Novel Truncated Cone Cavity for Surface Resistance Measurements of High T_c Superconducting Thin Films

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Abstract

A new truncated cone cavity is described which avoids degeneration between the TE_{01n} and TM_{11n} modes occuring in the most often used circular cylindrical cavities for material measurements. Analytical expressions for the field components are given. An error analysis is carried out which yields a sensitivity of 2.3 mΩ for surface resistance measurements at 18 GHz using samples with a diameter of 9 mm. One cavity was built and measurement results are given for the surface resistance of various $YBa_2Cu_3O_x$ thin films on MgO substrates. The samples were manufactured by means of laser ablation and magnetron sputtering.

Introduction

It is desirable to check the quality of high T_c superconducting thin films before devices such as filters and resonators are manufactured. A very popular nondestructive method to do this is to replace a part of the surface of a microwave cavity with the sample and to measure the Q-value. See for example /1-4/.

The commonly used TE_{01n}-mode cylindrical cavity offers the advantage of having no electric fields normal to the surface and of having only circumferential surface currents. To suppress the existing degenerate TM_{11n}-modes, which deteriorate the measurement accuracy empirical methods like circumferential grooves are used as "mode traps". In this paper a new cavity is described avoiding mode-degeneration completely, while preserving the advantages of the TE_{01n} cylindrical cavity. The design follows rigorous analytical expressions.

Theory

The geometry of the cavity is shown in Fig. 1. Using spherical coordinates r, θ, Φ the surface of the cavity is defined by the conditions

$$
\begin{array}{lll}
r = r_1 & 0 < \theta < \theta_0 & 0 \leq \Phi < 2\pi \\
r = r_2 & 0 < \theta < \theta_0 & 0 \leq \Phi < 2\pi \\
\theta = \theta_0 & r_1 < r < r_2 & 0 \leq \Phi < 2\pi \ .
\end{array} \quad (1)
$$

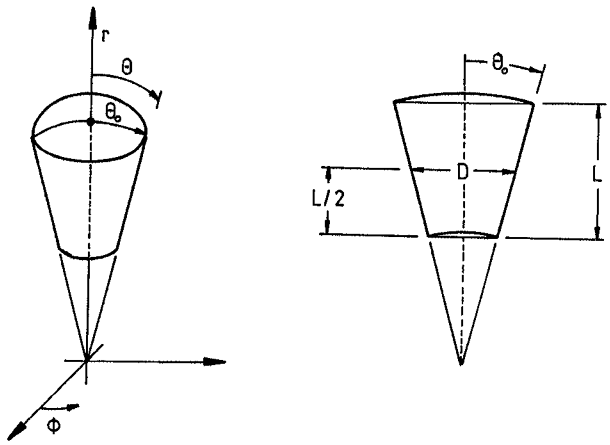

Fig. 1 Geometry of cavity

The boundary value problem to be solved is defined by Maxwells equations

$$
\begin{aligned}
\vec{\nabla} \times \vec{E} &= -j\omega\mu\vec{H} \\
\vec{\nabla} \times \vec{H} &= j\omega\varepsilon\vec{E}
\end{aligned} \quad (2)
$$

and the boundary condition $E_t \equiv 0$ at the cavity surface. A solution is carried out by dividing the field problem into two parts, one transversal electric (TE) and one transversal magnetic (TM) with respect to the r-direction /5/. Calculations lead to the following field components for the TE_{011} mode:

$$E_r \equiv 0$$

$$E_\theta \equiv 0$$

$$E_\Phi = \frac{E_o}{r}\sqrt{\frac{\pi kr}{2}}\left(J_{\nu+1/2}(kr) - \frac{J_{\nu+1/2}(kr_1)}{N_{\nu+1/2}(kr_1)} N_{\nu+1/2}(kr)\right)\frac{d}{d\theta} P_\nu(\cos\theta)$$

$$H_r = \frac{E_o}{j\omega\mu_o}\left\{\frac{d^2}{dr^2}\left[\sqrt{\frac{\pi kr}{2}} J_{\nu+1/2}(kr) - \frac{J_{\nu+1/2}(kr_1)}{N_{\nu+1/2}(kr_1)}\sqrt{\frac{\pi kr}{2}} N_{\nu+1/2}(kr)\right]\right.$$

$$\left. + k^2\left[\sqrt{\frac{\pi kr}{2}} J_{\nu+1/2}(kr) - \frac{J_{\nu+1/2}(kr_1)}{N_{\nu+1/2}(kr_1)}\sqrt{\frac{\pi kr}{2}} N_{\nu+1/2}(kr)\right]\right\} P_\nu(\cos\theta) \quad (3)$$

$$H_\theta = \frac{E_o}{j\omega\mu_o}\left\{\frac{d}{dr}\left[\sqrt{\frac{\pi kr}{2}} J_{\nu+1/2}(kr) - \frac{J_{\nu+1/2}(kr_1)}{N_{\nu+1/2}(kr_1)}\sqrt{\frac{\pi kr}{2}} N_{\nu+1/2}(kr)\right]\right\}\frac{d}{d\theta} P_\nu(\cos\theta)$$

$$H_\Phi \equiv 0$$

Since the Φ-component of the magnetic field vanishes identically, the surface currents are purely circumferential as in the case of a TE_{on} circular cylinder cavity. To compare the results with the commonly used circular cylinder cavity a mode chart (Fig. 2) was calculated. The scales in Fig. 2 are chosen exactly as in the usual mode charts for cylindrical cavities, i.e. the x-axis is scaled by $(D/L)^2$ and the y-axis is scaled by $(Df_o)^2$, where f_o is the resonance frequency. Obviously no degeneration occurs between the TE_{011} working mode and the TM_{111} mode. The ratio of their resonance frequencies (Fig. 3) depends on the angle θ chosen.

Measurement considerations for superconducting thin films

For small sample areas it is necessary to detect very small variations of the cavity quality factor Q. This can be carried out very efficiently by using a transmission type cavity and applying a curve fitting technique, which fits the known theoretical shape of the resonance curve to the measured trace. But most of measured curves are distorted by the degenerated mode and even a small distortion reduces the accuracy considerably. Therefore it is of great importance to avoid mode degeneration completely.

This problem is solved by using the new cavity with a sufficiently large inclination angle θ to guarantee that the two modes do not influence each other. The possible types of cavities are compared based on an error analysis: The unloaded quality factor Q_o is given by

$$Q_o \overset{Def}{=} \frac{C}{R_{Su}\cdot A + R_{Sa}\cdot B} \quad (4)$$

where

$$C = \omega_o \frac{\varepsilon_o}{2}\int_V |E|^2\, dv\ , \quad V = \text{volume of cavity} \quad (5)$$

$$B = \frac{1}{2}\int_{Sa} |H_t|^2\, da\ , \quad Sa = \text{surface of sample,} \quad (6)$$

$$A = \frac{1}{2}\int_{Su} |H_t|^2\, da\ , \quad Su = \text{surface of cavity except sample surface} \quad (7)$$

H_t = tangential H-fields

Carrying out the total derivative and introducing the geometry factor g: = A/B leads to an expression for the dependance between the surface resistance and the measurement accuracy for the Q-factor:

$$\left|\frac{dR_{Sa}}{R_{Sa}}\right| = \left(1 + g\frac{R_{Su}}{R_{Sa}}\right)\left|\frac{dQ_o}{Q_o}\right| \quad (8)$$

As can be seen, the geometry factor g chosen as small as possible minimizes the error. If sample areas are available as large or larger than the bigger topplate, the cavity offers a higher sensitivity when the sample serves as the topplate. In case of a small sample, the better choice is to replace a part of the bottomplate by the sample.

Experiment

A copper cavity with $\theta = 9^\circ$ and $(D/L)^2 \simeq 2$ was manufactured. The resonance frequency of the TE_{011} mode is 18.18 GHz. For ease of fabrication, the topplate and bottomplate were made of planar instead of spherical shape. To assess the influence of this well known perturbation methods could be applied /5/, but the deviation of the resonance frequency and the quality factor is negligible if a small angle θ and a sufficiently high (D/L)-ratio is chosen. A part of the bottom plate was replaced by 10 mm×10 mm superconducting $YBa_2Cu_3O_x$ thin film samples on MgO substrates /6,7/. To avoid currents across the sample boundary a circular aperture of 9 mm diameter was placed above it. Using eq. (8) leads to an error of $\pm$ 2.3 mΩ in the surface resistance assuming a relative accuracy of the Q_0 measurement of $3 \cdot 10^{-3}$. Measured results for the surface resistance versus temperature are shown in Fig. 4 for samples manufactured by magnetron sputtering /6/ and in Fig. 5 for samples manufactured by laser ablation /7/ respectively.

Conclusions

A novel truncated cone cavity is described, avoiding awkward degenerated modes. Analytical expressions for the field components of the TE_{011} mode and a mode chart are given. An error analysis was carried out, leading to a geometry factor which can be used to optimize the geometry of the cavity. Several small samples of $YBa_2Cu_3O_x$ thin films on MgO substrats were measured at a frequency of 18 GHz. The lowest surface resistance value obtained was 4.5 mΩ at 77 K for a film fabricated by laser ablation. The copper reference value was 22 mΩ at this temperature.

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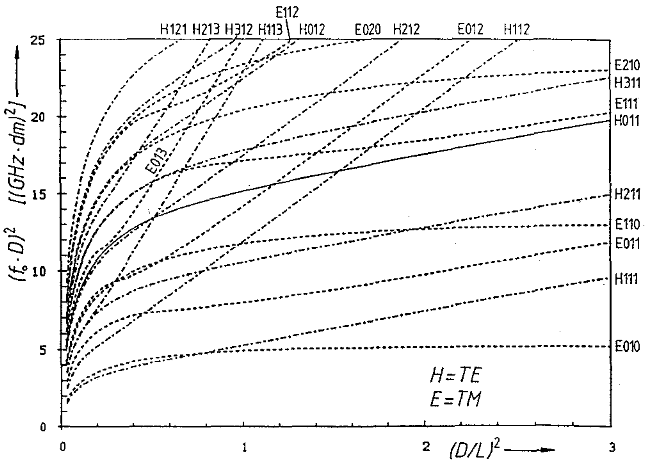

Fig. 2 *Mode chart* θ_0 = 10°.

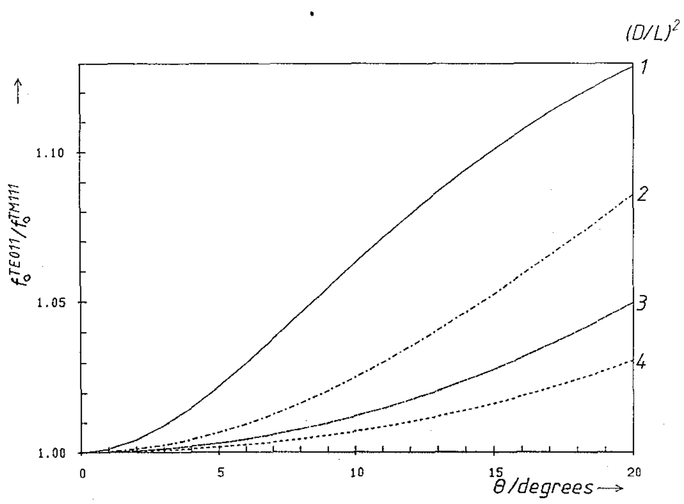

Fig. 3 *Ratio of resonance frequencies,* TE_{011}/TM_{111}.

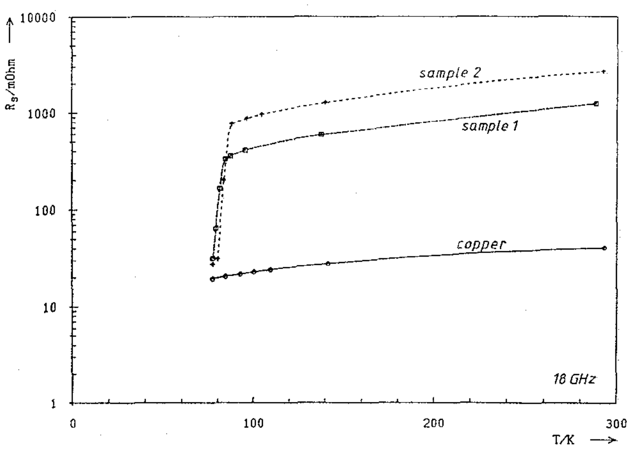

Fig. 4

Measured temperature dependence of $YBa_2Cu_2O_x$ ***on MgO manufactured by means of magnetron sputtering. Film thicknesses unknown.***

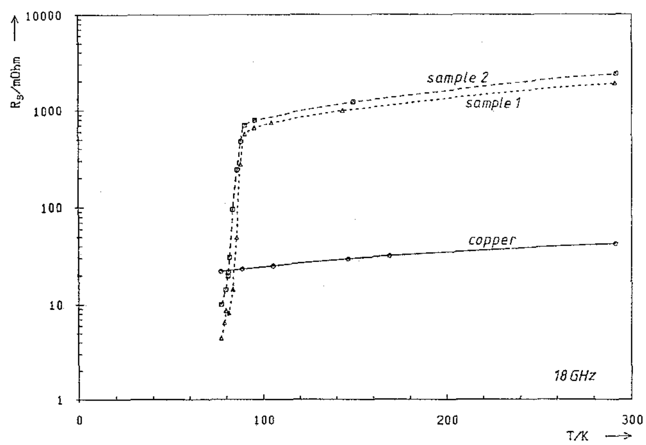

Fig. 5

Measured temperature dependence of $YBa_2Cu_2O_x$ ***on MgO manufactured by means of laser ablation. Film thicknesses approximately 300 nm.***