Design of sapphire rod resonators to measure the surface resistance of high temperature superconductor films.

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***Abstract* — Sapphire rod resonators of three types, as proposed in the IEC/ TC90 /WG8, have been commonly used to measure the surface resistance R_s of high temperature (high-T_c) superconducting (HTS) films. One is called an open-type resonator, where a sapphire rod having diameter D and length L is placed between two parallel HTS films, and the other is called a closed-type resonator, where the sapphire rod is set in a cavity constructed from two HTS films and a copper ring having diameter d and height h. Some mode charts for these resonators are calculated from the rigorous analysis based on the mode matching method, taking account of an uniaxial-anisotropic characteristic of a sapphire rod. An optimum dimension of a sapphire rod resonator is designed from the mode charts so as to separate the TE_{011} mode from the other modes. Moreover, it is verified that the radiations of the leaky state TM modes influence the unloaded Q_u values of the open-type resonator. As a result, the closed-type sapphire resonator having a dimension ratio $X^2=(D/L)^2$ of 4 and diameter ratio $S=d/D$ of 4 should be used.**

I. INTRODUCTION

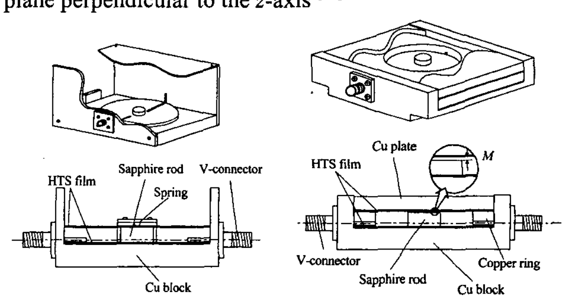
Dielectric resonator methods have been commonly used to measure the surface resistance R_s of high temperature (high-T_c) superconductors (HTS) [1]-[10]. However, it is reported that special attentions must be paid to the design of resonators, because unloaded quality factor Q_u values of TE_{011} mode are reduced by parasitic couplings of the other modes [2]. However, the theoretical examinations for the design of the resonator to prevent this unwanted coupling have never been reported. On the other hand, in the IEC TC90 WG8, three types of resonator structures, which are the open-type, the cavity-type and the closed-type resonators, are proposed to prevent this coupling.

In this paper, some useful mode charts for these resonators are calculated from the rigorous analysis based on the mode matching method, taking account of an uniaxial-anisotropic characteristic of a sapphire rod [12]. For the open-type resonator, a mode chart is calculated, taking into account of the leaky TM_{nm0} modes [11], which have an important role for parasitic coupling to the TE_{011} mode. Then for the closed-type resonator, a similar mode charts are calculated to realize an optimum design. The validity of the theoretical expectation will be verified by the experiments.

II. DESIGN OF SAPPHIRE ROD RESONATORS

A. Structures of open-type and closed-type resonators

Figure 1 (a) shows a structure of the open-type resonator. A TE_{011} mode sapphire rod with an uniaxial-anisotropic characteristic having diameter D, length L and loss tangent $\tan\delta$ 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 R_s, where the radiuses of the HTS films are assumed to be infinitely large. The relative permittivity of the sapphire rod 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) Open-type resonator (b) Closed-type resonator

Fig. 1 Sapphire resonator structures of two types.

Figure 1 (b) shows a structure of the closed-type resonator. The sapphire rod having D and L is shielded by an oxygen-free copper ring (Cu) with diameter d, height $h=L+M$ and surface resistance R_{sy} and the upper-side HTS film having R_s, where M is an air gap distance between the upper-side HTS film and the sapphire rod.

B. Mode chart of the open-type resonator

Figure 2 shows the mode chart of an open-type sapphire rod resonator calculated using the mode matching method in consideration of the uniaxial-anisotropic property [12]. In this chart, normalized frequencies for all trapped state modes and TM_{nm0} leaky state modes around TE_{011} mode are included, where subscripts of n, m, l are the numbers of the amplitude variation of the electromagnetic (EM) fields in the circumferential, radial and z-axis directions and Q_f is the damped free oscillation quality factor of

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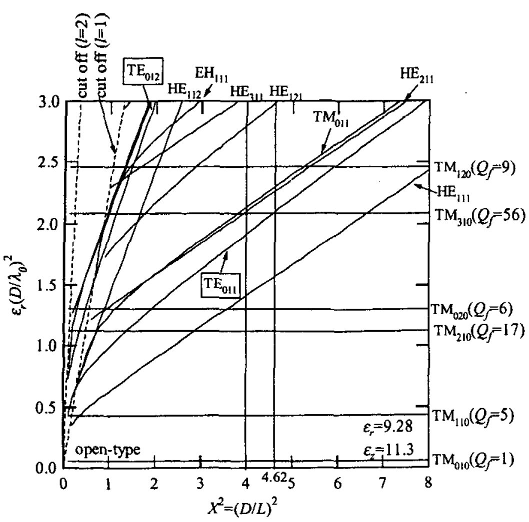


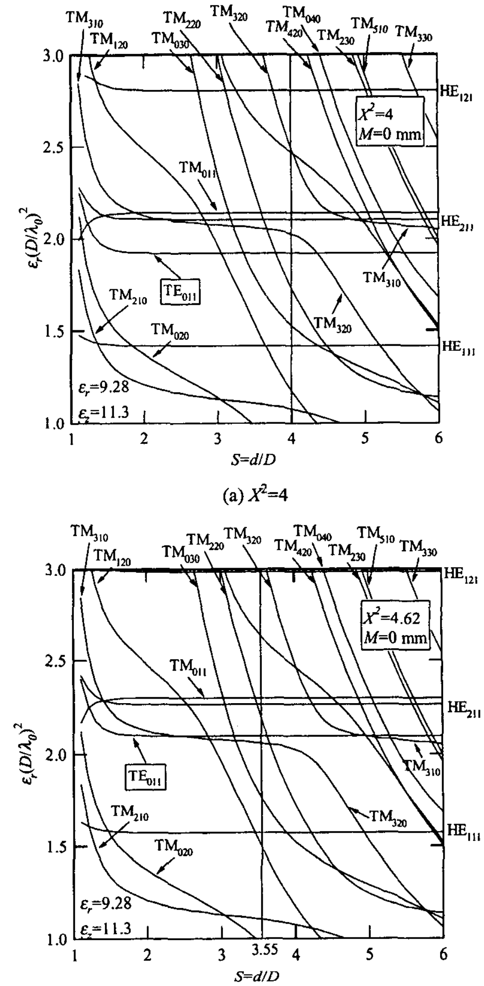
Fig. 2 Mode chart of the open-type sapphire rod resonator.

TM_{nm0} modes [11]. From this figure, we can see that unwanted TM_{310} mode is near the expected TE_{011} mode at the dimension ratio $X^2=(D/L)^2=4.62$, which realizes the minimum area of HTS films at 12GHz, as proposed by the IEC TC90 WG8. As a result, an unwanted coupling with the TM_{310} mode reduces Q_u values of the TE_{011} mode. In order to improve this, we chose $X^2=4$, where TE_{011} mode is separated from the leaky TM_{310} mode.

C. Mode chart of the closed-type resonator

At first, for simplicity, a closed-type sapphire rod resonator with M=0 mm is treated [12]. Figures 3 (a) and (b) show the mode charts for $X^2=4$ and $X^2=4.62$, respectively. In the figures, we can see that frequencies of the TM_{nm0} modes depend strongly on $S=d/D$. In addition, it is noted that the mode coupling between the TM_{310} and TM_{320} modes occurs near $S=4.5$; for example TM_{310} mode for S<4.5 transfers to the TM_{320} mode for S>4.5. In order to isolate TE_{011} mode from the others, we chose S of 4 for $X^2=4$ and S of 3.55 for $X^2=4.62$.

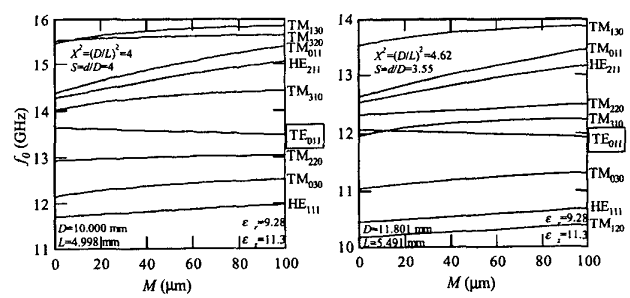
Furthermore, for the actual closed-type resonator structure, we should consider an effect of the air gap distance M. Figures 4 (a) and (b) show the mode charts calculated from the rigorous analysis for the image-type dielectric resonator method [13]. For $X^2=4$ and S=4, the TE_{011} mode is isolated from the other modes from M=0 μm to 100μm, as expected from Fig. 2. However, for $X^2=4.62$ and S=3.55, TE_{011} mode is coincident with the TM_{310} mode at M=10 μm. This fact requires the fine control of M for $X^2=4.62$ and S=3.55, for example, since the M value varies as the temperature changes, M=20μm at room temperature is designed so as to be M=10 μm at



(a) $X^2=4$

(b) $X^2=4.62$

Fig. 3 Mode chart of a closed-type sapphire rod resonator.



(a) $X^2=4$ and S=4

(b) $X^2=4.62$ and S=3.55

Fig. 4 Mode chart for closed-type resonator with the air gap.

20K considering the difference of the thermal expansions between the sapphire (coefficient of thermal expansion τ_α=5.3 ppm/K) and the Cu ring (τ_α=20 ppm/K). Then, the choice of X^2=4 and S=4 is recommended for the better design.

Finally, the Q-factors for the TE_{011} mode closed-type resonator are calculated by the perturbation method [14]. The Q_u value is given by

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

where Q_c is due to the losses of two HTS films, Q_{cy} is due to the loss of a copper ring and Q_d is due to $\tan\delta$, respectively. Figure 5 shows the calculated results of Q values for the closed-type resonator. From this figure, the loss of the copper 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.

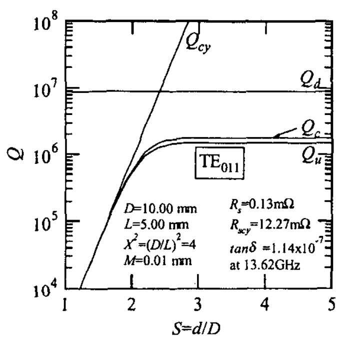


Fig. 5 Calculated results of Q values for TE_{011} closed-type resonator.

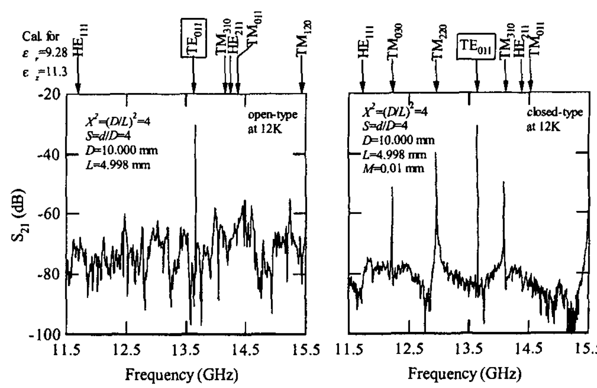
Thus, optimum dimensions of a closed-type sapphire rod resonator are obtained to be D=10.00 mm, L=5.00 mm, d=40.00 mm and h=5.02 mm at room temperature. Also, X^2=4 and S near 2.7 will be permitted to measure the R_s.

III. Experiments

A. Mode identification

In order to verify the usefulness of the mode charts, frequency responses of both the open-type and closed-type resonators are measured at 12K, where a sapphire rod (Union Carbide Co.) having D=10.000 mm and L=4.998 mm, two YBCO films deposited on a MgO substrate (ϕ=51 mm, t=0.5 mm, THEVA Co.) and an oxygen-free copper ring having d=40 mm and h=5.02 mm are used. In this measurement, a cryocooler with low mechanical vibrations and adjustment mechanism of the coupling loop antennas in low temperature are used [15]. Then, the coupling strength between the resonator and the loop antennas are adjusted finely to be the transmission coefficient $|S_{21}|$= -30dB and the reflection coefficient $|S_{21}|$ =$|S_{21}|$ at 12K.

Figures 6 (a) and (b) show the measured frequency responses of two types of the resonators and the calculated resonant frequencies from the mode charts shown in Fig. 2 and Fig. 4 (a), respectively. The measured resonance peaks for the TE_{011} mode of both resonators agree well with the calculated ones and are isolated from the other modes as expected.



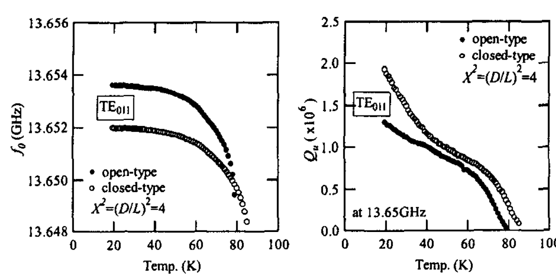
(a) Open-type resonator (b) Closed-type resonator

Fig. 6 The frequency response of the two types of the resonators at 12K.

We can see from these figures that the back ground level around the TE_{011} mode peak for the open-type resonator is about –65dB, compared with –80 dB for the closed-type resonator. For the open-type resonator, TM_{nm0} leaky state modes shown in Fig. 2 may propagate along the coupling loop antenna.

B. Measured results

In order to investigate the influence of radiations from the open-type resonator, we compare measured Q_u values of open-type resonator with ones of closed-type. Figures 7 (a) and (b) show the measured results of resonant



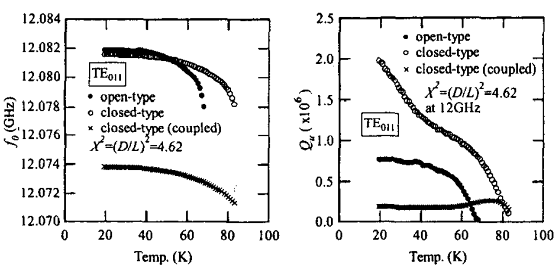
(a) f_0 - T (b) Q_u - T

Fig. 7 Measured results of open-type and closed-type resonators.

frequency f_0 and Q_u for the TE_{011} mode of two resonators. From the Fig. 7 (b), we can see that the Q_u values of open-type resonator are less than ones of closed-type. This shows that there are radiation losses for the open-type resonator.

IV. Discussions

We try to measure Q_u values using a sapphire rod of X^2=4.62, which is proposed as the international standard resonator. By using a sapphire rod having D=11.801 mm and L=5.491 mm and a copper ring having d= 42 mm and h=5.510 mm, we measure the f_0 and Q_u for open-type and closed-type resonators. The results are shown in Figs. 8 (a) and (b). Likewise the resonators of X^2=4, the Q_u values of open-type resonator are less than ones of closed-



(a) f_0 - T (b) Q_u - T

Fig. 8 Measured results of international standard resonator.

type. Then, in order to investigate the influence of coupling between TE_{011} and TM_{310} modes on the Q_u value, we prepare another copper ring with M=10 μm at 20K, which is decided by using Fig. 4 (b). The result is shown in Fig. 8 (b). We can see that the Q_u values of this resonator are reduced by the coupling even if the closed-type resonator is used. As a result, the case of X^2=4.62 needs the fine adjustment of the resonator structure. On the other hand, the case of X^2=4 makes the treatment easy, because the unwanted modes are sufficiently separated from the TE_{011} mode used for the R_s measurement.

Finally, we discuss the cavity-type resonator, which is constructed by housing the open-type resonator in the Cu cavity [2]. From the figures 3, as S value increases, the f_0 of the TM_{nm0} modes decreases. In particular, when HTS films having large area are used, it will be difficult to control the other modes. Therefore, we use the closed-type resonator for the R_s measurement.

V. Conclusions

The open-type and closed-type sapphire rod resonators are designed from the mode charts calculated by the mode matching method. As a result, the closed-type resonator having X^2=4 and S=4 should be used to measure the R_s of HTS films.

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