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Application of Dielectric-loaded Cavity Resonators with HTS Endplates for Tunable High-Q Resonators and Characterization Tools for Large HTS Films

고온초전도 박막이 설치된 유전체부하 공진기의 주파수 조절 가능한 High-Q 공진기 제작 및 대면적 고온초전도 박막의 특성평가에의 응용

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$TE_{01\delta}$ mode Cavity Resonators with a low loss dielectric rod and $YBa_2Cu_3O_{7-\delta}$ (YBCO) endplates were prepared and their microwave properties were studied at temperatures above 30 K. Both sapphire and rutile were used as the dielectrics. 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 dielectric rod and the top YBCO, was more than 1000000 at s = 0 mm and at 30 K and the resonant frequency of 19.56 GHz when a sapphire rod was used for the dielectric. The $TE_{01\delta}$ mode resonant frequency (f_0) appeared to decrease as the temperature is raised. Meanwhile, the temperature dependence of the $TE_{01\delta}$ mode f_0 of the rutile-loaded resonator appeared different with f_0 increasing according to the temperature and Q_0 more than 300000 at 30 K and f_0 = 8.56 GHz. Comparisons were made between the microwave properties of the sapphire-loaded and the rutile-loaded resonators. Also, applications of the $TE_{01\delta}$ mode cavity resonator for a tunable resonator with a very high Q_0 as well as a characterization tool for surface resistance measurements of HTS films are described.

1. 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 10^6 have 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]. Especially, when a dielectric-loaded cavity resonator is used in an open-ended scheme, the $TE_{01\delta}$ mode should be well 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 feeding lines and the resonator.

Here we report the tunability of the $TE_{01\delta}$ mode resonator as well as the dependence of the unloaded Q (Q_0) on f_0 for two different cases: one for the resonator based on YBCO films and sapphire and the other one with YBCO films replaced by oxygen-free high purity copper (OFHC) plates. Also the property of a large HTS film with a sapphire-loaded cavity resonator was studied.

2. Experimental

2-1. Preperation of a Sapphire-loaded Cavity Resonator

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 is made of well-polished oxygen-free high purity copper (OFHC) with the inner diameter of 15 mm. We used the dielectric rods that The dimensions of the sapphire are 5 mm x 5 mm for the diameter and the height, respectively, and the rutile, 3.88 mm x 2.73 mm. 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. 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. The YBCO films appeared to have T_C's about 88 K and the transition widths less than 1 K. Double sided YBCO film on LAO was used for studying the homogeneity of a large HTS film.

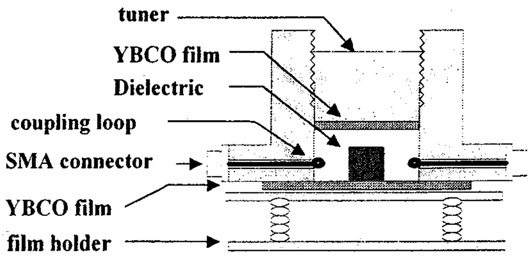

Fig. 1. A cross-sectional view of our dielectric-loaded cavity resonator with a movable top plate.

2-2. Measurement Procedure

In Fig. 1, the input and output lines were weakly coupled to the resonator and, for TE mode excitations, loop couplings were used. SMA connectors were used for all connections. The data were collected using a HP8510C network analyzer as the temperature was raised. Change in f_0 was realized by moving the top endplate and thereby changing s, the gap between the sapphire rod and the cavity top plate. In identifying the $TE_{01\delta}$ mode resonance signal, we compared experimentally observed f0 with both the calculated and simulated ones [4]. At 293 K, with ε_r = 9.4 used for the dielectric constant of the sapphire rod, the $TE_{01\delta}$ mode f_0's are 19.448 GHz, 19.497 GHz and 19.697 GHz for the experimental, calculated and simulated values, respectively, with the differences of less than 1.3 % among each other. At temperatures between 30 K and 80 K, the $TE_{01\delta}$ mode f0 appeared to be ~ 19.56 GHz, which agrees well with the calculated value of 19.58 GHz obtained from analytic expressions for the field distributions inside the cavity [4]. ε_r = 9.32 was used for the dielectric constant of the sapphire at 77 K. Q_L was measured using the conventional 3-dB method. For the weakly coupled case, $Q_0 \approx Q_L$.

2-3. Mode identification and Accurate Measurement of Q_0

The $TE_{01\delta}$ mode was identified by comparing experimentally observed $TE_{01\delta}$ mode f_0 with the calculated and simulated f_0s. The calculated $TE_{01\delta}$ mode f_0 was obtained from the field distributions inside the cavity, while the simulated one was obtained using a commercial software called '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

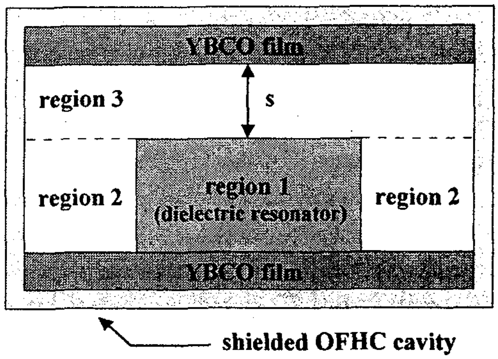

Fig. 2. A diagram of a dielectric-loaded cavity resoator for the field analysis.

report for the $TE_{01\delta}$ mode [8]. In calculating f_0, we used r = 9.4 for the dielectric constant of sapphire. The f_0's calculated from the field analysis are 19.497 GHz and 18.509 GHz at s = 0 mm and 1 mm, respectively, which is 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. The mode with f_0 = 19.697 at s = 0 mm can be easily identified as the TE_{011}mode.

In obtaining the Q_0 of a resonator, both the 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.

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 $\Delta(f) = 1 \quad (f_0^2 / f_2)$ [9].

3. Applicability of the dielectric-loaded cavity resonator for a tunable high-Q resonator

3-1. Comparison the YBCO Resonator wih the OFHC Resonator

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. 3, we see continuous increase in Q_L according to *s* for *s* up to 1.5 mm with Q_L ~ 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. 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 ($\tan\delta$) of the dielectric rod is known. With Q_0 = 11600 and $\tan\delta$ = 5 x 10^{-6} at 300 K for sapphire [12], 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 ~ 26 mΩ for pure copper at 10 GHz and at 300 K.

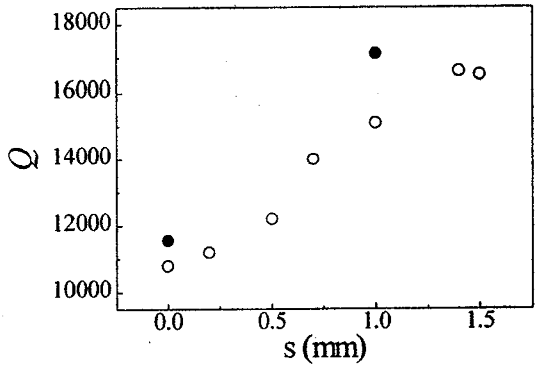

Fig. 3. Q_L (open circle) and Q_0 (filled circle) *vs* the gap distance (s) for the sapphire-loaded cavity resonators with OFHC endplates at room temperature.

The reasons for the difference between the measured and ideal R_S's are not clearly understood at the moment. Due to impurities, $\tan\delta$ of the sapphire can be different from 5 x 10^{-6} at the room temperature. If $\tan\delta$ = 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 about 11900. Surface roughness of the OFHC plate may also account

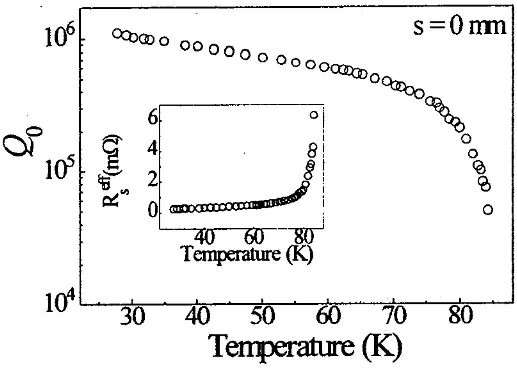

Fig. 4. Q_0 vs Temperature for the sapphire-loaded resonator with YBCO endplates. Inset : The dependence of the effective surface resistance (R_s^{eff}) of the YBCO films

for the difference, for which further studies are needed.

Q_0 of the HTS resonator was also measured for s = 0 mm at temperatures above 30 K. Fig. 4 shows Q_0 vs T data for the YBCO resonator at s = 0 mm. We see in Fig. 6 that Q_0 is as high as 1.0 x 10^6 and 3.1 x 10^5 at 30 K and 77 K, respectively, with f0 = 19.56 GHz. At 30 K and 77 K, the calculated R_S turns out to be 273 $\mu\Omega$ and 1 mΩ, respectively, with tan of the sapphire assumed to be 10^{-7}. These values are equivalent to R_S's of ~ 71 $\mu\Omega$ and 260 $\mu\Omega$ at 30 K and 77 K, respectively, at 10 GHz if the relation of $R_S \propto f^2$ is used [13].

3-2 Sapphire-loaded cavity resonator

Fig. 5 shows Q_0 vs T data for different values of the gap distance s for the cavity resonator with YBCO endplates (henceforth called 'the YBCO resonator'), with the inset displaying f_0 vs s data. In the figure, Q_0 appears to be ~ 1000000 with f_0 = 19.57 GHz at 30 K and s = 0 mm. The observed high Q_0 is attributed to the very low surface resistance (R_S) of the YBCO films as well as the extremely low loss tangent (tanδ) of the sapphire at low temperatures. Using the observed Q_0 of ~ 1000000, we calculated the effective surface resistance (R_S^{eff}) of the YBCO films, which turned out to be ~ 0.27 mΩ. For calculating R_S^{eff}, tan ~ 10^{-7} was used for sapphire and the intrinsic surface resistance (R_S) of the YBCO film at the bottom was assumed equal to the R_S of the YBCO film at the top. At 60 K and 77 K, Q_0's of the YBCO resonator remained as high as ~ 600000 and ~ 300000, respectively, which give R_S^{eff}s of 0.49 mΩ and 1 mΩ, respectively. That also means, R_S^{eff} would be as small as ~ 0.13 mΩ and 0.26 mΩ at 10 GHz at 60 K and 77 K, respectively. In the inset of Fig. 2, it is noted that f_0 changes more abruptly according to s at smaller s. For instance, there is variations of ~ 0.94 GHz in f_0 between s = 0 mm and s = 1 mm, while it is ~ 0.42 GHz between s = 1 mm and 2 mm. This is due to that field distributions inside the cavity are modified more according to s at smaller s. The observed f_0's also appear to agree well with the calculated ones, as seen in the inset. In Fig. 5, one interesting thing to point out is that Q_0 appears smaller as s increases at 30 K. This observation is in contrast with the increase of

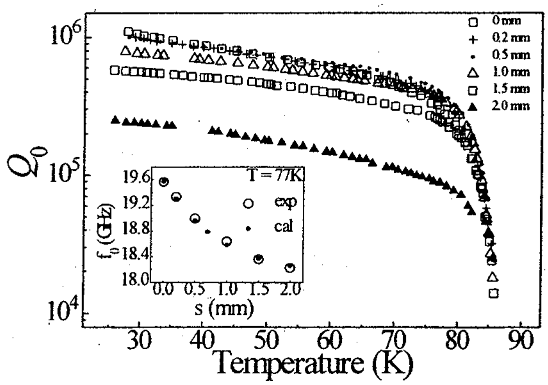

Fig. 5. Dependence of Q_0 on the temperature for different values of s for the YBCO resonator. Inset : Dependence of the experimental (open circule) and calculated (dot) $TE_{01\delta}$ mode resonant frequencies on the gap distance for the YBCO resonator.

Q_0 for increasing s for the OFHC resonator. In Fig. 5, we display Q_0 vs s data for the YBCO resonator at 30 K, 60 K and 77 K, with the inset showing the data for the OFHC resonator at the room temperature. In the figure, Q_0 appears to decrease as s increases at 30 K for the YBCO resonator with Q_0 = 1020000 and 560000 at s = 0 mm and 1.5 mm, respectively. Meanwhile, Fig. 3 shows that Q_0 increased from 12000 at s = 0 mm to 17000 at s = 1.5 mm for the OFHC resonator. The observed results for the OFHC resonator is attributed to that the magnitude of the magnetic field at the cavity surface becomes smaller for larger s, resulting in smaller signal loss at the cavity surfaces. Also decreasing Q_0 for increasing s is attributed to the fact that losses from the YBCO surface is less significant than the losses from the side walls made of OFHC. In Fig. 5 the dependence of Q_0 on s appeared somewhat complicated with Q_0 increasing according to s up to s = 0.5 mm and decreasing as s increased further at 60 K and 77 K. For explaining the unique behaviors observed at 60 K and 77 K, we calculated Q_0's for different values of s using the calculated values of Rs^{eff} = 0.27 mΩ, 0.49 mΩ and 1 mΩ for the YBCO film at 30 K, 60 K and 77 K, respectively. It is noted here that tan = 10^{-7} and = 5.22 x 10^{8} S/m was used for the loss tangent of the sapphire and the conductivity of the OFHC, respectively, throughout the calculation. Detailed procedures for calculating Rs^{eff}'s and Q_0's are described elsewhere [5]. From the calculation, Q_0 appeared to decrease as s increases with Q_0's of 980000 and 810000 at s = 0 mm and 0.5 mm, respectively. Meanwhile, at 77 K, the calculated Q_0 appeared to increase between s = 0 mm and 0.5 mm with Q_0 ~ 300000 and 320000 at s = 0and 0.5 mm. Also, at 60 K, the calculated Q_0's are 582000 and 589000 at s = 0 mm and 0.2 mm, showing a slight increase in Q_0 as s increases.

As far as tuning of f_0 is concerned, we have no significant advantages in using the YBCO resonator with the tuning range comparable to the corresponding value for the OFHC resonator. However, Q_0 of the YBCO resonator appears to be improved significantly compared to the one of the OFHC resonator. For instance, between s = 0 mm and 1 mm, Q_0's are more than 300000 with variations of 0.94 GHz (~ 4.8 %) in f0 at 77 K for the YBCO resonator. Meanwhile there are variations of 5600 in Q_0 from 17000 to 11600 and 0. 98 GHz in f0 for the OFHC between s = 1 mm and 0 mm at T = 300 K. Our results are also compared with the observed results from tunable microstrip YBCO resonators based on BST or STO, where Q_0 of several hundreds at 80 K have been reported with the tuning range of about 4 % [2]. It is also noted that the YBCO resonator can be used in making a tunable oscillator with very low phase noise, considering the high Q_0 of the $TE_{01\delta}$ mode YBCO resonator and the relatively large frequency tuning range.

3-3. Rutile-loaded Cavity Resonator

A rutile-loaded cavity resonator was also prepared in this experiment, for which its microwave properties were measured at low temperatures. Fig. 6 shows Q_0 vs T data for the rutile-loaded resonator with the inset displaying its R_s vs T data. Q_0 appeared as high as 400000 at 35 K. Fig. 7 shows the dependence of the resonant frequencies for the sapphire-loaded and the rutile-loaded resonator. One thing to note in Fig. 7 is the increase of f0 of resonator using rurile as dielectric according to the temperature, which is in contrast with the observed f_0 vs T data for the sapphire-loaded resonator. This is attributed to significant decrease in the dielectric constant of rutile according to the temperature, which is opposite to what have been observed from most dielectric materials. For reference, the

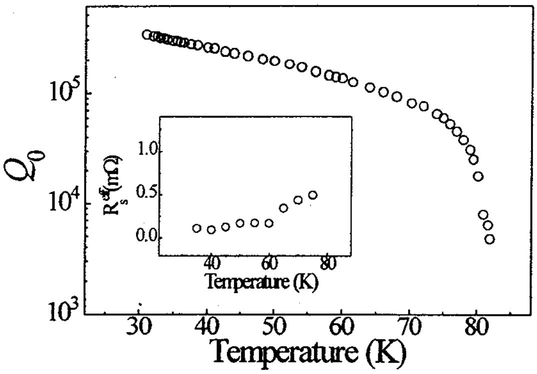

Fig. 7. Q_0 vs Temperature for the rutile-loaded resonator with YBCO endplates. Inset : The dependence of the effective surface resistance (R_s^{eff}) of the YBCO films

dielectric constant of sapphire is reported to be 9.4 and 9.32 at 300 K and 77 K, respectively. Meanwhile, the corresponding value for rutile is about 85 and 105 at 300 K and 77 K.

3-4. Property of Large HTS film Measured with Dielectric-loaded cavity Resonator

We used a double sided YBCO film on LAO for homogenity of large HTS film. Fig.8 shows that different positions of a sapphire for dielectric-loaded cavity resonator with YBCO films as endplates. Fixed top YBCO film, the Q_0 and f_0 was measured for different surface of bottom YBCO plate. In Fig. 9, it was obseved that relatively Q_0 of position a is much higher than position b and c about 200000 at 40 K . It

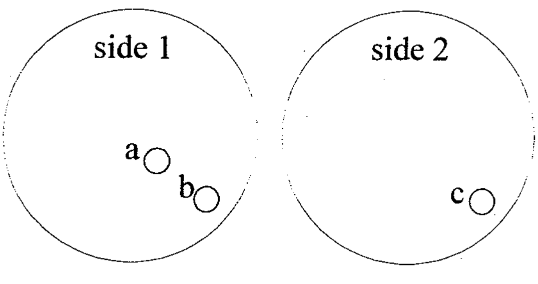

Fig. 8. Different positions of dielectric on a double sided YBCO film(bottom) measured using the sapphire-loaded resonator.

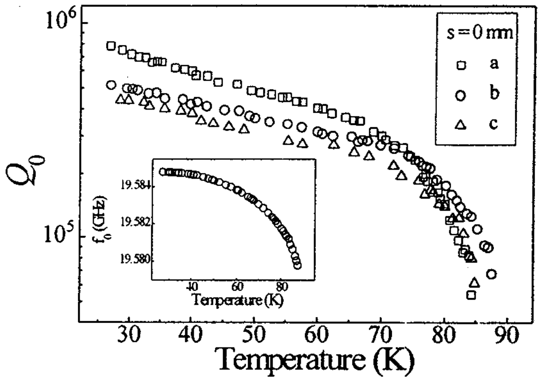

Fig. 9. Q_0 vs Temperature for different dielectric positions on a bottom plate of the sapphire-loaded resonator with YBCO/LAO(top) and YBCO/LAO/YBCO(bottom) films.

shows that Q_0 measured with sapphire-loaded cavity resonator for differenet position on a YBCO film enable to estimate a large YBCO film.

In summary, the $TE_{01\delta}$ mode sapphire-loaded resonators with YBCO endplates appeared to have Q_0 of ~ 1000000 and 400000 at 30 K and 77 K, respectively, with f_0 ~ 19.56 GHz. Also, the frequency tuning range of about 0.94 GHz was observed upon moving the top YBCO endplate of the cavity resonator by 1 mm. Q_0 vs the gap distance data appeared different between the YBCO resonator and the OFHC resonator, for which an explanation is provided based on the microwave losses from both the YBCO endplates and the surrounding OFHC walls. High Q_0 as well as the large tuning range observed from the YBCO resonator shows that the sapphire-loaded YBCO resonator can be used in making a tunable oscillator with very low phase noise.

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 $TE_{01\Omega}$ mode resonator enabled measurements of small

R_S of YBCO films, for which the measured value appeared as small as 260 $\mu\Omega$ at 77 K and 10 GHz.

References

[1] Y. Kobayashi, T. Imai and H. Kayano, Microwave measurement of temperaure and current dependences of surface impedance for high-TC superconductors IEEE Trans. on Microwave and Tech., 39, 1530-1538 (1991).

[2] J. Krupka, Surface resistance measurements of HTS films by means of saphire dielectric resonators, IEEE Trans. on Applied Supercond., 30, 3043-3048 (1993).

[3] R. Fletcher and J. Cook, Measurement of surface impedance versus temperature using a generalized sapphire resonator technique, Rev. Sci. Instrum., 65, 2658-2666 (1994).

[4] Z-Y. Shen, C. Wilker, P. Pang, W. L. Holstein, D. Face and D. J. Kauntz, High TC superconductor-sapphire mircowave resonator with extremely high Q-values up to 90 K, IEEE Trans. on Microwave Theory and Tech., 40, 2424-2432 (1992).

[5] J. Mazierska, Dielectirc resonator as a possible standard for characterization of high-TC superconducting film for microwave application, J. Supercond., 10, 73-84 (1997).

[6] Sang Young Lee, B. J. Soh, J. W. Ahn, J. Y. Cho, B. H. Park and C. S. Jung, V.B. Fedrov, A.G. Denisov, Y. H. Kim, T. S. Hahn. S. S. Choi, B. Oh and S. H. Moon, Use of a dielectric-loaded cylindrical cavity in measurements of the microwave surface resistances of high-TC superconducting thin films, IEEE Trans. on Applied Superconductivity, 7, 2013-2017 (1997).

[7] Sang Young Lee, H. J. Kwon, J. H. Lee, W. I. Yang, Jin Kook Kim, W. H. Lee and Jung Hur, "Microwave properties of tunable TE01 mode sapphire-loaded cavity resonators with YBa2Cu3O7- endplates", Supercond. Sci. Tech., in press (1999); see also Sang Young Lee, J. H. Kwon, J. H. Suh, J. H. Lee, Jung Hur, and V. B. Fedorov, "Effects of the finite HTS film thickness on the resonant frequency of the axially symmetric TE01 mode of a parallel plate resonator", IEEE Trans. on Applied Supercond., in press (1999).

[8] MicroStripes is a trademark of Kimberley Comunications Consultants, Ltd., in UK.

[9] See e.g., M.J. Lancaster, Passive Microwave Device Applications of Supperconductors, 1st ed., Cambridge, 136-141 (1997)