# Multiple Frequency Surface Resistance Measurement Technique Using a Multimode $TE_{01n}$ Cylindrical Cavity on a TlBaCaCuO Superconducting Film

J. S. Derov, A. J. Drehman, M. J. Suscavage, R. J. Andrews, E. Cohen, N. Ianno, and D. Thompson

*Abstract*— **A multiple frequency surface resistance measurement technique for high-temperature superconductors has been developed using a modified multimode cylindrical cavity made of niobium operating in the superconducting state. The surface resistance vs. frequency relationship of TlBaCaCuO high-temperature superconducting thin films was determined over the frequency range of 50–100 GHz with an extrapolation down to 1 GHz. The $TE_{01n}$ ($n$ = 1, 2, and 3) modes of the cylindrical niobium waveguide cavity had resonances at 52, 71, and 95 Ghz and the measured surface resistances at these frequencies were 5.1, 8.5, and 21.1 milli-ohms, respectively.**

## I. Introduction

FREQUENCY dependent surface resistances of high-temperature superconducting materials provide fundamental information for microwave and millimeter wave circuit design. Our purpose was to develop a technique to measure the surface resistance of high-temperature superconductors in the 50–100 GHz range using a single high-$Q$ $TE_{01n}$ cylindrical cavity for more than one frequency. Stripline resonators are typically used to make frequency dependent surface resistance measurements and work well below 50 Ghz [1], but this becomes more difficult above frequencies at which coaxial connectors are no longer available. $TE_{01n}$ mode cavity measurements have yielded surface resistance results at frequencies greater than 50 GHz, but these were single frequency measurements and required separate cavities for each frequency [2], [3]. In this letter we demonstrate the use of a single $TE_{01n}$ mode cylindrical waveguide reflection cavity to make frequency dependent surface resistance measurements at 52, 71, and 95 GHz. This allowed us to take all three frequency data points during one temperature cycling of the system. A superconducting niobium $TE_{01n}$ mode cavity ($n$) = 1, 2, 3 and with resonances at 52, 71, and 95 GHz was used to determine the frequency dependent surface resistance of a laser deposited Thallium–Barium–Calcium–Copper Oxide (TlBaCaCuO) thin film. This method can be extended to other high-temperature superconductors.

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J. S. Derov, A. J. Drehman, M. J. Suscavage, and R. J. Andrews are with the Rome Laboratory, Electromagnetics and Reliability Directorate, Hanscom AFB, MA 01731–5000.

E. Cohen is with ARCON, Inc., 260 Bearhill Road, Waltham, MA 02154.

N. Ianno is with the Department of Electrical Engineering, University of Nebraska, Lincoln, NE 68508.

D. Thompson is with SEI, Inglewood, CA.

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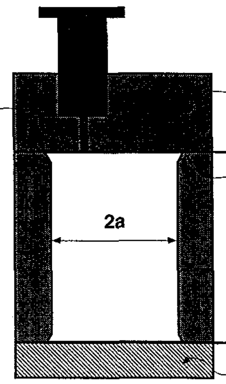


Fig. 1. Cavity cross-section and placement of the superconducting sample duringmeasurement. The cavity was a reflection type cavity and its dimensions where $a$ = 4.213 mm and $d$ = 5.31 mm.

## II. Cavity Modes

A frequency dependent surface resistance measurement can be made using the $TE_{01n}$ modes ($n$ = 1, 2, and 3) in a cylindrical waveguide cavity. The $TE_{01n}$ modes were chosen because of their unique field symmetry where no surface current flows between the cylindrical side walls and the end walls of the cavity [4]. Therefore, by replacing one end wall of the cavity with the superconducting film, no error is introduced in the loss measurement through discontinuities between the end wall and the cylindrical side wall. Since the $TE_{01n}$ mode can be degenerate with the $TM_{11n}$ mode, a chamfer was cut in the side wall of the cavity as shown in Fig 1. The chamfer affects the TM field distribution, while having a negligible effect on the TE field distribution. This removes the degeneracy. Another method for removing the degeneracy has been reported by B. Mayer *et al.* [5]. For this work, the cavity was built from niobium (Nb) because this material is known to have very low loss in the superconducting state. All the existing TE and TM modes of the cavity were determined [6] and a cylindrical cavity mode chart of the $TE_{011}$, $TE_{012}$, and $TE_{013}$ modes and their nearest neighboring modes was constructed. This is shown in Fig. 2. In our design, we chose $(2a/d)^2$ to be 2.4 with $a$ = 4.213 mm and coupling iris of about 1 mm in diameter. As seen from this figure, the neighbors of the $TE_{011}$ and the $TE_{012}$ modes are far apart, but the $TE_{013}$ is only 400 MHz from the unwanted $TE_{222}$ mode. Since we are using a niobium cavity whose quality factor was measured to be $8 \times 10^5$ at 95 GHz with a bandwidth on the

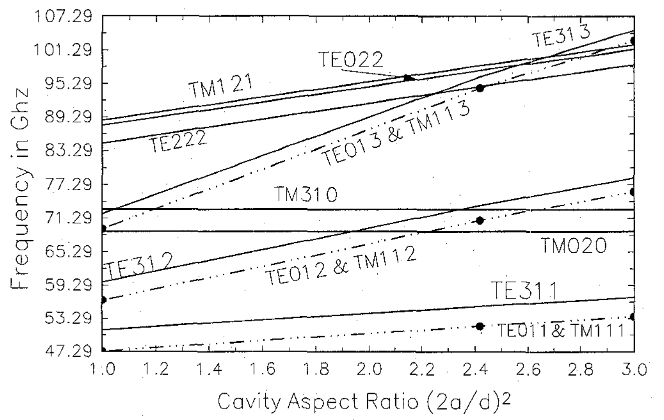


Fig. 2. Mode chart for the cylindrical cavity used to make the surface resistance measurements.

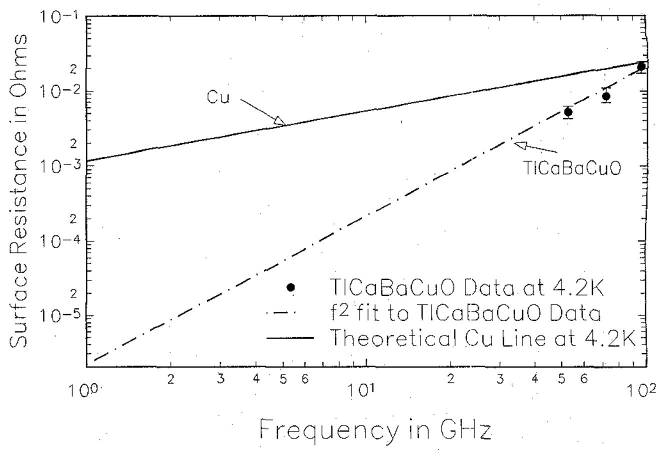


Fig. 3. Surface resistance versus frequency relationship for the measured TlBaCaCuO superconducting film.

order of 120 KHz, the two modes can easily be resolved.

The surface resistance of the high-temperature superconducting end wall in the Nb cavity can be determined from a measurement of the cavity $Q$. The relationship between the $Q$ of the cavity and the absolute value of the surface resistance $R_{Tl}$ for the thallium film is given by [7]

$$R_{T1} = \mu\pi f_o\left(\frac{1}{Q_{Tl}} - \frac{1}{Q_{Nb}}\right)\frac{\int_{\mathrm{vol}} |\boldsymbol{H}|^2 \rho d\rho\, d\phi\, dz}{\int_{\mathrm{end}} |\boldsymbol{H} \times \boldsymbol{z}_o|^2 \rho d\rho\, d\phi} + R_{Nb}, \tag{1}$$

where $\rho, \phi, z$, denote the axes of the cylindrical coordinate system with their respective unit vectors $\rho_o, \phi_o, z_o$. In (1), $f_o$ is the resonant frequency, $H$ is the magnetic field for the (0,1,$n$) mode, $Q_{Tl}$ and $Q_{Nb}$ are the values of $Q$ for the cavity with the thallium film as an end wall and with a Nb film as an end wall respectively, and $R_{Nb}$ is the surface resistance of the niobium.

## III. Measurement and Results

The cavity $Q$ was determined by a standard measurement which is based on measuring the resonant frequency and bandwidth of the cavity at the 3 db points [4], [8]. WR-15 waveguide, which has a cut-off frequency of 39.86 GHz, was used from the cavity to the top of the cryostat and a WR-10 to WR-15 waveguide transition was used between the source and the cryostat to make the 95-GHz measurement. The cavity $Q$ was measured with the thallium film as the end wall and with a niobium film as the end wall. The surface resistance of the thallium film was then calculated from (1). The calculated surface resistance for the thallium film was 5.2, 8.5, and 21.2 milli-ohms at 52, 71, and 95 GHz, respectively. Since we were using a niobium cavity, the measurements were preformed at 4.2 K. These surface resistance values are at least a factor of 15 greater than the minimum resolution of our system. The $Tl_2Ba_2CaCu_2O_x$ film on $LaAlO_3$ substrate had a Tc of 105 K. The film was 8000-Å thick, which is approximately four times the estimated London penetration depth. Therefore, the losses due to the finite thickness of the film where considered to be negligible. The results of the measurement are plotted in Fig. 3. The dashed line in the figure is a least-squares best fit to the data assuming a $f^2$ dependence for the surface resistance. The $f^2$ dependence of the loss is predicted by the two-fluid model for the surface impedance of a superconductor [9]. The curve is extrapolated down to 1 GHz to estimate the superconducting material's performance at lower frequencies. Note that the surface resistance of the superconducting material is approximately equal to that of copper at 100 GHz.

## IV. Conclusion

The surface resistance of a superconducting thallium film was measured using the $TE_{01n}$ ($n$ = 1, 2, and 3) cylindrical cavity technique. To date, this is the simplest most reliable technique for measuring surface resistance of superconductors in the frequency range of 50 to 100 GHz. The agreement between the data and the $f^2$ dependence of the two-fluid model gives further credibility to this technique.

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