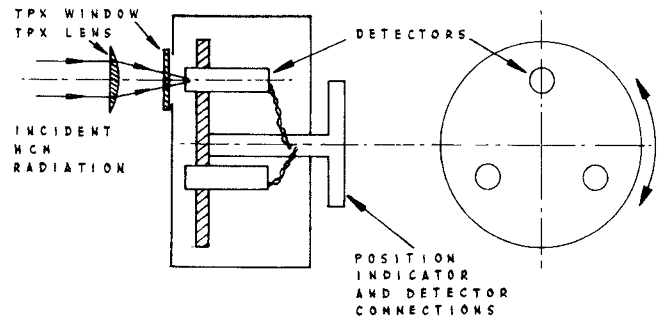

Fig. 4. Schematic diagram of the rotating disk supporting the detectors in an evacuable chamber.

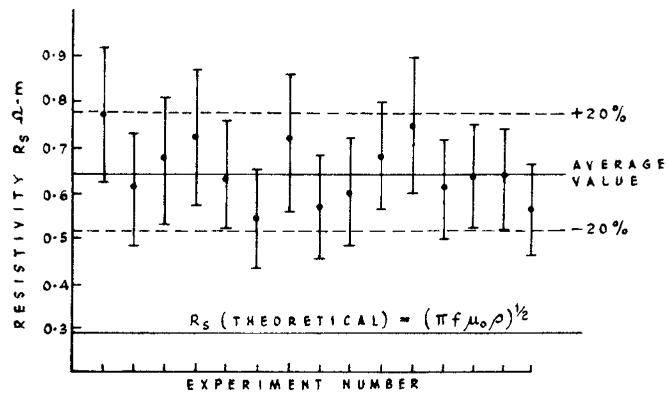

Fig. 5. Spread of experimental results for gold.

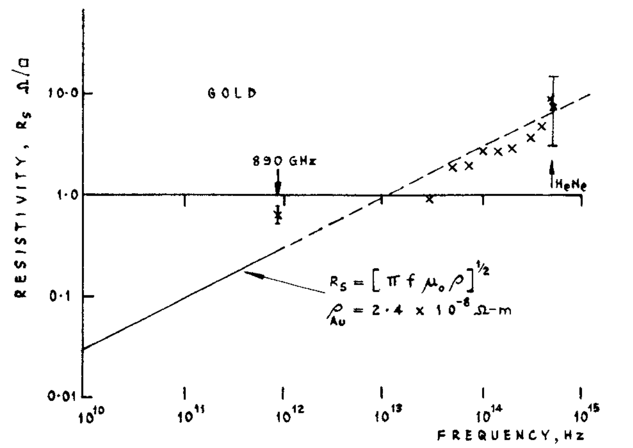

Fig. 6. Comparison of surface resistivity of gold with infrared data.

either the pyroelectric detector or the thermopile in turn in the path of the laser radiation at the focus of a TPX lens, as illustrated in Fig. 4. The surrounding chamber, even when not evacuated, reduces thermal convection losses and instabilities. The detectors were arranged on the disk to have their detecting elements in the same plane and 1.5-mm limiting apertures were placed immediately in front of them. A series of successive independent measurements of incident power P_i and absorbed P_a were then taken and the surface resistivity for gold deduced.

III. Experimental Results

Initial measurements with 890-GHz radiation incident on evaporated gold films give an experimental value for surface resistivity of 0.65 Ω/square with a spread of 20 percent, as shown in Fig. 5.

Fig. 6 shows this result together with the infrared reflectivity data [4] and the extended theoretical frequency variation using a value of 2.4×10^{-8} Ω · m for the dc bulk resistivity of gold.

The measured surface resistivity corresponds to a power reflectivity of 99.3 percent and may be compared with the theoretical surface resistivity of 0.29 Ω/square (reflectivity 99.7 percent) obtained using (2) and the above value for the dc bulk resistivity of gold. This gives a ratio of measured-to-theoretical surface resistivity for gold at 890 GHz of approximately 2.2. This ratio is the same order of magnitude as that for copper and silver measured in the region of 100–200 GHz.

IV. Experimental Limitations

The experiment has a number of uncertainties and limitations.

The first limitation is that the gold film was not specularly reflecting because of the crystalline nature of the surface of the pyroelectric detector element. However, this surface is likely to be similar to a machined waveguide surface. The theoretical value for surface resistivity assumes a specularly reflecting surface so the presence of surface roughness should give a result that is high. The second limitation involves an assessment of how much of the measured incident radiation power P_i is actually incident on the modified pyroelectric element because of geometric and diffraction effects. The 10-mm-diam disk area of the thermopile should ensure that all the radiation transmitted through the 1.5-mm-diam aperture placed in front of it was being measured. However, not all of this radiation may have been incident on the 4 × 2-mm modified pyroelectric element with its 1.5-mm-diam aperture. *If this is the case*, then our measured surface resistivity is *low*.

Additional uncertainties may be caused by differences in the waveforms and the power distribution across the absorbing film for the radiation and low-frequency heating. It is difficult to ensure that the incident beam and comparison electrical heating powers have the same time variation, and the Gaussian profile of the radiation heating across the surface will be different from the more uniform distribution of the heating by the low-frequency current.

V. Discussion

The power absorbed in a metal surface when it reflects incident radiation may be measured using a modified pyroelectric detector with that metal evaporated on the detector surface. The surface resistivity of the metal may be deduced from the absorbed power and the incident power determined by an additional independent measurement. The method has given values of surface resistivity for gold that have a similar ratio to the value calculated from the bulk resistivity as those obtained at either microwave or infrared frequencies for other metals. The ratio obtained at 890 GHz is 2.2 to 1. The scatter of measurements lie within ±20 percent, although the limitations outlined suggest that the uncertainty in the actual value may be somewhat greater than this. Improvements in measurement technique and geometric arrangements will reduce this uncertainty.

The technique should be applicable for the measurement of surface resistivity of many metals over the short-millimetric to optical region. A preliminary measurement with an He–Ne laser has been made and has given a value of 8 Ω/square for gold, also shown in Fig. 6. In this region of the frequency spectrum the assumed formulas are questionable. By an appropriate arrangement, the absolute measurement of surface resistivity should be possible.

The modified pyroelectric detector arrangement with a metal front surface of known reflectivity should find use for the absolute measurement of submillimetric power at microwatt levels. This proposal is being investigated.

Acknowledgment

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References

[1] S. Ramo, J. R. Whinnery, and T. Van Duzer, *Fields and Waves in Communication Electronics.* New York: Wiley, 1967.
[2] F. A. Benson, *Millimetre and Submillimetre Waves.* London: Iliffe, 1969, ch. 14.
[3] N. Marcuvitz, *Waveguide Handbook.* New York: McGraw-Hill, 1951.
[4] A. F. Harvey, *Coherent Light.* New York: Wiley, 1970, ch. 2.
[5] N. W. B. Stone *et al.*, "Electrical standards measurement—Part 3: Submillimetre-wave measurements and standards," *Proc. IEE*, vol. 122, pp. 1054–1070, Oct. 1975.
[6] D. W. E. Fuller, N. R. Cross, and J. Chamberlain, "Measurement of power at submillimetre wavelengths," in *Proc. Conf. Precision Electromagnetic Measurements*, pp. 95–97, 1974.

Reflectivity of Common Materials in the Submillimeter Region

M. D. BLUE AND S. PERKOWITZ

***Abstract*—The appearance of an illuminated scene at submillimeter wavelengths is determined by surface reflectivity. Reflectivities of some man-made and natural materials have been measured. The results provide some insight for evaluating possible applications of submillimeter radiation.**

Introduction

THE gradual realization of practical submillimeter-wave sources, including optically pumped lasers throughout the submillimeter region [1], and relativistic electron-beam devices [2], gives rise to the possibility of practical terrestial systems operating within the atmospheric windows [1]. Systems calculations are handicapped by a lack of data concerning dielectric properties of common materials in this spectral region. Recent transmission data and active imaging experiments indicate the potential utility of this technology [3]. The work reported here represents an initial attempt to characterize the far-infrared submillimeter reflectivity of common materials, and can be used as a guide for initial estimates of system performance. The contrast expected in imaging systems in this wavelength region between man-made and natural objects is of interest and is difficult to predict. In addition to military applications, several applications for civil systems might be envisioned, such as a system for locating and identifying aircraft on remote airport taxiways and runways during periods of severe weather.

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Experimental Methods

The room-temperature reflectivity measurements employed a modified Grubb Parsons Mark II Fourier-transform spectrometer [4]. Light-pipe optics carried the radiation to a sample holder which was open to the atmosphere so that the sample could be studied under natural conditions. Conventional disiccant and a constant flow of dry nitrogen gas were used to eliminate water-vapor absorption from the sample light pipe and holder and the remainder of the spectrometer was evacuated. The radiation impinged on the samples at an angle of 12°, negligibly different from normal incidence. The sample holder was mounted horizontally to accomodate loose samples such as sand. The detector was a Unicam quartz-window Golay cell with the usual polyethylene filtering. All data were taken at a resolution of 8 cm^{-1}. A sample in/sample out