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Two-Sapphire-Rod-Resonator Method to Measure the Surface Resistance of High-T_c Superconductor Films

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SUMMARY Precise designs are presented for sapphire rod resonators of three types, which have been proposed by the IEC/TC90/WG8 in the standard measurement method of the surface resistance R_s of high-T_c superconductor (HTS) films; an open-type, a cavity-type and a closed-type. In order to separate TE_{011} and TE_{013} modes, which are used in R_s measurements, from the other modes, appropriate dimensions for these three resonators are determined from mode charts calculated from a rigorous analysis based on the mode matching method, taking account of an uniaxial-anisotropic characteristic of sapphire. Comparison of the open-type resonator with the closed-type is performed. For the open-type, the unloaded Q values of both the TE_{011} and TE_{013} modes are reduced by radiations of a leaky state TM_{310} mode. Finally, validity of the design and a two-sapphire-rod-resonator method will be verified by experiments.

key words: *two-sapphire-rod-resonator method, surface resistance, high-T_c superconductor, open-type, cavity-type, closed-type, mode chart*

1. Introduction

Dielectric resonator methods have been used to measure the surface resistance R_s of high-T_c superconductor (HTS) films in the microwave range. A resonator used in these methods is constructed by placing a dielectric rod between two parallel HTS films having the same R_s, where a circularly-symmetric TE_0 mode is used to eliminate an air-gap effect. In the early stage of the R_s measurement, the loss tangent $\tan\delta$ of the dielectric rod has been ignored by using a low loss material such as a sapphire or a $LaAlO_3$, which is called a Hakki-Coleman method [1]–[6].

A two-dielectric-resonator method has been proposed to measure $\tan\delta$ and R_s separately by using two ceramic rods with the same diameter D, where a short length L_1 is for a TE_{011} mode resonator and a long length L_3=3L_1 is for a TE_{013} [7]. When HTS films have low R_s values such as 0.1 mΩ at 10 GHz, however, R_s cannot be evaluated accurately because of the large value of the $\tan\delta$. In order to eliminate the problem, a two-sapphire-rod-resonator method has been proposed [8], [9]. Recently, this method has been adopted as the international standard measurement method of R_s of HTS films at microwave frequencies by the IEC/TC90/WG8 [10]. In this standard method, resonator structures of three types have been proposed, which are called an open-type, a cavity-type and a closed-type. However, the theoretical discussions have not been performed sufficiently for precise designs of the structures.

On the other hand, it has been presented [2] that special attentions must be paid to the design of resonators, because high values of unloaded quality factor Q_u of TE_0 mode are reduced by parasitic couplings of the other modes. Thus, in order to separate the TE_{011} mode from the other modes, appropriate dimensions for the TE_{011} sapphire resonators of three types have been determined [11], taking account of an uniaxial-anisotropic characteristic of sapphire [12].

In this paper, designs for both the TE_{011} and TE_{013} sapphire rod resonators of three types are performed. Then, discussions for radiations occurring from both the TE_{011} and TE_{013} open-type resonators are described. Finally, the validity of the design and a two-sapphire-rod-resonator-method will be verified by experiments.

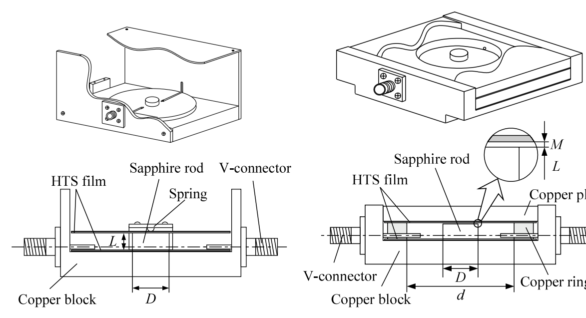
2. Design of Sapphire Rod Resonators

2.1 Resonator Structures of Three Types

A structure of the open-type resonator is shown in Fig. 1(a) [7]–[10]. A sapphire rod having diameter D and length L is placed in the center of a lower-side HTS film having R_s and pressed by a metal plate spring on an upper-side HTS film having the same R_s value. The relative permittivity of the sapphire rod with an uniaxial-anisotropic characteristic is defined as ε_z in the c-axial direction lying along the z-axis and ε_r in the plane perpendicular to the z-axis [12].

A structure of the cavity-type resonator is constructed by housing the open-type resonator in a copper circular cavity having diameter d [2], [6].

A structure of the closed-type resonator is shown in Fig. 1(b) [3]–[5]. The sapphire rod is placed in the center of the lower-side HTS film and is shielded by the upper-side film and an oxygen-free copper (Cu) ring having the surface



(a) Open-type resonator. (b) Closed-type resonator.

Fig. 1 Sapphire rod resonator structures of two types.

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resistance R_{sy}, diameter d and height $h = L + M$, where M is an air gap distance between the upper-side film and the rod.

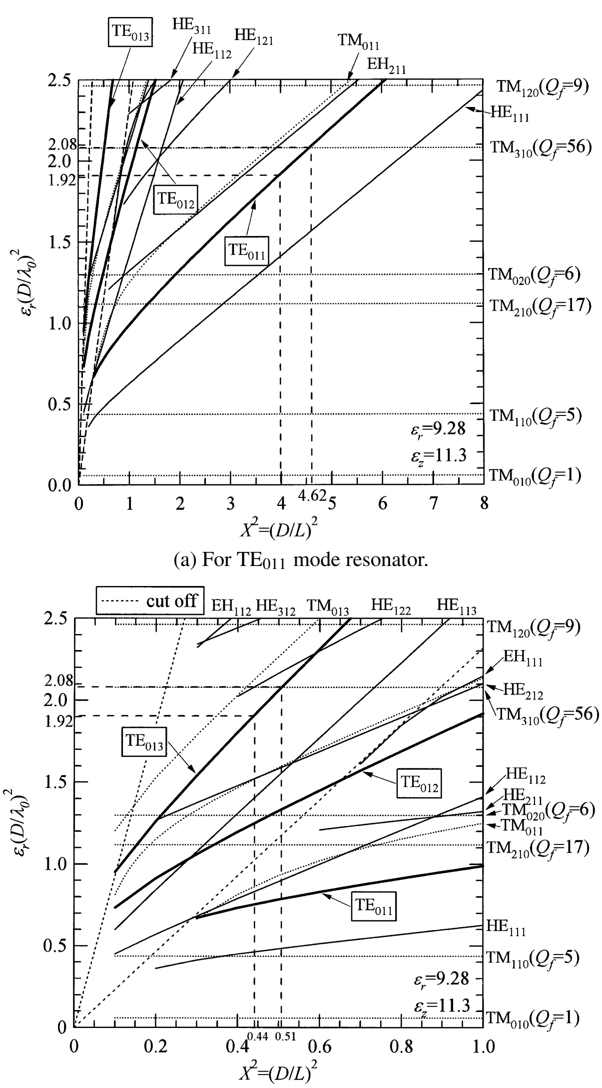
2.2 Design of the Open-Type Resonator

Mode charts of the open-type sapphire rod resonators for TE_{011} and TE_{013} modes calculated using the mode matching method in consideration of the uniaxial-anisotropic property are shown in Figs. 2(a) and (b), respectively [12], where the radius of the HTS films is assumed to be infinitely large. In these charts, all the modes including the trapped state modes TE_{0mp}, TM_{0mp}, HE_{nmp} and EH_{nmp} and the leaky state modes TM_{nm0} are indicated, where subscripts of n, m, p are the numbers of the amplitude variation of the electromagnetic (EM) fields in the circumferential, radial and z-axis directions and Q_f is a quality factor of a damped free oscillation for the TM_{nm0} modes [13].

We have recommended a dimension ratio $X^2 = (D/L)^2 = 4.62$, that is, $D = 2.15L$, to realize the minimum area of HTS films at 12 GHz [8]. However, this value is moderate for non-anisotropic materials. Then, we performed the recalculation considering the uniaxial-anisotropic property of sapphire. As shown in Fig. 2(a), it is seen that an unwanted TM_{310} mode is near the TE_{011} mode at $X^2 = 4.62$. As a result, the ranges of X^2 to separate the TE_{011} mode from the others are $X^2 = 2.2\sim4.2$ and $4.8\sim5.7$ and that of TE_{013} mode are $X^2 = 0.24\sim0.46$, respectively. Hereafter, the cavity-type and closed-type resonators will be designed by using the sapphire rod having $X^2 = 4$ for the TE_{011} mode and 0.44 for the TE_{013} mode, which we recommend in this paper, and X^2=4.62 and 0.51, which are IEC standard, respectively.

2.3 Design of the Cavity-Type Resonator

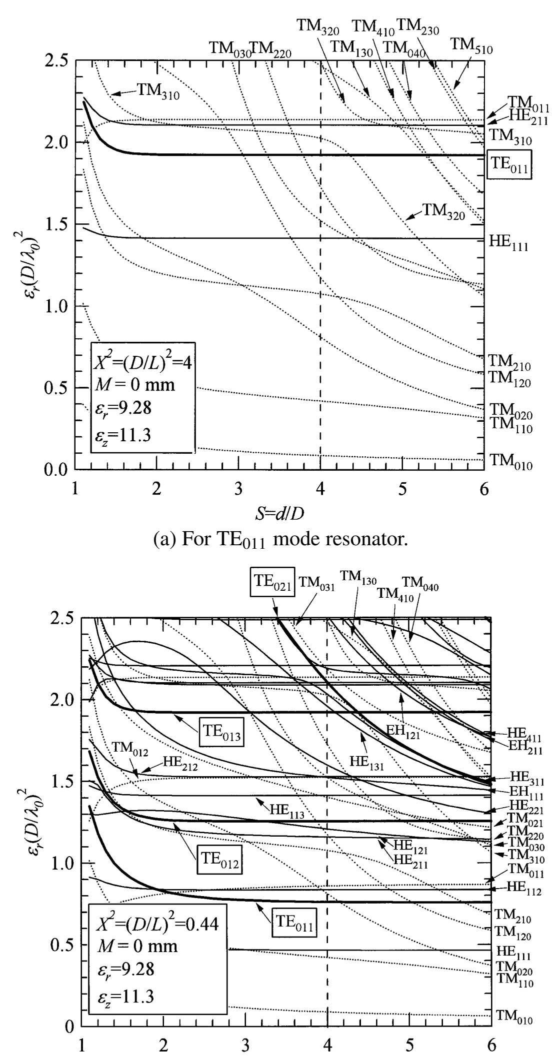
Mode charts of the cavity-type sapphire rod resonators for $X^2 = 4$ and 0.44 are shown in Figs. 3(a) and (b), respectively. In the figures, it is seen that frequencies of the TM_{nm0} modes depend strongly on $S = d/D$. The bigger the S value is, the



(a) For TE_{011} mode resonator.

(b) For TE_{013} mode resonator.

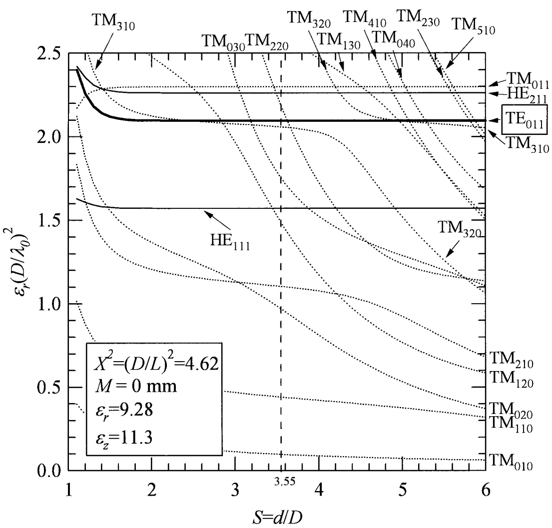
Fig. 2 Mode charts of the open-type resonator.



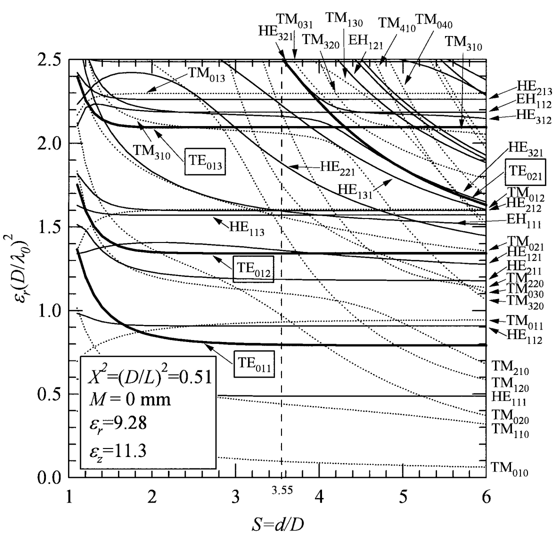
(a) For TE_{011} mode resonator.

(b) For TE_{013} mode resonator.

Fig. 3 Mode charts of the cavity-type resonator for X^2 =4.



(a) For TE_{011} mode resonator.



(b) For TE_{013} mode resonator.

Fig. 4 Mode charts of the cavity-type resonator for X^2=4.62.

lower higher-order-modes are. It is necessary that the moderate value of S must be selected to prevent the unwanted coupling with the other modes. In addition, it is noted that a mode coupling between TM_{310} and TM_{320} modes occurs near $S = 4.5$; for example the TM_{310} mode for $S < 4.5$ transfers to the TM_{320} mode for $S > 4.5$. As a result, the ranges of S to separate the TE_{011} and TE_{013} modes simultaneously from the others are S = 1.8~2.8, 3.8~4.1, and 4.8~5.2.

Similarly, mode charts for the X^2 = 4.62 and 0.51 resonators are shown in Figs. 4(a) and (b), respectively. The ranges of S to separate the TE_{011} and TE_{013} modes simultaneously from the others are S = 1.5~2.2 and 3.4~3.6.

In addition, the Q-factors for the TE_{0mp} mode of the cavity-type resonator can be calculated rigorously [14]. The Q_u value is given by

$$\frac{1}{Q_u} = \frac{1}{Q_c} + \frac{1}{Q_{cy}} + \frac{1}{Q_d} \quad (1)$$

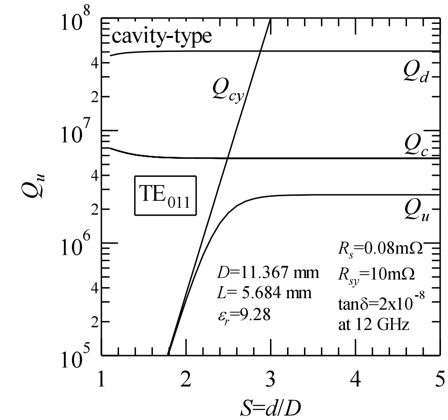
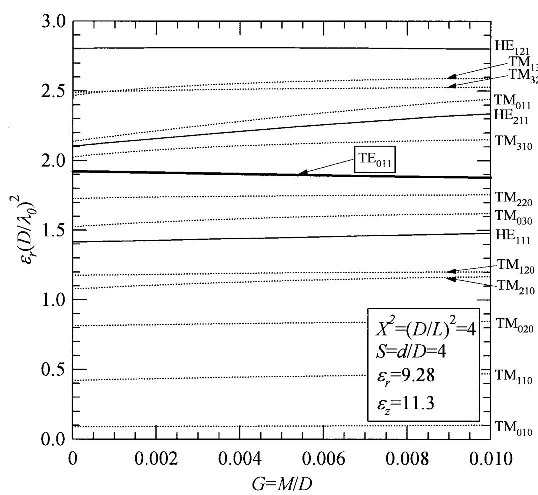
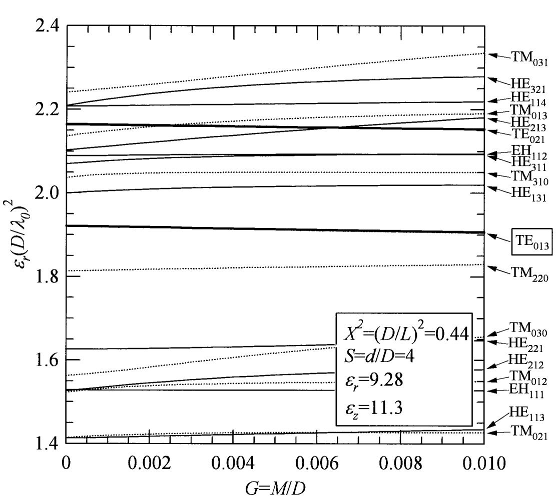


Fig. 5 Calculated results of Q values for the TE_{011} mode cavity-type resonator.



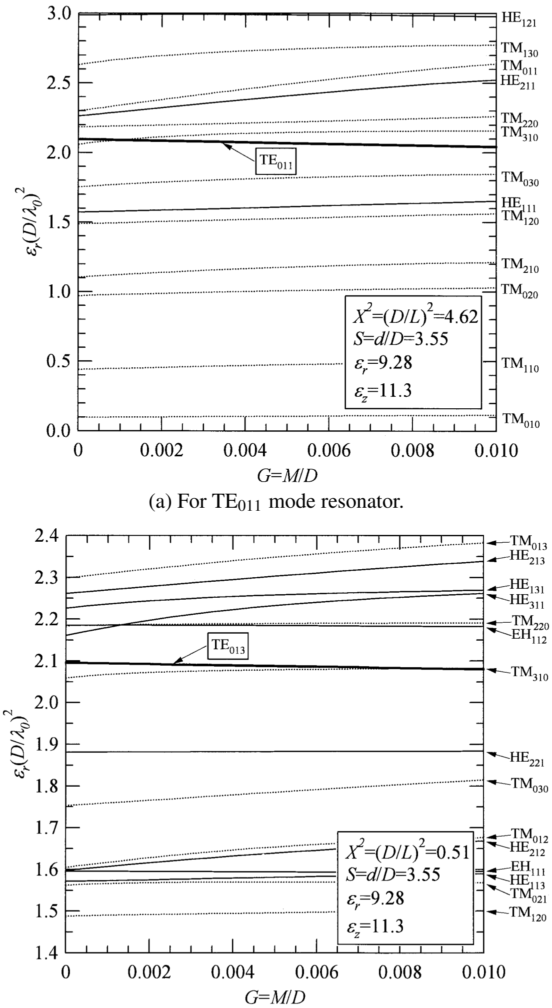
(a) For TE_{011} mode resonator.



(b) For TE_{013} mode resonator.

Fig. 6 Mode charts of the closed-type resonator for X^2=4.

where Q_c is due to R_s of two HTS films, Q_{cy} is due to R_{sy} of a Cu ring and Q_d is due to $\tan\delta$ of a rod, respectively. Figure 5 shows the calculated results of Q values for the TE_{011} mode cavity-type resonator with X^2 = 4, where it is



(a) For TE_{011} mode resonator.

(b) For TE_{013} mode resonator.

Fig. 7 Mode charts of the closed-type resonator for X^2=4.62.

assumed that a sapphire rod has ε_r= 9.28, D = 11.367 mm, L_1 = 5.684 mm, $\tan\delta = 2 \times 10^{-8}$ and two HTS films have R_s = 0.08 mΩ and a Cu ring has d=45.468 mm and R_{sy} = 10 mΩ, which were measured at 12 GHz and 20 K. From this figure, the loss of the Cu ring can be ignored if the S value is larger than 3. However, when $S < 2.5$, the loss of the Cu ring should be considered to obtain the accurate value of R_s. Thus, we chose the appropriate S values to be S= 4 for the X^2= 4 and 0.44 resonators and S = 3.55 for the X^2 = 4.62 and 0.51 resonators, respectively.

2.4 Design of the Closed-Type Resonator

For the closed-type resonator, we should consider an effect of the air gap distance M. Figures 6 and 7 show the mode charts calculated from the rigorous analysis for an image-type dielectric rod resonator [12], [15].

For X^2 = 4 and S = 4, the TE_{011} mode is separated from the others in the range of $G = M/D$ = 0 to 0.01 as shown in Fig. 6(a). Also, for X^2 = 0.44 and S = 4, the same results are obtained for the TE_{013} mode as in Fig. 6(b).

On the other hand, for X^2 = 4.62 and S = 3.55, the TE_{011} mode is coincident with the TM_{310} mode at G= 0.001 as in Fig. 7(a). Similarly, for X^2 = 0.51 and S = 3.55, the TE_{013} mode agrees with the TM_{310} mode at G = 0.01 as in Fig. 7(b). These facts require the fine control of M for these resonators. Thus, the appropriate G value for the IEC standard resonators to separate the TE_{011} and TE_{013} modes simultaneously from the other modes is G = 0.002~0.004.

3. Measurement Principle

For the open-type resonator, the measurement principles of ε_r and $\tan\delta$ of the rod and R_s of the HTS films have been already presented in Ref. [10]. On the other hand, for the cavity-type and closed-type, ε_{r01p} for a TE_{01p} mode can be calculated from a resonant frequency f_{01p} by [3]

$$\varepsilon_{r01p} = \left(\frac{c}{\pi D f_{01p}}\right)^2 \left\{u_p^2 + v_p^2\right\} + 1 \tag{2}$$

where c is the velocity of light and v_p is given by

$$v_p^2 = \left(\frac{\pi D f_{01p}}{c}\right)^2 \left\{\left(\frac{pc}{2h f_{01p}}\right)^2 - 1\right\} \tag{3}$$

where we take $h = L$ as the length for the cavity-type and $h = L + M$ for the closed-type, because there is no electric field in the air-gap region and the air-gap effect [16] can be neglected for small value of M. Also, an eigen value u_p is given by

$$\frac{1}{u_p}\frac{J_1(u_p)}{J_0(u_p)} = -\frac{1}{v_p}\frac{I_1(v_pS)K_1(v_p) - I_1(v_p)K_1(v_pS)}{I_0(v_p)K_1(v_pS) + I_1(v_pS)K_0(v_p)} \tag{4}$$

where $J_n(x)$ is a first-order Bessel function and $I_n(x)$ and $K_n(x)$ are modified first and second-order Bessel functions.

In the two-sapphire-rod-resonator-method, two sapphire rods having D and L_1 for the TE_{011} mode, and L_3=3L_1 for the TE_{013} mode are prepared. For the TE_{01p} mode, the unloaded quality factor Q_{up} of the resonator is given by

$$\frac{1}{Q_{up}} = \frac{1}{A_p}\left(\tan\delta + B_pR_s + C_pR_{sy}\right) \tag{5}$$

where geometry factors A_p, B_p and C_p are given in Ref. [17]. Then, assuming both the TE_{011} and TE_{013} sapphire rods have the same $\tan\delta$ values, we can calculate $\tan\delta$ and R_s separately from the measured f_{011}, f_{013} and Q_{u1}, Q_{u3} by

$$\tan\delta = \frac{1}{B_1 - B_3}\left\{\frac{A_3B_1}{Q_{u3}} - \frac{A_1B_3}{Q_{u1}} + (B_3C_1 - B_1C_3)R_{sy}\right\} \tag{6}$$

$$R_s = \frac{1}{B_1 - B_3}\left\{\frac{A_1}{Q_{u1}} - \frac{A_3}{Q_{u3}} - (C_1 - C_3)R_{sy}\right\} \tag{7}$$

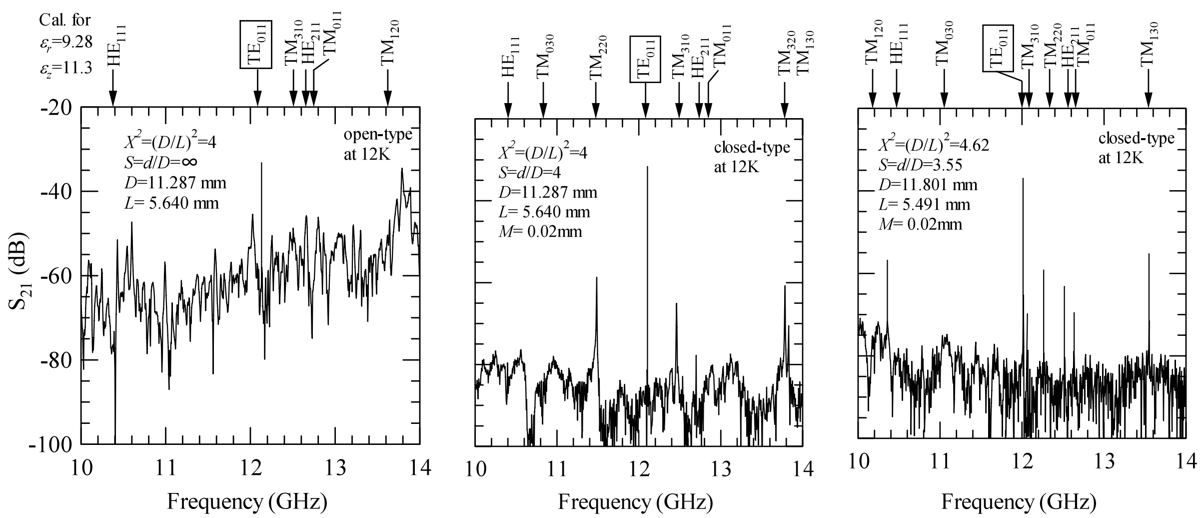
4. Experiments

4.1 Mode Identification

In order to verify the usefulness of the mode charts, frequency responses of an open-type resonator for X^2=4 and

Table 1 Sizes of sapphire rods and Cu rings (@293K).

	Sapphire rod			Copper ring	
X^2	D_0 (mm)	L_0 (mm)	supplier	d_0 (mm)	h_0 (mm)
4	11.287	5.640	Shinko-Sha	45.12	5.68
0.44	11.581	16.636		46.32	16.68
4.62	11.801	5.491	Union Carbide Co.	42.00	5.53
0.51	11.803	16.478		42.00	16.52



(a) Open-type (X^2=4). (b) Closed-type (X^2=4). (c) Closed-type (X^2=4.62).

Fig. 8 Measured frequency responses for TE_{011} resonators at 12 K.

closed-type resonators for X^2=4 and 4.62 are measured at 12 K. We prepared four sapphire rods and Cu rings shown in Table 1 to measure the temperature dependence of R_s at 12 GHz. In order to realize M= 0.02 mm at 20 K, we estimated D_0, L_0, d_0 and h_0 at room temperature, taking account of a difference of thermal expansions between the sapphire (coefficient of thermal expansion τ_α=5.3 ppm/K) and the copper (τ_α=18.5 ppm/K). Then, two $YBa_2Cu_3O_7$ (YBCO) films deposited on a MgO substrate (diameter of 51 mm, thickness of 0.5 mm, THEVA Co.) were prepared. Each resonator was set in a GM type cryostat with low mechanical vibrations (AISIN Co.) and cooled down from room temperature to 12 K. The distances between the resonator and coupling loops were adjusted by three-dimensional mechanical stages in the cryostat, so that the reflection coefficients $|S_{11}|$ and $|S_{22}|$ were adjusted to have the equal values and the transmission coefficient $|S_{21}|$ was adjusted to be about −30 dB at 12 K [18].

Figures 8(a), (b) and (c) show the measured frequency responses of the three resonators at 12 K and the calculated resonant frequencies from the mode charts shown in Fig. 2(a), Fig. 6(a) and Fig. 7(a), respectively. For the closed-type resonators, the measured resonance peaks agree well with the calculated ones and are isolated from the other modes as expected. For the open-type, however, there are more measured peaks than the calculated ones and the peaks seem to disagree with the calculated ones. Also, it is seen from Figs. 8(a) and (b) that the back ground level around the TE_{011} peak for the open-type is about −65 dB, compared with −90 dB for the closed-type. We consider that the radiation of TM_{nm0} leaky state modes with low Q_f indicated in Fig. 2(a) occurs for the open-type. On the other hand, for the closed-type, radiation of TM_{nm0} modes doesn't occur because EM fields are concentrated into the resonator. As a result, many peaks due to case modes in the cryostat occur and the peaks of the trapped state modes only agree with the calculated ones.

4.2 Comparison of the Resonator Structures

In order to compare the measured results of the open-type with that of the closed-type, we evaluated $\tan\delta$ and R_s using the same sapphire rods and YBCO films. Measured Q_u values of each resonator are shown in Fig. 9(a). Then, $\tan\delta$ and R_s are calculated. The results are shown in Figs. 9(b) and (c). It is seen that for both the TE_{011} and TE_{013} modes, Q_u values of the open-type are reduced, compared with that of the closed-type. Also, $\tan\delta$ values for the open-type indicate the negative sign below 63 K. As a result, R_s values of the open-type are evaluated about twice higher than that of the closed-type.

The radiation losses of the open-type are estimated. Q-factors of the open-type and closed-type are represented by

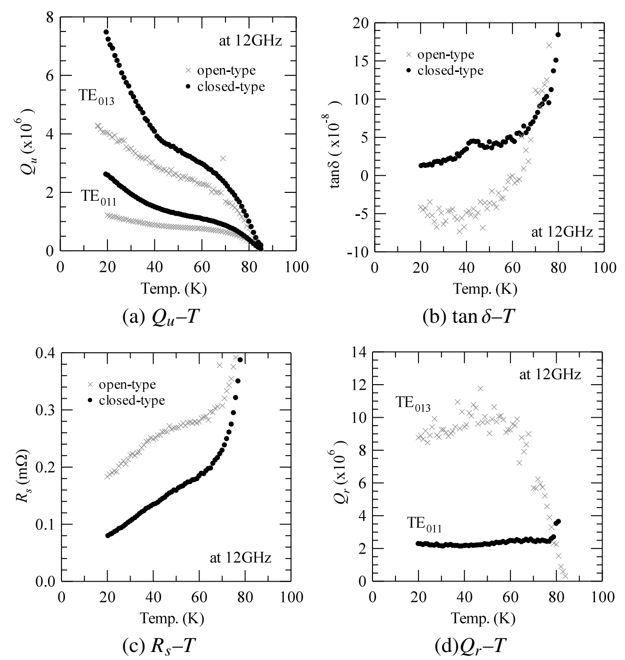
$$\frac{1}{Q_{u(open)}} = \frac{1}{Q_d} + \frac{1}{Q_c} + \frac{1}{Q_r} \quad (8)$$

$$\frac{1}{Q_{u(closed)}} = \frac{1}{Q_d} + \frac{1}{Q_c} + \frac{1}{Q_{cy}} \quad (9)$$

where Q_r is Q value due to the radiation loss of the open-type. In the measurements, Q_d and Q_c values in Eqs. (8) and (9) are the same because the same sapphire rods and YBCO films are used. Therefore, Q_r can be calculated from the measured Q_u values of the open-type and the closed-type and Q_{cy} values by

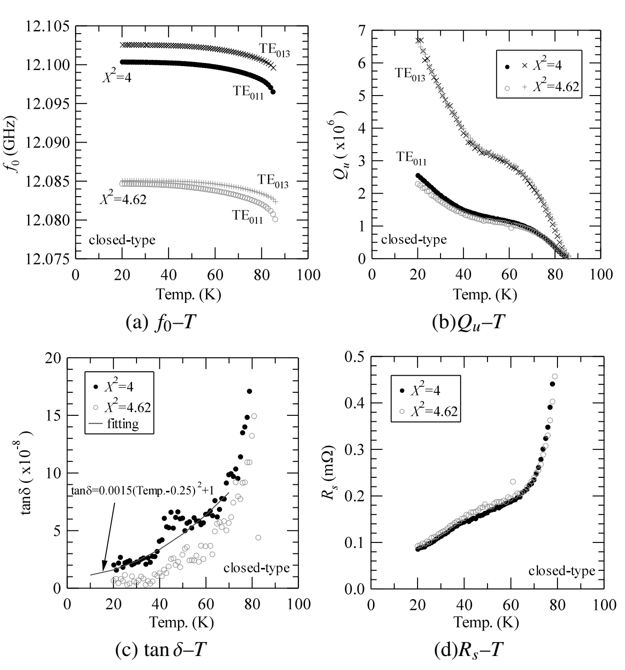
$$\frac{1}{Q_r} = \frac{1}{Q_{u(open)}} - \frac{1}{Q_{u(closed)}} + \frac{1}{Q_{cy}} \tag{10}$$

The values of Q_r are calculated from Fig. 9(a) by



(a) Q_u–T (b) $\tan\delta$–T (c) R_s–T (d) Q_r–T

Fig. 9 Measured results of open-type and closed-type resonators for X^2=4.



(a) f_0–T (b) Q_u–T (c) $\tan\delta$–T (d) R_s–T

Fig. 10 Measured results of closed-type resonators for X^2=4 and 4.62.

Eq. (10). The results are shown in Fig. 9(d), where Q_{cy} values are ignored because of their larger value of $Q_{cy} > 10^9$, compared with the Q_u values. It is seen that Q_r values of the TE_{011} and TE_{013} modes are about 2.5×10^6 and 9×10^6, respectively. Thus, Q_u values of both the TE_{011} and TE_{013} modes for the open-type are reduced by the radiation of the TM_{nm0} leaky state modes near the TE_{011} or TE_{013} modes. As a result, for the precise evaluations of $\tan\delta$ and R_s, the closed-type resonator should be used.

4.3 Precise Evaluations of $\tan\delta$ and R_s

In order to verify the validity of the resonator designs and the two-sapphire-rod-resonator-method, we evaluated the YBCO films by using two kinds of the closed-type resonators having $X^2 = 4$ and 0.44, and $X^2 = 4.62$ and 0.51.

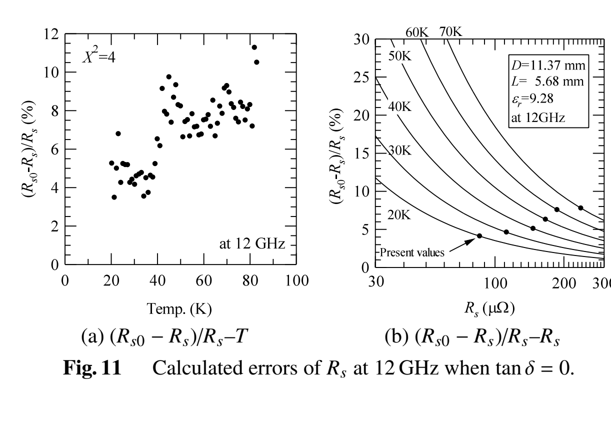
At first, we measured f_0 and Q_u for the TE_{011} and TE_{013} modes of each resonator. The results are shown in Figs. 10(a) and (b). Then, the values of $\tan\delta$ and R_s are calculated by Eqs. (6) and (7), respectively. The results are shown in Figs. 10(c) and (d). It is seen from Fig. 10(d) that the R_s values for both resonators agree within 10 percents. As a result, it is found that the case of $X^2 = 4.62$ needs the fine adjustment of the resonator structure but the case of $X^2 = 4$ makes the treatment easy, because the unwanted modes are sufficiently separated from the TE_{011} and TE_{013} modes.

5. Discussions

In the Hakki-Coleman method [1]–[6], R_s is evaluated from only the measured results of the TE_{011} mode, that is, $\tan\delta = 0$ is assumed. In this chapter, discussions for errors between this method and the two-sapphire-rod-resonator method are performed. Figure 11(a) shows the errors estimated from the measured results of the $X^2 = 4$ resonator shown in Fig. 10, where the errors are calculated by

$$\frac{R_{s0} - R_s}{R_s} = \frac{\tan\delta}{B}\frac{1}{R_s} \tag{11}$$

where R_{s0} is the surface resistance when $\tan\delta$=0 is assumed. It is seen that the errors are 4∼10%. However, when the quality of HTS films is improved, the errors increase. Figure 11(b) shows the estimated errors between two methods at 12 GHz when R_s of HTS films changes from 30 to 300 $\mu\Omega$,



(a) $(R_{s0} - R_s)/R_s$–T (b) $(R_{s0} - R_s)/R_s$–R_s

Fig. 11 Calculated errors of R_s at 12 GHz when $\tan\delta = 0$.

where the errors are calculated by Eq. (11) using the value of $\tan\delta$ calculated from the fitting curve indicated in Fig. 10(c) by blue solid line. It is seen that errors at 70 K are 10% for R_s=200 $\mu\Omega$ and 20% for R_s=100 $\mu\Omega$, respectively. Thus, it is not the Hakki-Coleman method but the two-sapphire-rod-resonator method to be able to evaluate R_s accurately when HTS films with higher quality are developed in the near future.

6. Conclusions

The appropriate dimensions of the open-type, cavity-type and closed-type sapphire rod resonators were designed from the mode charts calculated by the mode matching method. As a result, the closed-type resonators having the diameter ratio d/D=4, the value of $G = M/D < 0.01$ and the dimension ratio $(D/L)^2$=4 for the TE_{011} resonator and $(D/L)^2$=0.44 for the TE_{013} resonator are recommended to measure the R_s of HTS films because of the easy-to-treatment.

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