A TWO-MODE DIELECTRIC ROD RESONATOR METHOD FOR MEASURING SURFACE IMPEDANCE OF HIGH-T_C SUPERCONDUCTORS

Yoshio Kobayashi Hiromichi Yoshikawa

Saitama Univ., Dept. of Electrical and Electronic Engineering
Urawa, Saitama, 338-8570, Japan

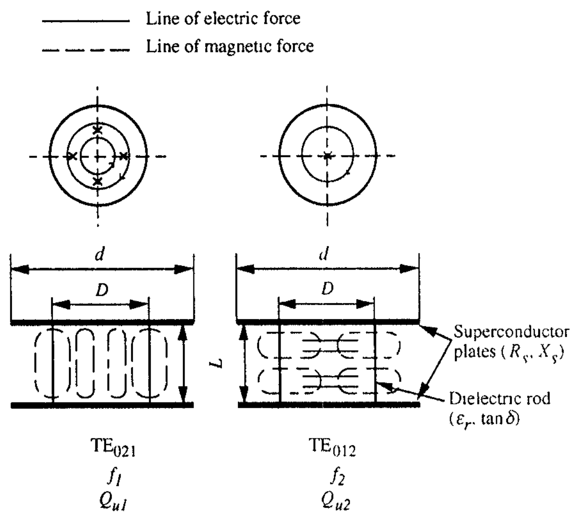
ABSTRACT

A novel technique is proposed to measure the surface impedance Z_s of high-T_c superconductors at microwave frequency by using two resonant modes in a dielectric rod resonator, the TE_{021} and TE_{012} modes. The repeatability of measurement is superior to the conventional method using two dielectric resonators.

INTRODUCTION

Measurement of the surface impedance $Z_s=R_s+jX_s$, where R_s is the surface resistance and X_s is the surface reactance, of high-T_c superconductors at microwave frequency, is essential for the material evaluation and development and for research of superconductor physics. For the R_s measurements, many papers have been presented. For the X_s measurements, however, there are few papers [1]-[3], and the measurement accuracies are not sufficient.

In this paper another method is proposed to measure the temperature dependences of X_s as well as R_s, simultaneously. In this method, which will be called one-resonator method, two resonant modes in a dielectric rod resonator, the TE_{021} and TE_{012} modes are used [4], [5]. It was verified an accurate measurement of R_s can be realized because the measurements for these two modes can be performed simultaneously at a given temperature [5]. A high accuracy can be expected also for the X_s measurements.



(a) Mode 1 (b) Mode 2

$$\varepsilon_{rp} = \left(\frac{c}{\pi D f_p}\right)^2 \left(u_p^2 + v_p^2\right) + 1$$

where $$v_p^2 = \left(\frac{\pi D f_p}{c}\right)^2 \left\{\left(\frac{cp}{2L f_p}\right)^2 - 1\right\} \quad \text{for } p=1 \text{ or } 2$$

$$D = D_0\left[1 + \tau_\alpha (T - T_0)\right] \qquad L = L_0\left[1 + \tau_\alpha (T - T_0)\right]$$

$$\tan\delta_0 = \frac{B_1 f_1^n f_0 \dfrac{A_2}{Q_{u2}} - B_2 f_2^n f_0 \dfrac{A_1}{Q_{u1}}}{B_1 f_1^n f_2 - B_2 f_2^n f_1} \quad \text{at } f_0$$

$$R_{s0} = \frac{f_0^n f_2 \dfrac{A_1}{Q_{u1}} - f_0^n f_1 \dfrac{A_2}{Q_{u2}}}{B_1 f_1^n f_2 - B_2 f_2^n f_1} \quad \text{at } f_0$$

where n=2 for superconductor and n=0.5 for normal conductor.

Fig. 1. Field plots of the TE_{021} and TE_{012} modes in a dielectric rod resonator placed between two parallel conducting plates and formulas to measure the temperature dependences of ε_r, $\tan\delta$ and R_s.

0-7803-4471-5/98/$10.00 (c) 1998 IEEE

MEASUREMENT PRINCIPLE OF X_s

In this method, two resonant modes TE_{021} and TE_{012} are used in a dielectric rod resonator having ε_r, diameter D, and length L, which is placed between two parallel conductor plates having Z_s and diameter d. Field plots of these modes are shown in Fig. 1, together with measurement formulas [5]. The ε_{rp} is obtained from the measured f_p value and the values of $\tan\delta_0$ and R_{s0} at $f=f_0$ are obtained from the measured unloaded Q values Q_{u1} and Q_{u2}.

Using the formula for ε_{rp}, which is derived under the condition $R_s=X_s=0$, we can calculate ε_{r1} from the measured resonant frequency f_1 for the TE_{021} mode (p=1) and similarly ε_{r2} from f_2 for the TE_{012} mode (p=2). The measured values ε_{r1} and ε_{r2} values are different each other due to the different effect of X_s, depending strongly on the modes. An actual relative permittivity ε_{act} can be calculated by taking the effect of X_s to ε_r into account; that is,

$$\varepsilon_{act} = \varepsilon_{r1} + \Delta\varepsilon_{r1} = \varepsilon_{r2} + \Delta\varepsilon_{r2} \tag{1}$$

where $\Delta\varepsilon_{r1}$ and $\Delta\varepsilon_{r2}$ are correction terms due to X_{s1} for the TE_{021} mode and due to X_{s2} for the TE_{012} mode, respectively.

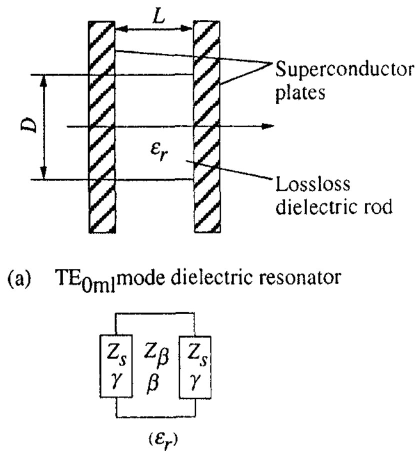
Derivation of $\Delta\varepsilon_r$ as a function of X_s is described below. Fig. 2 shows an analytical model used in this analysis on the assumption of $d=\infty$ and $\tan\delta=0$. From an equivalent circuit of this resonator shown in Fig.2. (b), the resonance condition is given by

$$Z_s + \mathrm{j}\,Z_\beta \tan\beta L = -\frac{Z_s}{Z_\beta}\left(Z_s + \mathrm{j}\,Z_\beta \tan\beta L\right) \tag{2}$$

where

$$Z_\beta = \frac{\omega\mu}{\beta} \qquad Z_s = R_s + \mathrm{j}X_s = \frac{\mathrm{j}\omega\mu}{\gamma} \tag{3}$$

and $\mu=\mu_0=4\pi\times 10^{-7}$ H/m, Z_β and β are the characteristic impedance and phase constant in a dielectric waveguide, and γ is the propagation constant in superconductor. From Eqs. (2) and (3),



(a) TE_{0ml} mode dielectric resonator

(b) Equivalent circuit

Fig. 2. Analytical model.

$\Delta\varepsilon_r$ is derived by the perturbation technique; that is,

$$\Delta\varepsilon_{rp} = -2\left(1 + W_p\right)\left(\frac{\beta_p}{k_p}\right)^2 \frac{2X_{sp}}{\omega_p \mu L} \tag{4}$$

where

$$W_p = \frac{J_1^2(u_p)\left\{K_0(v_p)K_2(v_p) - K_1^2(v_p)\right\}}{K_1^2(v_p)\left\{J_1^2(u_p) - J_0(u_p)K_2(u_p)\right\}} \qquad k_p = \frac{\omega_p}{c} \tag{5}$$

When X_s is assumed to be proportional to f for superconductor, the surface reactance X_{s0} at f_0, which is given arbitrarily near f_1 and f_2, is obtained from the measured values ε_{r1} and ε_{r2} by

$$X_{s0} = \frac{\varepsilon_{r2} - \varepsilon_{r1}}{\left(C_1 - C_2\right)} \tag{6}$$

where

$$C_p = -2\left(1 + W_p\right)\left(\frac{\beta_p}{k_p}\right)^2 \frac{1}{\pi f_0 \mu L} \tag{7}$$

which is derived from substitution of Eq. (4) into Eq. (1).

Furthermore, based on the two-fluid model [1], the complex conductivity σ can be obtained from measured Z_s value by

$$\sigma = \sigma_1 - \mathrm{j}\sigma_2 = \frac{\mathrm{j}\omega\mu_0}{Z_s^2} \tag{8}$$

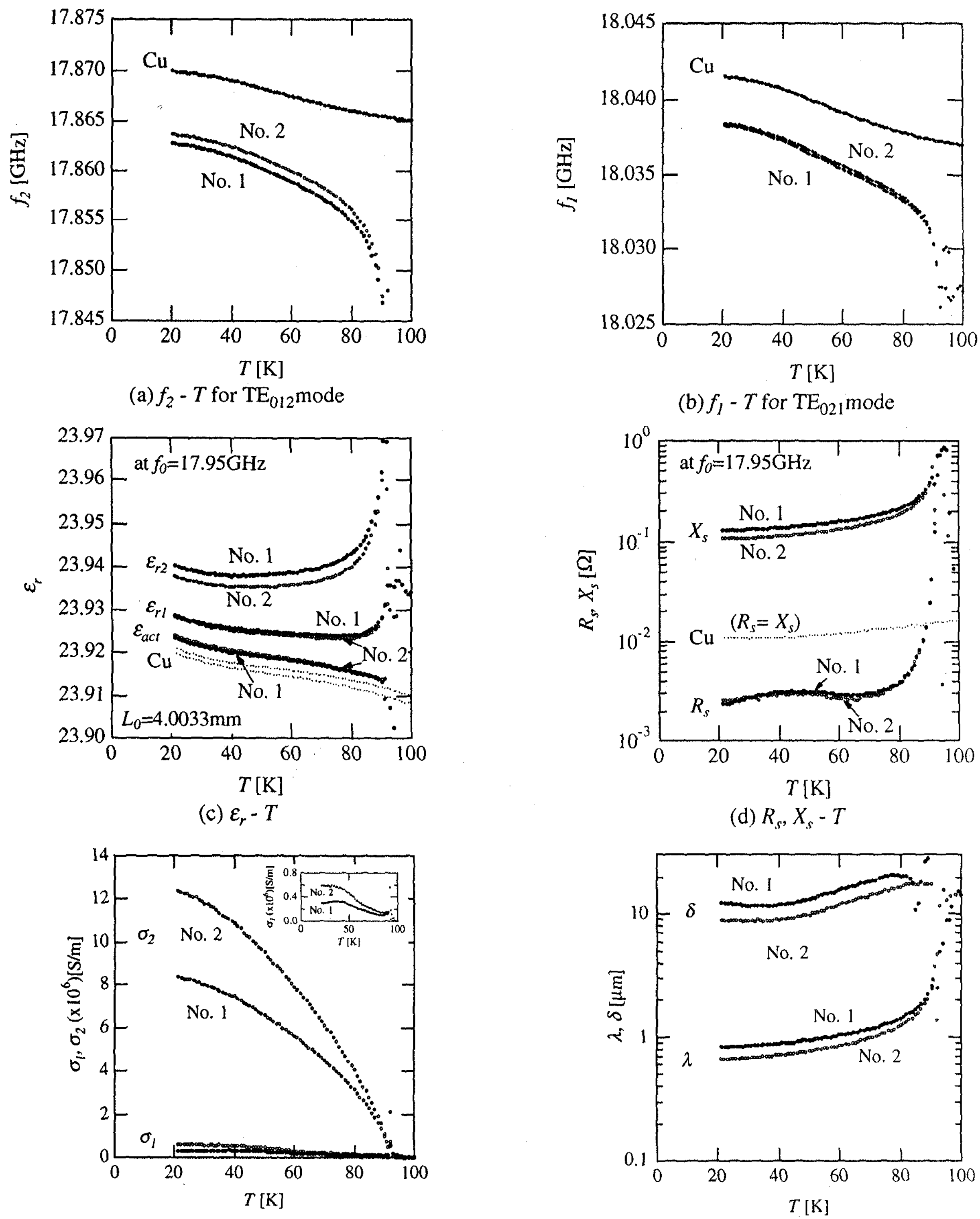


Fig. 3. Measured results for ε_r and $\tan\delta$ of a BMT ceramic rod and Z_s of melt-textured YBCO bulk plates by one-resonator method.

(Nos. 1 and 2 are for the first and second measurements, respectively.)

and the skin depth δ and the penetration length λ are given by

$$\delta = \sqrt{\frac{2}{\omega\mu_0\sigma_1}} \quad (9)$$

$$\lambda = \sqrt{\frac{1}{\omega\mu_0\sigma_2}} \quad (10)$$

MEASURED RESULTS

A program was developed to measure the T dependencies of ε_r, $\tan\delta$ and Z_s automatically. In comparison with superconductor, at first, a BMT ceramic rod (ε_r=24, τ_α=6.3ppm/K, MURATA MFG. CO.) having D=6.994±0.001mm and L=4.003±0.001mm [5] was placed between two copper plates of d=35mm, which is greater than estimated value 28mm required for measurement. The values of f_1, Q_{u1}, f_2 and Q_{u2} were measured as a function of T. The values of ε_r were calculated from these measured values, where L_0=4.0035mm was used in calculation, so that two ε_r values take the same values. Furthermore, the actual length of the rod was decided to be L_0=4.0033mm by taking the skin depths of two copper plates δ≒0.2μm into account. The detail is given in [5].

Then the two copper plates were changed into two melt-textured YBCO bulk plates (IMURA MATERIAL R&D CO.) of d=33mm [5]. Similarly the values of f_1, Q_{u1}, f_2 and Q_{u2} were measured as a function of T. A similar measurement was repeated.

The f_1 and f_2 for the Cu and YBCO plates are shown in Fig. 3 (a), (b) where the Nos. 1 and 2 indicate in the curves are for the first and second measurements, respectively. The ε_r values calculated from these f_1 and f_2 values are shown in Fig. 3 (c). The ε_{act} and X_s values calculated from the ε_{r1} and ε_{r2} values are given in Fig. 3 (c) and (d), respectively. The R_s values in Fig. 3 (d) have already presented in [5]. The σ_1 and σ_2 values calculated using the measured Z_s values are shown in Fig. 3 (e). Furthermore, λ and δ values calculated using σ_1 and σ_2 values are shown in Fig. 3 (f). The reproducibility of these measured results is considerably good.

CONCLUSION

It was verified that the one-resonator method is useful to measure the T dependence of Z_s, because they can be obtained from only one measurement for these two modes. The excellent reproducibility of measurements can be obtained, compared with the conventional two-resonator method.

References

[1] S. Sridhar; " Microwave response of thin-film superconductor," J. Appl. Phys., Vol. 63, No. 1, pp. 159-166, Jan. 1988.

[2] Y. Kobayashi, T. Imai and H. Kayano; " Microwave measurement of current dependence of surface impedance for high-Tc superconductor," IEEE Trans. Microwave Theory Tech., Vol. 39, No.9, pp. 1530-1538, Sept. 1991.

[3] H. Kitano, T Shibauchi, K. Uchinokura, A Maeda, H. Asaoka and H. Takei; "C-axis microwave conductivity of $YBa_2Cu_3O_{7-d}$ in the superconducting state," Phys. Rev. B, Vol. 51, No. 2, pp. 1401-1404, Jan. 1995.

[4] Xu Deming and Li Zhaonian; "A novel method for characterizing the surface resistance of two conducting plates shorted at both ends of a dielectric resonator," 15th European Microwave Conf. Proc. , pp. 912-916, Sept. 1985.

[5] Y. Kobayashi and H. Yoshikawa; "Automatic measurements of surface resistance of superconductors using two modes in a dielectric rod resonator," 27th European Microwave Conf. Proc., pp. 703-708, Sept. 1997.