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Loss of Gold Plated Waveguides at 210-280 GHz

A. R. Kerr, C. Litton, G. Petencin, D. Koller, and M. Shannon
National Radio Astronomy Observatory
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Abstract: The loss at 210-280 GHz of room temperature waveguides plated with BDT 200 bright gold and Pur-A-Gold 125 soft gold is within ~10% of the theoretical loss based on the DC conductivity of pure gold and the classical skin effect. This is not the case for some other types of gold plating meeting the same ASTM (or MIL) specs but in which a trace of nickel is used as a brightener.

Introduction

Following the recent replacement of the NRAO-CDL bright-gold plating solution used for the ALMA Band 6 SIS mixers, it was noticed that an initial darkening of the surface occurred on immersion of the brass parts in the bath. Although the final plating had good adhesion and appeared to be of high quality, we were disconcerted by the change in behavior of the bath and decided to measure the microwave loss of plated waveguide samples. Our concern was that the manufacturer might have made a subtle change in the composition of the solution which would not affect its ASTM specification but could increase the microwave loss. Recently, we had observed that the nickel brightener used in some commercial gold plating baths could cause significantly increased microwave loss, even though the plating met the appropriate ASTM (or MIL) specs.

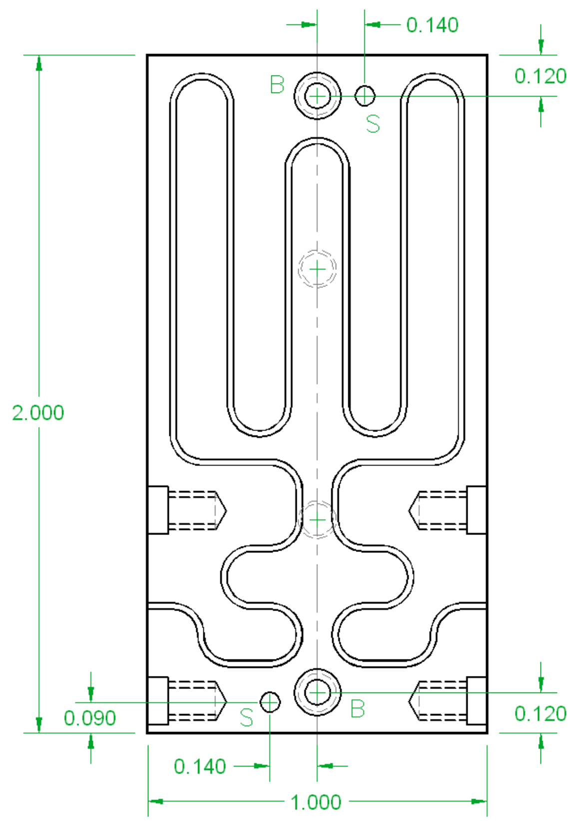

Fig. 1. The waveguide pattern in the test pieces. The waveguide is WR-3.7 (0.037" x 0.0185"). The total waveguide length is 10.000 inches.

Plating Processes

The NRAO-CDL plating lab uses two gold plating processes, one for hard, bright, gold based on the Enthone BDT 200 bath [1] which uses an arsenic brightener, and the other for soft, wire-bondable gold based on the Enthone Pur-A-Gold 125 bath [1]. According to the manufacturer's data sheets, BDT 200 meets ASTM B 488-01 Type I (purity > 99.7%) Code C (hardness 130-200 KH_{25}), while Pur-A-Gold 125 meets ASTM B 488-01 Type III (purity > 99.9% Code A (hardness ≤ 90 KH_{25}). The test waveguides were plated with 75 μ-in of gold, which is about ten skin depths in the frequency band of measurement.

Measurements

The brass split-block test pieces contain 10" of WR-3.7 waveguide (0.037" x 0.0185") machined in a meandering pattern as shown in Fig. 1. The waveguide is split along the centers of its broad walls, thereby minimizing the excitation of modes in any gaps between the block halves. The waveguide channels were machined using an end-mill on a CNC machine, and de-burred but not polished prior to plating.

Oleson WR-3.4 extenders were used on an HP 8510 VNA to cover the band 210-280 GHz. (The small mismatch between WR-3.4 and WR-3.7 causes a reflection coefficient < -30 dB at each interface which is not significant in the loss measurement.) 801 frequencies were measured, with averaging of 255 samples at each frequency. Smoothing was not used.

Fig. 2 shows the measurements on the waveguide plated with bright gold. Also shown is the theoretical loss assuming classical skin effect, with a conductivity of 3.63 x 10^7 S/m which gave a best fit to the measured S_{21} data. The loss is given by [2]:

$$\alpha = 1.163 \times 10^{-6} \sqrt{\frac{f}{\sigma}} \left[\frac{2\frac{b}{a}\left(\frac{f_c}{f}\right)^2 + 1}{b\sqrt{1-\left(\frac{f_c}{f}\right)^2}} \right] \quad \text{dB/inch,} \tag{1}$$

where σ (S/m) is the conductivity of the metal (for pure annealed gold σ = 4.2 x 10^7), a and b (m) are the waveguide dimensions ($a > b$), and f_c (Hz) its cutoff frequency.

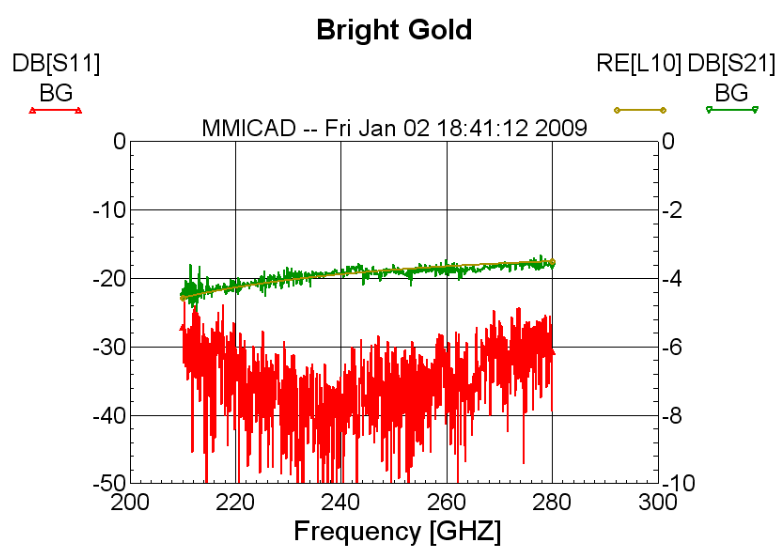

Fig. 2. Bright-gold plated waveguide. The best-fit loss curve is obtained for σ = 3.63 x 10^7 S/m.

Fig. 3. shows the measurements of the waveguide plated with soft gold. Also shown is the theoretical loss assuming classical skin effect, with a conductivity of 3.84 x 10^7 S/m which gives the best fit to the measured S_{21} data.

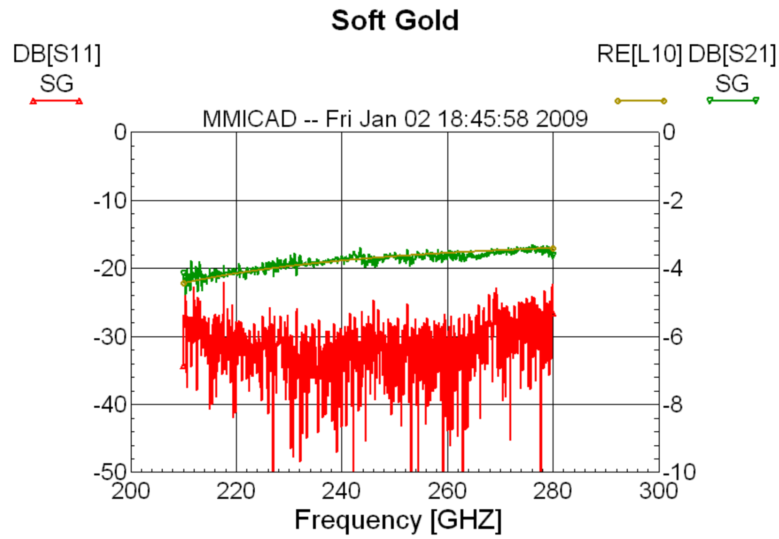

Fig. 3. Soft gold plated waveguide. The best-fit loss curve is obtained for σ = 3.84 x 10^7 S/m.

Fig. 4 shows the S_{21} data for the waveguides plated with bright and soft gold on an expanded scale for comparison.

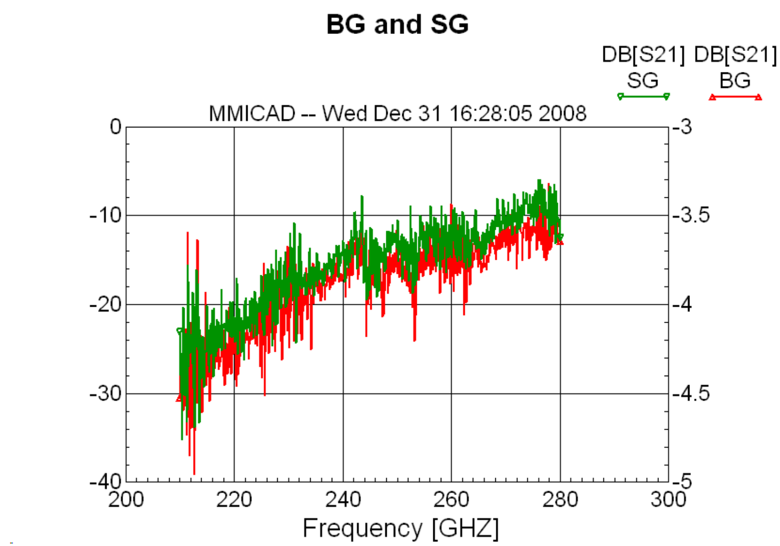

Fig. 4. S_{21} data for the two waveguides on an expanded scale.

Measurements were also made on a 1-inch WR-3.4 calibration waveguide included in the Oleson standards kit – Fig. 5. The best fit loss curve in this case was obtained for σ = 0.94 x 10^7 S/m, which is about four times the best fit value for the other samples. The material of the waveguide is not known.

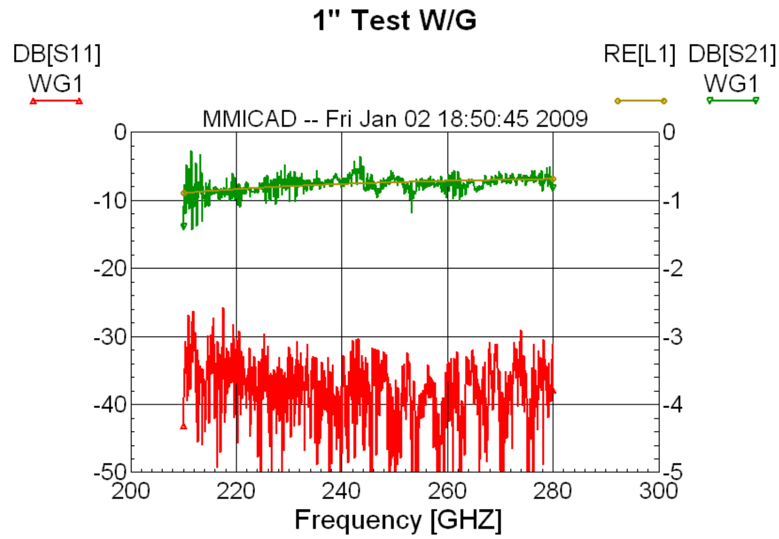

Fig. 5. The 1-inch standard waveguide section supplied in the Oleson calibration kit. The best-fit σ = 0.94 x 10^7.

Stability of the measuring system. After initial calibration of the VNA, a measurement was made with the heads connected directly together. This was repeated during and after the measurements. The S-parameters are shown in Fig. 6, and show a drift in S_{21} of the order of 0.1 dB.

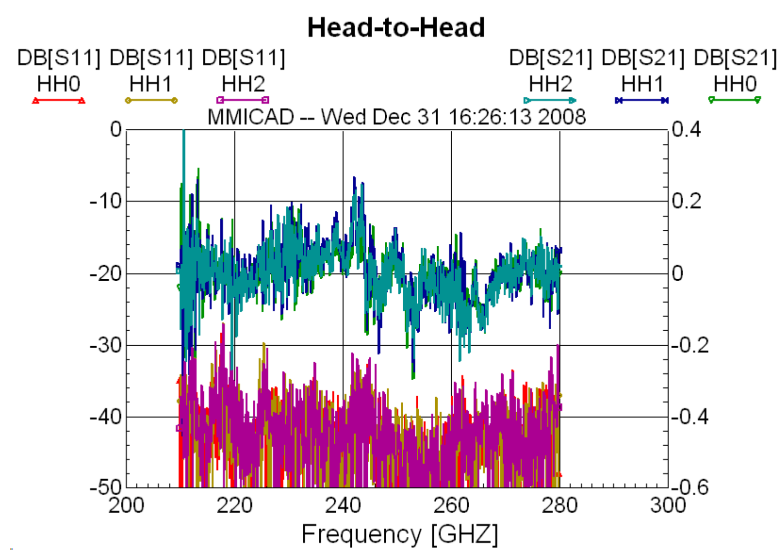

Fig. 6. Measurements with the VNA heads connected directly together, before, during, and after the loss measurements.

Discussion

The measured loss of metal waveguides is usually larger than the theoretical value, often by as much 50% [3]. Waveguides gold plated at the CDL with BDT 200 and Pur-A-Gold 125 had a loss within 10% of the theoretical value based on the DC conductivity of pure gold and classical skin effect. This is seen in Figs. 7 and 8, which show the measured loss (the same data as in Figs. 2 and 3) and the theoretical loss calculated using the DC conductivity of pure gold, $\sigma = 4.2 \times 10^7$ S/m.

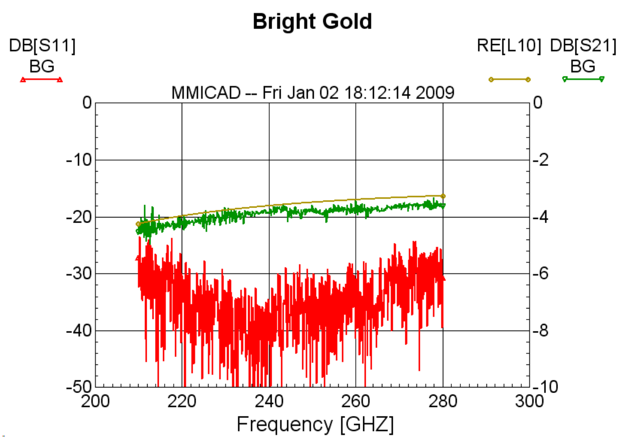

Fig. 7. Bright-gold plated waveguide. The theoretical loss curve is for gold with $\sigma = 4.2 \times 10^7$ S/m

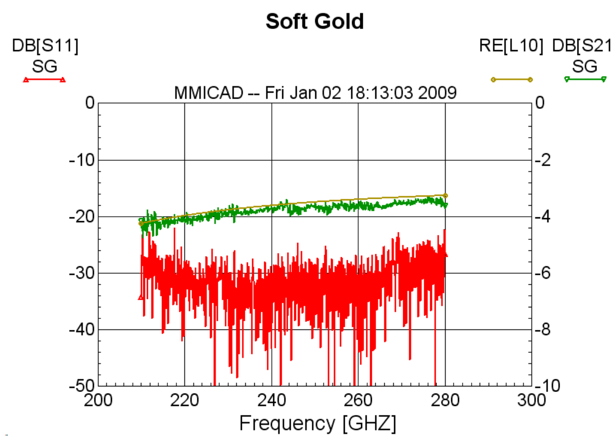

Fig. 8. Soft-gold plated waveguide. The theoretical loss curve is for gold with $\sigma = 4.2 \times 10^7$ S/m.

During the testing of some millimeter wave orthomode transducers for ALMA receivers in 2008, it had been found that some commercial gold plating meeting the same ASTM (or MIL) specification was at least twice as lossy as the CDL plating. This appears to result from the use of a nickel brightener, and the OMT problem was solved by specifying gold without a nickel brightener but with the same ASTM specification.

A note on cryogenic operation: The observed agreement between the measured waveguide loss and the theoretical loss based on the classical skin effect and the DC conductivity is not expected to apply at temperatures at which the skin depth is comparable to or smaller than the electron mean free path, resulting in anomalous skin effect behavior. For gold at room temperature and 245 GHz, the classical skin depth $\delta = 0.16$ µm which is substantially greater than the electron mean free path $l = 0.035$ µm [4]. The current transport mechanism is thus in the classical skin effect regime. At cryogenic temperatures, the conductivity of pure metals can be larger by orders of magnitude than at room temperature. Because l/δ varies as $\sigma^{3/2}$, millimeter waveguides of pure metals at low temperatures are likely to be in the anomalous limit and, while having less loss than at room temperature, will have greater loss than calculated from the classical skin effect [4].

References

[1] Enthone, Inc., West Haven, CT 06516. http://enthonedata.cooksonelectronics.com/.

[2] R. E. Collin, Foundations for Microwave Engineering, 2nd ed., p. 188):

[3] E. Maxwell, "Conductivity of Metallic Surfaces at Microwave Frequencies," J. Appl. Phys., Vol. 18, No. 7, pp. 629-638, July 1947. http://dspace.mit.edu/bitstream/handle/1721.1/5025/RLE-TR-021-14257547.pdf?sequence=1.

[4] R. Finger and A. R. Kerr, "Microwave Loss Reduction in Cryogenically Cooled Conductors," Int J Infrared Millimeter Waves, vol. 29, no. 10, pp. 924-932, Oct. 2008. http://springerlink.com/content/k0j72513131h1q11/fulltext.pdf