An Improved Dielectric Resonator Method for Surface Impedance Measurement of High-Tc Superconductors.

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Abstract—**An improved dielectric resonator method is proposed to measure temperature characteristics of surface impedance Z_s of superconductors automatically with high resolution and with good reproducibility. Perturbation formula for this resonator is derived to determine Z_s from measured values of resonant frequency and unloaded Q. Some measured results verify the usefulness of this method. A consideration of the effect of surface roughness enables one to compare measured temperature dependence of the complex conductivity with the BCS and three-fluid models.**

I. Introduction

To design microwave components using high-Tc superconductors, the surface impedance $Z_s = R_s + jX_s$, where R_s is the surface resistance and X_s is the surface reactance, is one of the most important parameters. A TE_{011} mode cavity method[1] and a TE_{011} mode dielectric rod resonator method [2] are known to measure Z_s in microwave region. However there are two experimental difficulties in these methods; one is the poor reproducibility of measured Z_s values and the other is the limit of R_s measurement below 10^{-3} Ω at 10 GHz. The former occurs from uncertain mechanical contacts and the latter occurs from strong influence of the conductor plate loss on unloaded Q.

To overcome these difficulties, this paper proposes an improved method using a dielectric-loaded cavity. A perturbation formula for this resonator is derived. The accuracy of Z_s measurement by this method is compared with those by two methods described above. For some high-Tc superconductors the Z_s values are measured by this method at 10GHz. The effect of the surface roughness on Z_s measurement is discussed. Measured temperature dependence of the complex conductivity is compared with those by the BCS model[3][4] and the three-fluid model[5].

II. Measurement Principle

Figure 1 shows an analytical model of a dielectric-loaded cavity. A cylindrical cavity having diameter d and height h consistes of a cylinder and an upper plate of perfect conductor with $Z_s = 0$ and a lower plate of superconductor with Z_s. A lossless dielectric rod having diameter D, length L, and relative permittivity ε_r is placed in the center of the superconductor plate . For this structure a perturbation formula is given by[6][7]

$$Z_s = R_s + jX_s = \frac{2\pi\mu_0 f_0^2}{\left(-\dfrac{\partial f}{\partial L}\right)}\left(\frac{1}{2Q_c} - j\frac{\Delta f_0}{f_0}\right) \qquad (1)$$

where Q_c is due to the superconductor plate loss , Δf_0 is a frequency difference between the cases of $Z_s \neq 0$ and $Z_s = 0$, and $(-\partial f/\partial L)$ is the change of f_0 for a small change of L, which is calculated for three resonator structures; the cavity, the dielectric resonator, and the dielectric-loaded cavity[6][7].

Firstly, when $\varepsilon_r = 1$, $M = 0$,and $d = D$ in Fig. 1, $(-\partial f/\partial L)$ for the cavity is given by

$$\left(-\frac{\partial f}{\partial L}\right) = \frac{c^2}{4L^3 f_0} \qquad (2)$$

where c is the light velocity.

Secondly, when $d = \infty$ and $M=0$ in Fig. 1, $(-\partial f/\partial L)$ for the dielectric resonator is given by

$$\left(-\frac{\partial f}{\partial L}\right) = \frac{c^2}{4L^3 f_0} \cdot \frac{1 + W_d}{\varepsilon_r + W_d} \qquad (3)$$

Finally, for the dielectric-loaded cavity, $(-\partial f/\partial L)$ is calculated numerically from the following characteristic equation:

$$\det H\,(f_0;\, D, L, M, d, \varepsilon_r) = 0 \qquad (4)$$

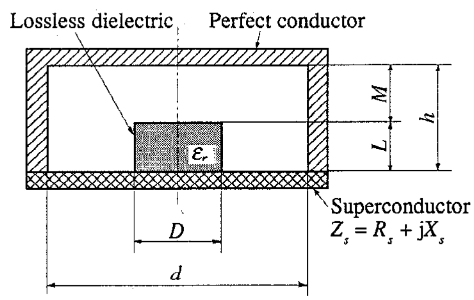

Fig. 1 Analytical model of an $TE_{01(1+\delta)/2}$ mode dielectric-loaded cavity.

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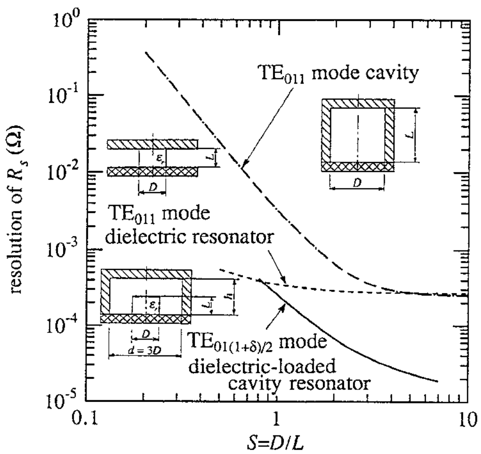
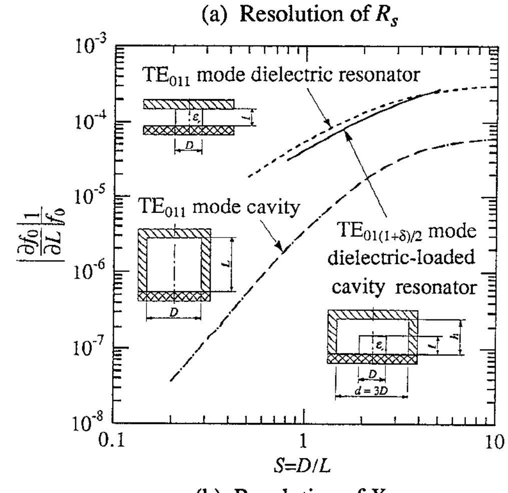
III. Precision Of Z_s Measurement

For the resolutions of Z_s measurement we compare three methods described above. The method of the estimation is given elsewhere [7]. Figure 2 shows the results calculated as a function of the dimensional ratio $S=D/L$ under the following conditions: $\varepsilon_r=24$, loss-tangent of dielectric $tan\delta=4.7\times10^{-6}$, and surface resistance of the conductor cylinder and plate $R_{sm}=7.9$ mΩ at 10GHz. Particularly, for the dielectric-loaded cavity, appropriate values of h for given S values were determined so as to minimize the conductor loss. The higher resolving power of R_s is realized by smaller value of the R_s resolution in Fig. 2(a). As a result, this method can realize the highest R_s resolution in these three methods. On the other hand, the higher resolving power of X_s is realized by greater value of the ratio $(-\partial f/\partial L)/f_0$ in Fig. 2(b). As a result, this method improves the X_s resolution by one order of magnitude, compared with the cavity method and is comparable to the dielectric resonator method.



(a) Resolution of R_s



(b) Resolution of X_s

Fig. 2 Resolution of R_s and X_s calculated for three resonator methods.
($\varepsilon_r=24$, $tan\delta=4.7\times10^{-6}$, $R_{sm}=7.9$mΩ at 10GHz)

IV. Measured Results

A. Experimental Apparatus

Figure 3 shows an experimental apparatus which is set in the cryostat. This structure is constructed from a copper plated brass cylinder having d=18.033 mm and h=7.016 mm, two copper plated brass plates, and a BMT ceramic rod having ε_r=24.5, D=8.007 mm, L=3.328 mm, and the coefficient of thermal linear expansion τ_α=6.3 ppm/K (Murata Mfg. Co. Ltd.). Automatic measurement system of temperature dependence of Z_s was developed using a HP network analyzer and computer.

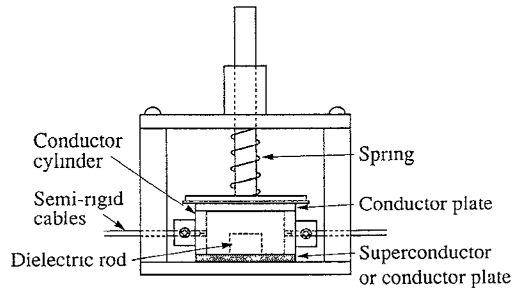
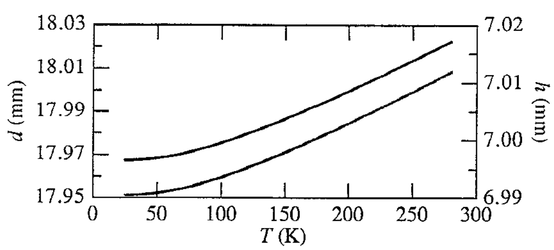


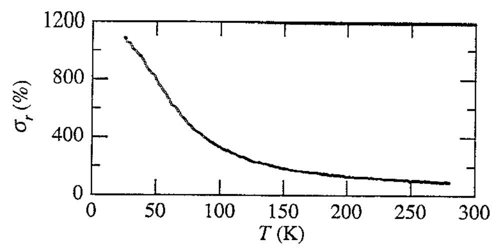
Fig. 3 Experimental apparatus of the dielectric-loaded cavity.

B. Temperature Dependence of Parameters for Cavity and Dielectric Rod

In advance, we measured d, h, and relative conductivity σ_r for the copper plated brass and ε_r and $tan\delta$ for the BMT ceramic rod as a function of temperature T. These results are shown in Figs. 4 and 5. The reproducibility of f_0 for the dielectric-loaded cavity is compared experimentally with one for the dielectric resonator at room temperature. These results are shown in Fig. 6. The reproducibility of measured values for this method is improved over one order, compared with one for the dielectric resonator method.



(a) d and h



(b) σ_r

Fig. 4 Measured results of d, h, and σ_r for cavity.

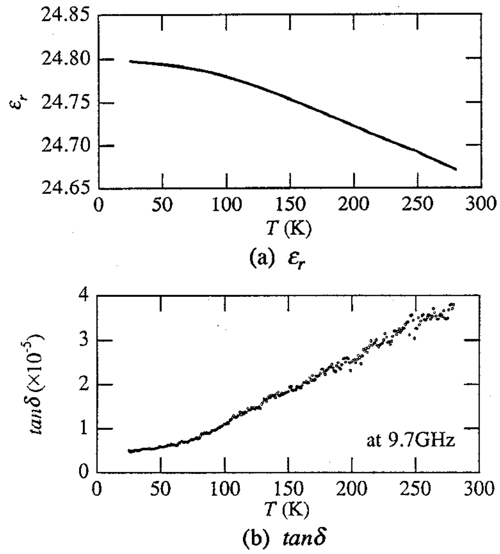


Fig. 5 Measured results of ε_r and $tan\delta$ for dielectric rod.

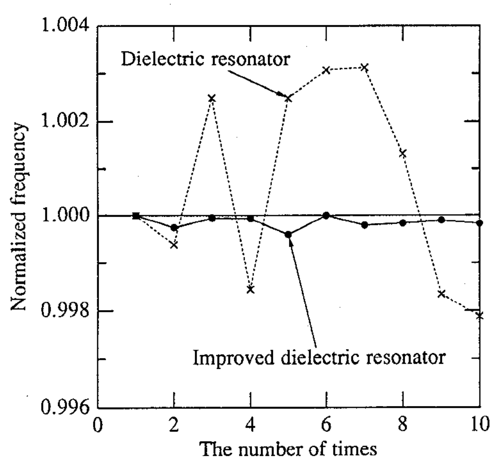


Fig. 6 The f_0 results measured repeatedly by two dielectric resonator methods at room temperature.

C. Temperature Dependence of Z_s for Superconductors

The temperature dependence of Z_s were measured for high-Tc superconductors such as Y-Ba-Cu-O(YBCO) bulk, Bi-Pb-Sr-Ca-Cu-O(BPSCCO) bulk, YBCO film of thickness 0.5 μm on MgO substrate, and Eu-Ba-Cu-O(EBCO) film of thickness 0.5 μm on MgO substrate. The measured results of f_0 and Q_u are shown in Fig. 7. For the film materials, the f_0 and Q_u values could not be measured in the range $T>T_c$ because the resonant curve disappeared. For Fig. 7(a), the results and error bars for copper, YBCO, and BPSCCO plates indicate the averages and the meansquare errors of three,three, and two measurements, respectively. Also for three curves, the measured f_0 values decrease with the increase of the scatter. It is expected from this fact that an air gap between the dielectric rod and the conductor plate occurs from the surface roughness of them. The results of surface roughness calculated from the f_0 scatter are compared with

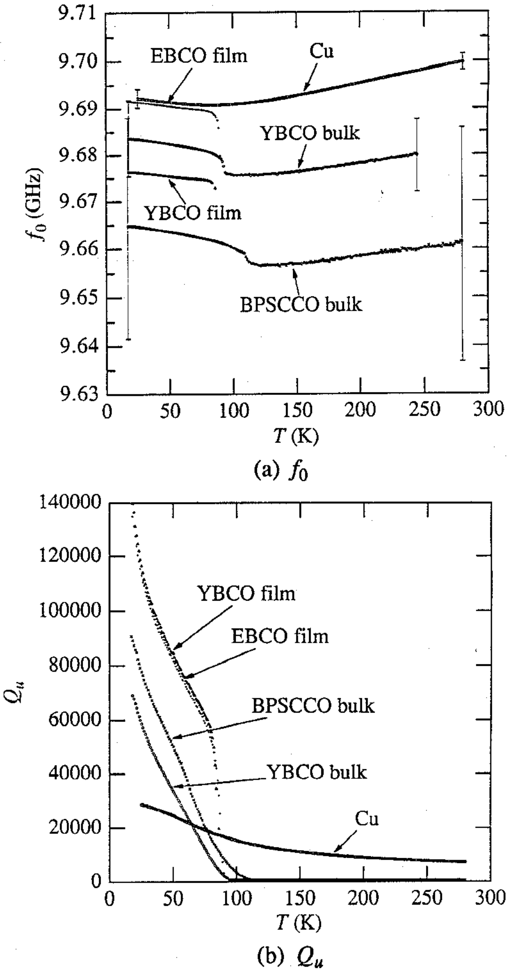


Fig. 7 The f_0 and Q_u results measured for Cu and some high-Tc superconductors as the lower conductor.

Table 1 Measured results of surface roughness for Cu and superconductors.

Lower plate	Surface roughness calculated from f_0 scatter and f_0 scatter	Surface roughness measured mechanicaly*
Cu	1.48 μm (0.00196 GHz)	1.5 μm
YBCO bulk	6.25 μm (0.00822 GHz)	4.6 μm
BPSCCO bulk	17.6 μm (0.02324 GHz)	13 μm

* included surface roughness of 1μm for dielectric

the ones measured mechanically, shown in Table 1. It is found that the scatter in the f_0 measurements is approximately proportional to the surface roughness measured mechanically. On the other hand, the Q_u measurements in Fig. 7(b) have the scatter within 1 % and good reproducibility. The R_s and X_s values were calculated from Fig. 7 using Eq. (1). These results are shown in Fig. 8. For the films, low R_s values below 10^{-3} Ω can be measure at 9.7 GHz, but the X_s values cannot be obtained because there are not the measured results of f_0 and Q_u in the range of

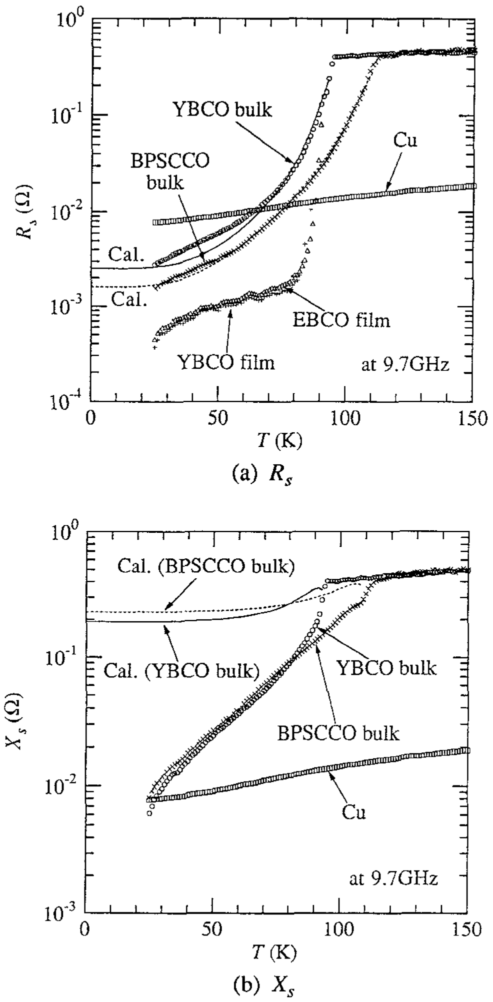


Fig. 8 The R_s and X_s results measured for Cu and some high-Tc superconductors and calculated by using three-fluid model.

$T>T_c$. For the plates,the scatter in the R_s measurements is within 2 %, and the reproducibility of this method is very good, compared with the scatter of 20 % for the dielectric resonator method. On the other hand, the X_s measurements in the range $T<T_c$ have the scatter over one order because of the poor reproducibility in the f_0 measurements. Furthermore, solid and broken curves in Fig. 8 indicate the results calculated by three-fluid model[5][7]. The measured results of R_s agree well with these calculated ones, while the measured results of X_s do not agree with the calculated ones because the surface roughness of about 3μm result in deference between the measured and calculated results. Figure 9 shows calculated results of σ for two plates and experimental ones estimated in consideration of the surface roughness. Furthermore, the experimental results of $\sigma 1$ are compared with ones calculated by BCS and three-fluid models. The experimental results of $\sigma 1$ near Tc show the behavior of BCS model as shown in Fig. 10. As a result, three-fluid model is useful in the range of$T<0.95T_c$.

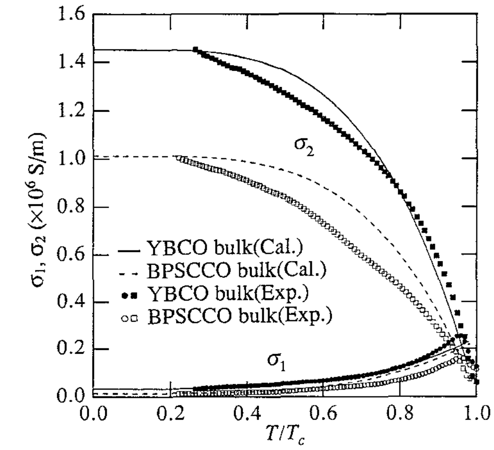


Fig. 9 The σ_1 and σ_2 results measured and calculated by three-fluid model for high-Tc superconductors at 9.7GHz.

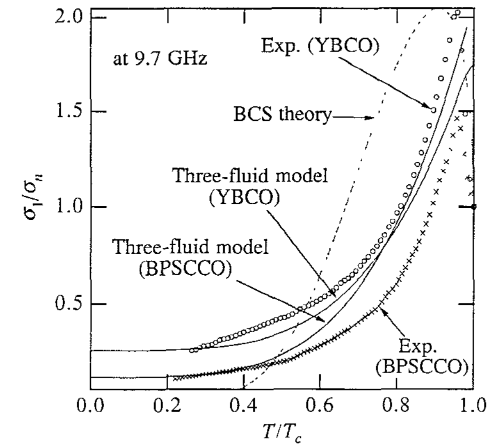


Fig. 10 The σ_1 results measured and calculated by BCS and three-fluid models for high-Tc superconductors.

V. Conclusion

The improved dielectric resonator method proposed is useful to measure temperature characteristics of Z_s automatically with high resolution and good reproducibility. Also, it was verified that surface roughness of materials affects strongly the X_s measurement.

Acknowledgment

The authors would like to thank M. Katoh for fabrication of the resonator and T. Sakakibara for their assistance with the experiment.

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