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Accurate Measurements of the Unloaded Q of a Dielectric-loaded High-Q $TE_{01\delta}$ mode Cavity Resonator with HTS Endplates

H. J. Kwon*, Jung Hur+, and Sang Young Lee*#
* *Department of Physics and Center for Advanced Materials and Devices*
+ *Department of Electronic Engineering*
Konkuk University, Seoul 143-701, Korea

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Abstract

Methods for mode identification and accurate measurements of the unloaded Q (Q_0) of a dielectric-loaded $TE_{01\delta}$ mode cavity resonator with HTS endplates are proposed. A resonator with a sapphire rod and $YBa_2Cu_3O_{7-x}$ (YBCO) endplates was prepared and its microwave properties were studied at temperatures above 30 K. The $TE_{01\delta}$ mode Q_0 of the resonator, designed to work as a tunable resonator with variations in the gap distance (s) between the sapphire rod and the top YBCO, was more than 1000000 at $s = 0$ mm and at 30 K with the resonant frequency of 19.56 GHz. The $TE_{01\delta}$ mode Q_0 decreases as s increases for $s < 2$ mm until mode couplings between the $TE_{01\delta}$ mode and other modes appeared at $s = 2$ mm. Significant dependence of the $TE_{01\delta}$ mode Q_0 on the input and output coupling constants was also observed. Applications of the open-ended $TE_{01\delta}$ mode cavity resonator for a tunable resonator with a very high Q as well as a characterization tool for the surface resistance measurements of HTS films are described.

Keywords: $YBa_2Cu_3O_{7-x}$ films, $TE_{01\delta}$ mode, dielectric-loaded cavity resonator, microwave properties, unloaded Q

I. Introduction

Dielectric-loaded $TE_{01\delta}$ mode cavity resonators with HTS endplates (henceforth called 'the HTS resonator') have been regarded useful both as a resonator with a very high Q and as a characterization tool for measurements of the surface resistances of HTS films [1]-[3]. Unloaded Q (Q_0) more than 1000000 has been easily achieved with the HTS resonator at 5.5 GHz and 77 K [4], demonstrating that it can be used as a high Q resonant element in realizing an oscillator with a very low phase noise. Also such a very high Q_0 enables measurements of the surface resistance of HTS films with high sensitivity. As a result, it is believed that a characterization method based on the HTS resonator can be a standard for evaluating microwave properties of HTS films for microwave applications [5]. It is noted that use of a low loss dielectric with a high dielectric constant enables not only realization of high Q_0 but also investigation of the homogeneity in the microwave properties of a large HTS film [6]. Furthermore, if the HTS resonator is used in an open-ended scheme with a gap between the dielectric and the top endplate, the resonant frequency (f_0) of the HTS resonator becomes tunable according to the gap distance [7]. We note here that, in using the $TE_{01\delta}$ mode resonator, the $TE_{01\delta}$ mode should be correctly identified. Especially, when a dielectric-loaded cavity resonator is used in an open-ended scheme, the $TE_{01\delta}$ mode should be separated from other modes and clearly identified. Additionally, Q_0 needs to be measured with accuracy at low temperatures with considerations of the loading effect. For example, the $TE_{01\delta}$ mode Q_0 of the HTS resonator often exceeds 10^6. In this case, special care needs to be taken to correctly measure Q_0 by minimizing the couplings between the

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#Corresponding author. Fax: +82 2 450 3166
e-mail: sylee@kkucc.konkuk.ac.kr

feeding lines and the resonator.

Here we investigated a method that can be used in identifying the $TE_{01\delta}$ mode of a dielectric-loaded cavity resonator with HTS endplates and measuring its $TE_{01\delta}$ mode Q_0 with good accuracy. Effects of mode couplings and the coupling strength between the feeding lines and the resonator on the measured Q_0 are described.

II. Experimental

Fig. 1 shows the cross-sectional view of the sapphire-loaded cavity resonator with YBCO endplates (henceforth called 'the YBCO resonator'), which was used throughout this experiment. The cylindrical cavity was made of well-polished oxygen-free high purity copper (OFHC) with the inner diameter of 15 mm. In the figure, a sapphire rod is seen inside the cavity. The dimensions of the sapphire are 5 mm x 5 mm for the diameter and the height, respectively. For the top and bottom endplates, we used YBCO on CeO_2-buffered sapphire substrate (CbS) and YBCO on $LaAlO_3$ (LAO), respectively. Loop couplings were used for TE mode excitations, with the coupling strength between the input/output lines and the resonator controlled by the distance between the coupling loop and the sapphire rod. Care was taken to make the couplings symmetrical. An off-axis dc magnetron-sputtering method was used in preparing the YBCO film at the top (YBCO on CbS) and a laser ablation process was used for the YBCO at the bottom (YBCO on LAO), respectively. In preparing the YBCO on CbS, we first prepared a CeO_2 layer on a r-cut sapphire substrate at 780 °C using an rf magnetron-sputtering process. Later the CeO_2 layer was post-annealed at 1000 °C in an oxygen environment. Both YBCO films appeared to have T_c's about 88 K and the transition widths less than 1 K. In measuring the microwave properties of the resonator, a HP 8510C network analyzer with the maximum frequency resolution of 1 Hz was used. Measurements at cryogenic temperatures were done using a closed-cycle refrigerator. Temperature stability was better than +/-0.2 K during measurements. Tuning of the resonant frequency was made by moving the top endplate.

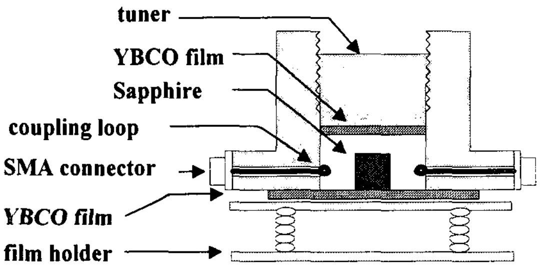

Fig. 1. A cross-sectional view of our sapphire-loaded cavit resonator with a movable top plate.

III. Results and Discussion

1. Mode identification

The $TE_{01\delta}$ mode was identified by comparing experimentally observed $TE_{01\delta}$ mode f_0 with the calculated and simulated f_0's. The calculated $TE_{01\delta}$ mode f_0 was obtained from the field distributions inside the cavity, while the simulated one was obtained using 'Micro-Stripes' [8]. Fig. 2 shows the diagram of the dielectric-loaded cavity used for the field analysis. Field analysis was done in a similar way as described in our earlier report for the $TM_{01\delta}$ mode [6]. For the analysis, travelling modes were assumed in regions 1 and 2 with evanescent modes assumed in region 3. Details are described elsewhere [9]. In calculating f_0, we used $\varepsilon_r = 9.4$ for the dielectric constant of sapphire. The f_0's calculated from the field analysis were 19.497 GHz and 18.509 GHz at $s = 0$ mm and 1 mm, respec-

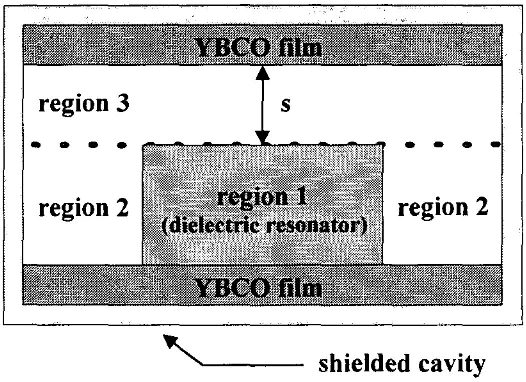

Fig. 2. A diagram of a dielectric-loaded cavity resonator used for the field analysis.

tively, which was slightly different from the corresponding experimental values of 19.444 GHz and 18.462 GHz by 0.27 % and 0.25 %, respectively. The $TE_{01\delta}$ mode could also be identified by computer simulations. In Table I, the simulated results for different gap distances are listed. The TE_{011} mode f_0's are 19.697 GHz and 18.663 GHz at s = 0 and 1mm, respectively, which are a little different from the corresponding experimental values of 19.444 GHz and 18.462 GHz. However, the mode with f_0 = 19.697 at s = 0 mm can be easily identified as the TE_{011}mode because the neighboring modes are well separated from the TE_{011} mode with their f_0's of 16.062 GHz (H_z excitation) and 22.416 GHz (H_ϕ excitation). One thing to note in Table I is the mode coupling between the $TE_{01\delta}$ mode and another mode with the $TE_{01\delta}$ mode f_0 becoming equal to f_0 of another mode at s = 1.6 mm. Mode coupling was also observed experimentally, as displayed in Fig. 3. Fig. 3 shows the S_{21} response of the sapphire-loaded cavity resonator with OFHC endplates (henceforth called 'the OFHC resonator) at 295 K, where the mode coupling is seen for s = 2.0 mm. It is noted here that the tuning range of the resonator can be limited by this kind of mode coupling when the cavity resonator is used as a tunable resonator.

Table I. Simulated f_0 of the YBCO resonator used in this experiment. 's' denotes the gap between the sapphire rod and the top endplate. H_ϕ and H_z denote the field components used for excitation of the TE mode resonator.

s (mm)		f_0 (GHz)		
		TE_{111}		TE_{011}
0	H_ϕ	14.589		
	H_z	16.062		* 19.697
0.3	H_ϕ			
	H_z	14.993	17.426	* 19.340
0.6	H_ϕ			
	H_z	14.979	17.706	* 19.215
1.0	H_ϕ	14.846	18.220	
	H_z	14.891	**18.218**	*** 18.663**
1.3	H_ϕ			
	H_z	14.784	**18.312**	*** 18.526**
1.6	H_ϕ			
	H_z	14.713	**18.390**	*** 18.390**
2.0	H_ϕ	14.568		18.418
	H_z	14.579		*18.394

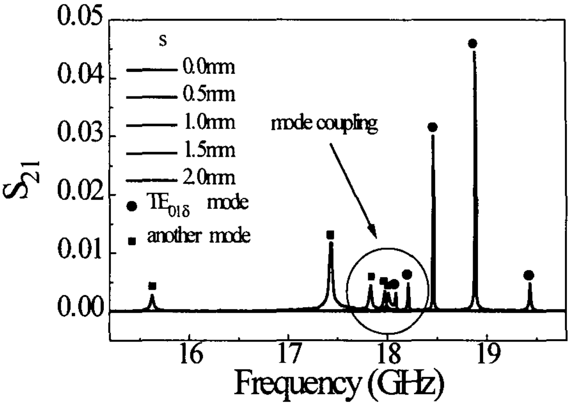

Fig. 3. Frequency resoponse showing $TE_{01\delta}$ and other mode for different gap distandes (s) in the OFHC resonantor at 29 K.

Furthermore, due to the mode coupling, the gap distance (s) should be properly chosen when an open-ended $TE_{01\delta}$ mode dielectric- loaded resonator is used for measurements of R_S.

2. Measurements of Q_0

In obtaining the Q_0 of a resonator, both the loaded Q (Q_L) and the input and output coupling constants (β_1 and β_2) need to be known. Q_L is often measured directly from the S_{21} data using the conventional 3-dB method and Q_0 can be calculated from the following relation.

$$Q_0 = Q_L\,(1 + \beta_1 + \beta_2). \qquad (1)$$

It is noted here that accurate measurements of β_1 and β_2 can only be accomplished by performing a correct calibration process, which, however, is very difficult to realize if the measurements are done at low temperatures. Above all, there is no calibration set available for low temperature measurements. In this regard, accurate measurements of Q_0 at low temperatures can only be done either by using a calibration set specially designed for cryogenic purposes or by using a weak coupling scheme of $\beta_1 \approx \beta_2 \approx 0$, when $Q_0 \approx Q_L$ in Eq. (1). In this experiment, we used the weak coupling scheme with the coupling strength controlled by changing the distance between the coupling loops and the sapphire rod. In Fig. 4, the Q_0 vs T data at s = 1 mm are displayed for different coupling distances with the inset showing the Q_L vs T data. In the inset, we see that the measured Q_L can be different for different coupling constants with Q_L appearing higher for larger coupling distances (i.e., smaller coupling constants). However, in the inset, Q_L remains almost unchanged if the coupling distance is more than 5.5 mm. Accordingly, Q_0 appears almost the same regardless of the coupling strength, as seen in Fig. 4. The observed results show that Q_0 can be measured accurately even without calibration if the feeding lines and the resonator are weakly coupled. For reference, in Fig. 4, the coupling distances of 4 mm, 5 mm, 5.5 mm and 5.8 mm correspond to the insertion losses of 1.5 dB, 8 dB, 19 dB and 33 dB, respectively, when the calibration was done at the room temperature.

Another thing to mention is the dependence of the coupling constants on Q_0, which is the usual case for any HTS-based resonator with its Q_0 being strongly temperature-dependent. Since the coupling constants increases according to Q_0, β_1 and β_2 need to be small enough even when the resonator Q is at its highest value (usually the case at the lowest temperature). It is also noted here that the transmitted signal becomes too weak to be observed if β_1 and β_2 are too small. Besides the coupling constants, frequency resolution is another thing to be considered for accurate measurements of Q_0. This is because even 1 KHz frequency resolution implies more than +/- 10 % error in the measured Q_L if Q_L exceeds 10^6 at f_0 = 10 GHz. In this case, higher frequency resolution is required to reduce measurement errors in Q_L. Also errors in Q_L can be reduced if Q_L is obtained from a fit to the following equation.

$$|S_{21}(f)| = \frac{|S_{21}(f_0)|}{\sqrt{1+Q_L^2\Delta^2(f)}} \qquad (2)$$

where $\Delta(f) = f - (f_0^2/f^2)$ [10].

Based on the measurement method described above, data for the dependence of the $TE_{01\delta}$ mode Q of the OFHC resonator on s were collected. In Fig. 5, we see continuous increase in Q_L according to s for s up to 1.5 mm with $Q_L \sim 10800$ and 15100 at s = 0 mm and 1mm, respectively, which is attributed to weaker electromagnetic fields and reduced power loss at the surface of the top OFHC plate [7]. The $TE_{01\delta}$ mode Q_0 calculated using Eq. (1) turned out to be 11600 and 17100 at s = 0 mm and 1 mm, respectively. Using analytic expressions for the electric and magnetic field inside the cavity, the surface resistance of the OFHC plate can be calculated if the loss tangent (tan δ) of the dielectric rod is known. With Q_0 = 11600 and tan δ = 5 x 10^{-6} at 300 K for sapphire [11], we get R_S = 44.3 mΩ at f_0 = 19.50 GHz for the OFHC. If we convert the calculated R_S at 19.50 GHz to the value at 10 GHz using $R_S = (\omega\mu/2\sigma)^{1/2}$, we get R_S = 31.7 mΩ at 10 GHz, a value comparable to the ideal value of $R_S \sim 26$ mΩ for pure copper at 10 GHz and at 300 K.

The reasons for the difference between the measured and ideal R_S's are not clearly understood at the moment. Due to impurities, tan δ of the sapphire can be different from 5 x 10^{-6} at the room temperature. If tan δ = 1.5 x 10^{-5} is used for the calculation at 300 K, the difference between the calculated and experimental Q_0's would be within 3 % with the calculated Q_0 of

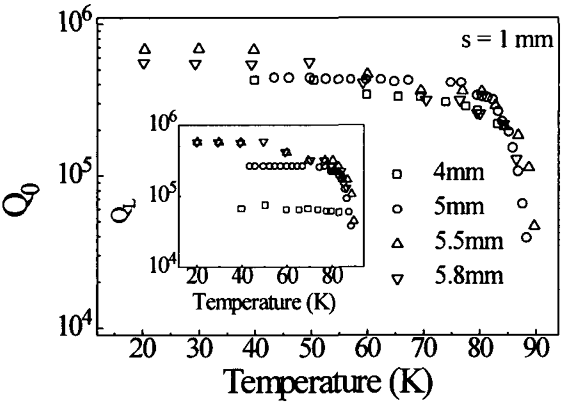

Fig. 4. Unloaded Q *vs* Temperature for different coupling distances between the coupling loop and the YBCO resona tor. The gap distance s is set to 1 mm.

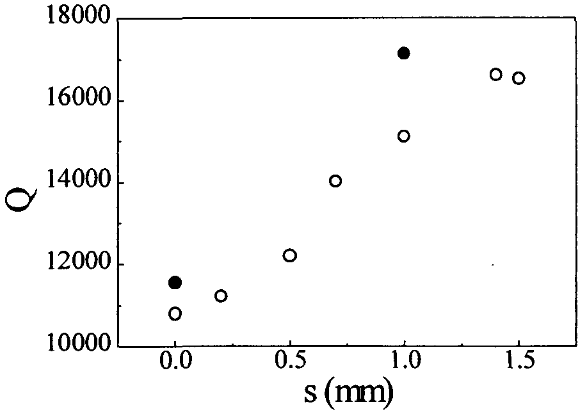

Fig. 5. Q_L (open circle) and Q_0 (filled circle) *vs* the gap distance (s) for the sapphire-loaded cavity resonators with OFHC endplates.

about 11900. Surface roughness of the OFHC plate may also account for the difference, for which further studies are needed. The $TE_{01\delta}$ mode Q_0 of the HTS resonator was also measured for s = 0 mm at temperatures above 30 K using the weak coupling scheme. Fig. 6 shows Q_0 vs T data for the YBCO resonator at s = 0 mm. We see in Fig. 6 that Q_0 was as high as 1.0 x 10^6 and 3.1 x 10^5 at 30 K and 77 K, respectively, with f_0 = 19.56 GHz. At 30 K and 77 K, the calculated R_S turned out to be 273 μΩ and 1 mΩ, respectively, with tan δ of the sapphire assumed to be 10^{-7}. These values are equivalent to R_S's of ~ 71 μΩ and 260 μΩ at 30 K and 77 K, respectively, at 10 GHz if the relation of $R_S \propto f^2$ is used [12].

In summary, a sapphire-loaded cavity resonator with YBCO endplates was prepared and its $TE_{01\delta}$ mode could be identified by comparing the $TE_{01\delta}$ mode f_0 with the calculated value from analytic expressions for the field distributions inside the cavity and the simulated result obtained from a commercial software. Q_0 of the $TE_{01\delta}$ mode YBCO resonator could be measured with accuracy and reproducibility by maintaining weak couplings between the feeding lines and the resonator as well as by using high frequency resolution. The frequency tuning range of an open-ended cavity resonator appears limited by mode couplings between the $TE_{01\delta}$ mode and other modes. The sapphire-loaded cavity resonator was also used for measurements of R_S. The measured R_S of the OFHC plate is 33.6 mΩ at 10 GHz and at 300 K, a value comparable with the ideal value of 26 mΩ. High Q_0 of the $TE_{01\delta}$ mode resonator enabled measurements of small R_S of YBCO films, for which the measured value appeared as small as 260 μΩ at 77 K and 10 GHz.

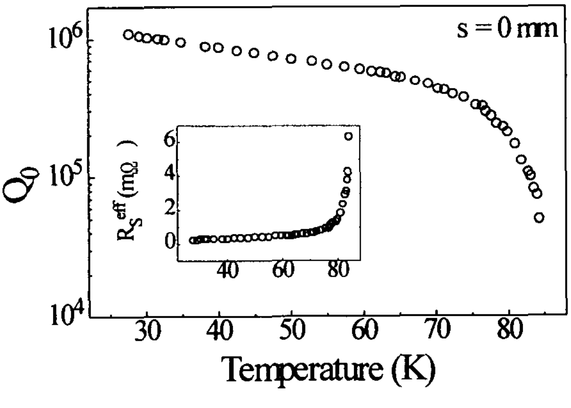

Fig. 6. Unloaded Q vs Temperature for the YBCO resonator Inset: Th e dependence of the effective surface resistance (R_S^{eff}) of the YBCO films used as the endplates of the YBCO resonator.

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