Design of an image-type dielectric resonator to measure surface resistance of a high-T_c superconductor film.

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***Abstract* — A new measurement method using two resonant modes, the TE_{021} and TE_{012} modes, in an image-type dielectric resonator is proposed to measure the surface resistance R_s of a high-T_c superconductor (HTS) film and the loss tangent tanδ of a sapphire rod separately, precisely and nondestructively.**

A sapphire resonator is set in a cavity constructed from two HTS films and a copper cylinder. This resonator structure is designed from the mode charts calculated on the basis of the rigorous analysis by the mode matching method. It is verified that the mode chart also is effective to identify many resonant modes observed in measurement. The temperature dependence of R_s of a YBCO film was measured at 20GHz by this method. The measured result agrees very well with one by the conventional two-resonator method.

I. Introduction

Dielectric resonator methods have been commonly used to measure the surface resistance R_s of high-T_c superconductor (HTS) films in the microwave range. In the conventional dielectric resonator method, TE_{011} mode sapphire or $LaAlO_3$ resonators have been used to measure the R_s values ignoring the influence of their values of loss tangent tanδ [1]-[5]. In order to measure tanδ and R_s separately, we have proposed a two-dielectric-resonator method, using the TE_{011} and the TE_{013} modes resonators [6][7]. As a result, it was found that the influence of tanδ can not be ignored. Furthermore, the influence of the difference of tanδ between two sapphire rods to the measurement precision has been discussed, since it is known sapphire rods have different tanδ values due to the lattice defects and the off-c-axis [7]. To prevent this influence, we have proposed a one-dielectric-resonator method, using two resonant modes in a dielectric resonator [8]. In the methods described above, however, two HTS films having the same characteristics must be prepared.

On the other hand, a TE_{011} mode image-type dielectric resonator method has been proposed to measure R_s of one HTS film [9]. In this method, the R_s values were measured ignoring the tanδ value in a similar way to the conventional TE_{011} mode sapphire resonator method.

In this paper, a new measurement method using two resonant modes, the TE_{021} and the TE_{012} modes, in an image-type dielectric resonator is proposed to measure R_s and tanδ separately. A sapphire resonator, placed in a cavity constructed from two HTS films and a copper cylinder, is designed from mode charts calculated from the rigorous analysis by the mode matching method [10]. The temperature dependence of R_s of a YBCO film is measured actually at 19.3 GHz to verify the validity of this method.

II. Measurement Principle

A. Designation of resonant modes

Figure 1 shows the structure of an image-type sapphire resonator used in this measurement. A sapphire rod having diameter D and length L is placed on the center of a lower-side HTS film having surface resistance R_{sl}, and is shielded by a copper cylinder with diameter d, height h and surface resistance R_{sy} and an upper-side HTS film with surface resistance R_{su}. The relative permittivity of the sapphire is defined as ε_z for the c-axial direction which is parallel to the z-axis and ε_r (and the loss tangent tanδ) in the plane perpendicular to the z-axis, because of the uniaxial-anisotropic characteristic of sapphire.

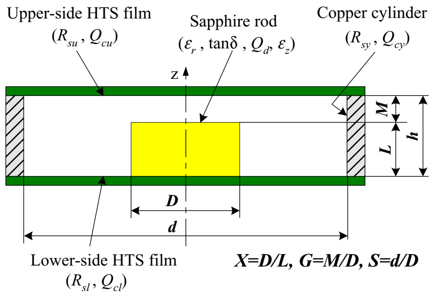


Fig. 1 The structure of an image-type sapphire resonator.

To eliminate an air-gap effect between a lower-side HTS film and a sapphire rod, we use the circularly-symmetric TE_0 mode. Figure 2 shows the fields plots of two resonant modes used in this method. The fields distribute mainly to the radial direction for the $TE_{02(1+\delta)/2}$ mode and to the axial direction for the $TE_{01(3+\delta)/2}$ mode. These modes are designated as halves of the $TE_{021+\delta}$ and the $TE_{013+\delta}$ modes, denoted for a dielectric rod resonator

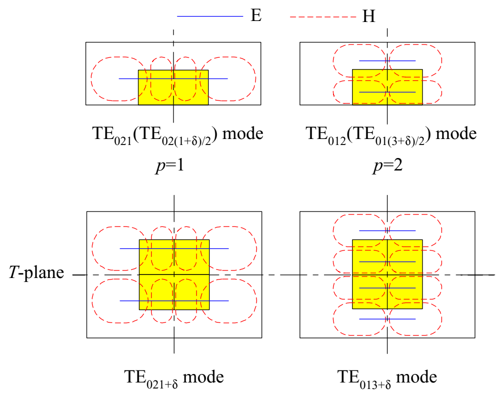


Fig. 2 Fields plots of the TE_{021} and TE_{012} modes.

placed in the center of a circular cavity. For simplicity, the $TE_{02(1+\delta)/2}$ and $TE_{01(3+\delta)/2}$ modes will be called the TE_{021} and TE_{012} modes hereafter.

B. Analysis of an image-type sapphire resonator

The resonant frequencies of TE, TM, and hybrid (HEM) modes for this resonator have been already analyzed by the mode matching method. The equation is given by

$$\det H\left(\varepsilon_r; f_0, \varepsilon_z, D, L, M, d\right) \tag{1}$$

where the matrix elements are given elsewhere [10].

The Q-factors for TE mode can be computed accurately by the perturbation method [11]. The unloaded quality factor Q_u is determined from

$$\frac{1}{Q_u} = \frac{1}{Q_{cl}} + \frac{1}{Q_{cu}} + \frac{1}{Q_{cy}} + \frac{1}{Q_d} \tag{2}$$

where Q_{cl} and Q_{cu} are due to the losses of the lower-side and upper-side HTS films, Q_{cy} is due to the loss of the copper cylinder and Q_d is due to the tanδ, respectively. They are given by

$$Q_{cl} = \frac{1}{AR_{sl}},\ Q_{cu} = \frac{1}{BR_{su}},\ Q_{cy} = \frac{1}{CR_{sy}},\ Q_d = \frac{1}{D\tan\delta} \tag{3}$$

and A, B, C, D are given by

$$A = \frac{\left(-\frac{\partial f}{\partial L}\right)}{\pi\mu f_0^{\,2}},\ B = \frac{\left(-\frac{\partial f}{\partial M}\right)}{\pi\mu f_0^{\,2}},\ C = \frac{2\left(-\frac{\partial f}{\partial d}\right)}{\pi\mu f_0^{\,2}},\ D = \frac{2\varepsilon_r\left(-\frac{\partial f}{\partial \varepsilon_r}\right)}{f_0} \tag{4}$$

These partial differentials are calculated as $\partial f/\partial x \fallingdotseq \Delta f/\Delta x$ from equation (1).

C. Measurement method of ε_r, tanδ and R_{sl}

The values of ε_r can be determined independently from the measured resonant frequencies f_1 for the TE_{021} mode and f_2 for the TE_{012}mode by using eq. (1).

We will derive the measurement formulas for tanδ and R_s below. At first, the substitution of eq. (3) into eq. (2) yields

$$A_p R_{slp} = \frac{1}{Q_{up}} - B_p R_{\sup} - C_p R_{syp} - D_p \tan\delta_p \tag{5}$$

where p=1 for the TE_{021} mode and p=2 for TE_{012} mode.

Then, on the basis of the measured results for sapphire, copper and YBCO, the frequency dependence of tanδ, R_{su}, R_{sl} and R_{sy} are assumed to be

$$\frac{\tan\delta}{f} = \frac{\tan\delta_p}{f_p} \tag{6}$$

$$R_{slp} = \left(\frac{f_p}{f}\right)^k R_{sl},\ R_{\sup} = \left(\frac{f_p}{f}\right)^k R_{su},\ R_{syp} = \left(\frac{f_p}{f}\right)^k R_{sy} \tag{7}$$

for any frequency f near f_1 and f_2, where k=0.5 for the normal conductor or k=2 for the superconductor. The substitution of eqs. (6) and (7) into eq. (5) yields

$$\tan\delta = \frac{1}{A_2^{'}D_1^{'} - A_1^{'}D_2^{'}} \times\left\{\left(\frac{A_2^{'}}{Q_{u1}} - \frac{A_1^{'}}{Q_{u2}}\right) - \left(A_2^{'}B_1^{'} - A_1^{'}B_2^{'}\right)R_{su} - \left(A_2^{'}C_1^{'} - A_1^{'}C_2^{'}\right)R_{sy}\right\} \tag{8}$$

$$R_{sl} = \frac{1}{A_2^{'}D_1^{'} - A_1^{'}D_2^{'}} \times\left\{\left(\frac{D_1^{'}}{Q_{u2}} - \frac{D_2^{'}}{Q_{u1}}\right) - \left(B_2^{'}D_1^{'} - B_1^{'}D_2^{'}\right)R_{su} - \left(C_2^{'}D_1^{'} - C_1^{'}D_2^{'}\right)R_{sy}\right\} \tag{9}$$

where

$$A_p^{'} = A_p\left(\frac{f_p}{f}\right)^k,\ B_p^{'} = B_p\left(\frac{f_p}{f}\right)^k,\ C_p^{'} = C_p\left(\frac{f_p}{f}\right)^k,\ D_p^{'} = D_p\frac{f_p}{f} \tag{10}$$

As a result, tanδ and R_{sl} at $f = (f_1+f_2)/2$ can be obtained from the measured values of Q_{u1} and Q_{u2} by using eqs. (8) and (9), if values of R_{su} and R_{sy} are known.

III. Design of Resonator

Designing the resonator at 19 GHz, we consider that a sapphire rod has ε_r=9.3, tanδ=1x10^{-7} and ε_z=11.3 and two YBCO films have R_{sl}=R_{su}=0.3 mΩ and a copper cylinder has the relative conductivity σ_r=950 % at 20 K, which were measured by two-resonator method [12].

Furthermore, R_{sy} is given by

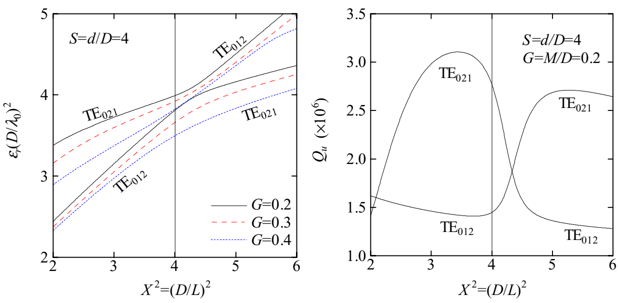
$$R_{sy} = \sqrt{\frac{\pi\mu_0 f_0}{\sigma_0\sigma_{ry}}} \tag{11}$$

where the conductivity of the international standard copper is σ_0=58x10^6 S/m and the permeability in vacuum is μ_0=4πx10^{-7} H/m.

We will determine dimension ratios of this resonator, $X=D/L$, $G=M/D$ and $S=d/D$, taking account of the following issues:

1) Q_{cu} and Q_{cy} are greater than Q_{cl} and Q_d to decrease the influence of the cylinder and the upper-side HTS film.
2) f_1 is close to f_2 and they must be isolated from the other modes.

Figure 3 shows a mode chart and Q_u values calculated for the TE_{021} and TE_{012} modes at S=4, where the effect of R_{sy} is sufficiently small. The mode coupling between the TE_{021} and the TE_{012} modes occurs at X^2=4.3 as shown in Fig. 3 (a) and Q_u values of two modes are the same, as shown in Fig. 3 (b): thus, tanδ and R_{sl} can not be measured in this case. The greater value of G is better for the R_{sl} measurement, but makes f_1 and f_2 too separate : thus, G=0.2 was determined at first. Then, to obtain sufficiently great difference of Q_u values between two modes, X^2=4 was chosen. Finally, to separate optimally two modes from the other modes , the values of G and S were adjusted finely : thus, G=0.25 and S=4.6 were determined.



(a) X - f (b) X – Q

Fig. 3 Determine the X value for ε_r=9.3.

A mode chart including all modes around the TE_{021} and TE_{012} modes was calculated for G=0.25 and S=4.6. The result is shown in Fig. 4. For the TM_{nm} and HEM_{nm} modes, n value is the number of the amplitude variation of the fields to the circumferential direction and m value is numbered from the lowest resonant frequency for m=1 toward higher frequencies.

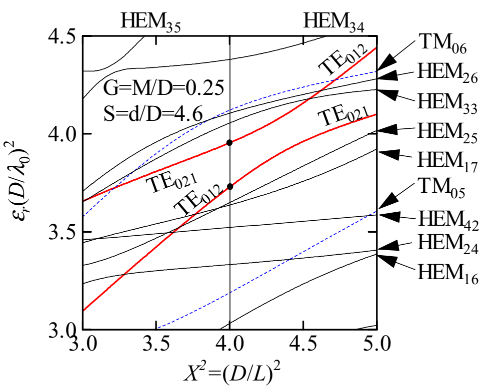


Fig. 4 The mode chart for the image-type sapphire resonator for ε_r=9.3 and ε_z=11.3.

IV. Experiments

To measure R_{sl} at 19GHz by this resonator, D=10 mm, L=5 mm, d=46 mm and h=7.5 mm were determined from the dimension ratios, $X=D/L$=2, $G=M/D$=0.25 and $S=d/D$=4.6, determined above. As shown in Fig. 1, a sapphire rod (τ_α=5.3 ppm/K, Union Carbide Co.) having D=10.000±0.001 mm and L=4.998±0.001 mm is placed on the center of the lower-side YBCO film on a MgO substrate (ϕ=51 mm, t=0.5 mm, THEVA Co.) and shielded by a copper cylinder having d=46 mm and h=7.5 mm and another upper-side YBCO film.

The resonant frequency peaks measured at 20K by using this resonator are shown in Fig. 5, together with ones calculated from the mode chart shown in Fig. 4.

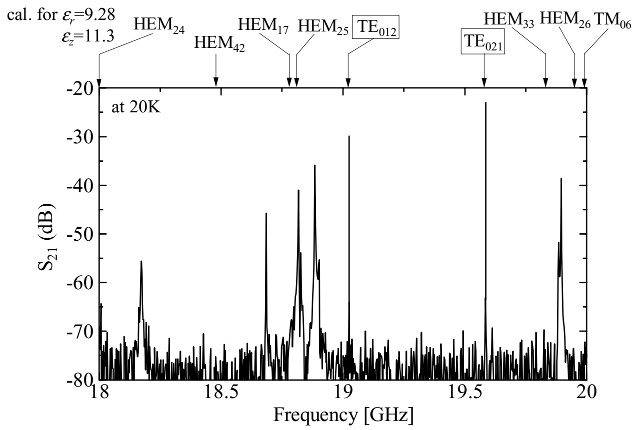


Fig. 5 The frequency response measured with the sapphire rod and the YBCO film at 20K and calculated frequencies from the mode chart.

The measured resonant frequency peaks for the TE_{021} and the TE_{012} modes agreed well with the calculated ones and no other peaks appeared between two modes, as expected from Fig. 4.

Finally, the temperature dependences of f_0 and Q_u of this resonator were measured. The results are shown in Figs. 6 (a) to (c). Figure 6 (d) shows the ε_r values calculated using Fig. 6 (a) and (b). Figures 6 (e) and (f) shows the tanδ and R_{sl} values calculated using Fig. 6 (a) to (c), respectively. For comparison to this, the R_s values measured by two-resonator method [7] is indicated in Fig. 6 (f). These values agree within 10 percents: Thus the validity of this method was verified.

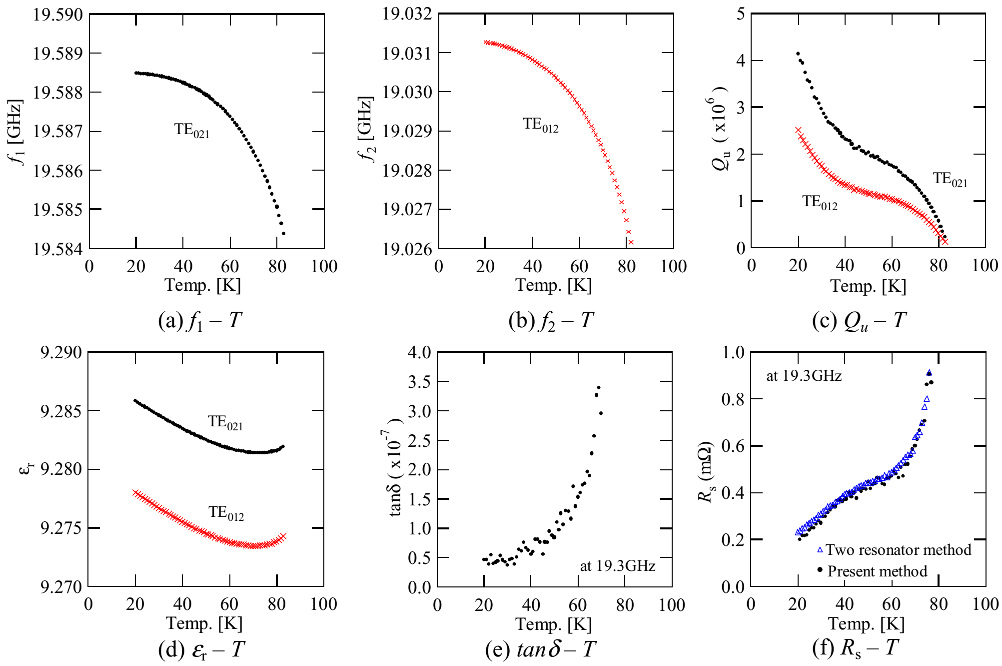


Fig. 6 Measured results of temperature dependence for YBCO film and sapphire rod.

V. Conclusions

A sapphire resonator was designed from the mode charts calculated on the basis of the rigorous analysis by the mode matching method. The image-type dielectric resonator method proposed in this paper is useful to evaluate R_s values of one HTS film with no damage.

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