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An automated measurement system for the microwave surface resistance of high-T_C superconductor films

J. H. Lee, J. Lim, Junghun Lee and Sang Young Lee
Department of Physics, Konkuk University, Seoul 143-701, Korea

Abstract

A prototype for a highly sensitive, automated measurement system for the microwave surface resistance of high-T_C superconductor films was set up, and tested by measuring the microwave surface resistances of high-T_C $YBa_2Cu_3O_{7-\delta}$ (YBCO) films at the frequency of about 19.6 GHz and the temperature of 30 K ~ 90 K. An open-ended TE_{011} mode sapphire-loaded cylindrical cavity resonator was used as the measurement probe, where YBCO films were used as the endplates of the cylindrical cavity. The characteristics of the measurement system include functions to display the unloaded Q and the resonant frequency of the TE_{011} mode resonator as well as the microwave surface resistance of the YBCO films, all simultaneously as a function of temperature. Applicability of the measurement system for investigating the homogeneity in the microwave properties of large high-T_C superconductor films is discussed.

Keywords : automated system, sapphire-loaded cavity, high-T_C superconductor film, $YBa_2Cu_3O_{7-\delta}$, surface resistance

I. Introduction

It has been known that the properties of high-T_C superconductive (HTS) devices including filters and oscillators are superior to those of conventional devices and enable to take important roles in setting up the third generation mobile communication system (so called 'IMT-2000) and satellite communication systems [1]. Flexible use of available frequency bands and data transfer at a very high speed are regarded as the two most important aspects that can be realized by use of the HTS microwave devices, which are crucial for information and communication industries to provide better services to their customers. For instance, it has been reported that receiver front-ends with HTS filter are better in performance than the conventional ones with regard to the coverage area of each base station, quality of the signal as well as its immunity against interference signals [2].

The importance of HTS microwave devices has already been appreciated by many world-wide industrial companies, where many studies were performed to commercialize such devices. As a result, receiver front-ends with HTS filters for base-stations for mobile phone services or PCS are in the market places due to strong efforts by STI, Conductus and ISC. Also, in Korea, studies to commercialize receiver front-ends based on $YBa_2Cu_3O_{7-\delta}$ are currently under progress in LG [3]. Furthermore, other HTS devices including high-power filters for transmitter modules and oscillators with low phase noise are about to be commercialized [4], revealing that HTS microwave technologies are going to be a serious threat to the conventional technologies in the very near future.

Here it is noted that superiority of HTS microwave technologies to conventional ones are mostly attributed to the low surface resistance (R_S) of HTS materials in the microwave region with the typical R_S of YBCO films at 77 K less than 1/40 of that of oxygen-free high purity copper (OFHC) at 10 GHz, and less than 1/400 of that of OFHC at 2 GHz and 77 K [5]. In this regard, an efficient, accurate and reproducible measurement method for R_S of HTS films needs to be established, which is more so when it comes to controlling the homogeneity in the microwave properties of large HTS films with the diameter of more than 2 inches.

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

R_S of HTS films have been studied largely using three different methods including i) a method using a microstrip resonator [6, 7], ii) another one based on parallel plate resonator [8], and iii) the other based on dielectric-loaded cavity resonator [9-11] (henceforth called 'DR resonator'). The microstrip resonator method has been applied to making a measurement system by Wu et al. [12], who designed a system to measure the unloaded Q of the resonator automatically. Also, the parallel plate resonator method, originally suggested by Taber, has been known as a useful method to measure R_S with high sensitivity [13]. However, it is noted that, in using the microstrip resonator method, HTS films need to be patterned into the form of a microstrip prior to the measurements of R_S. It is also noted that it takes much time to measure R_S using the parallel plate resonator method, let alone the difficulties in coupling with the resonator during measurements, which makes it difficult to set up an automated measurement system for R_S. Compared with the other methods for measuring R_S, the DR resonator method has its merits because R_S can be measured with high sensitivity and can be used as a local probe to investigate the homogeneity of large HTS films. It is due to the extremely high Q of the DR resonator and the concentration of electromagnetic energy inside a dielectric with high permittivity. In using the DR resonator method for measurements of R_S, Q of TE_{011} mode was usually measured due to its large magnitude of Q, from which R_S could be calculated [14, 15]. However, since it takes time to collect data and analyze them for obtaining R_S, there were needs to develop some other measurement procedures for R_S which can be used to get R_S faster without sacrificing the measurement sensitivity.

Here we report on fabrication of an automated measurement system for R_S and its applicability for investigating the homogeneity in the R_S of large HTS films. A sapphire-loaded cavity resonator was used for this purpose. Usefulness and various functions of the automated measurement system are described.

II. Experimental

Figure 1 shows the diagram of an open-ended sapphire-loaded cavity resonator with YBCO endplates, where the sapphire rod is placed at the center of the cavity. Our measurement system uses the cavity resonator shown in Fig. 1 and equipped with a program that enables to collect and analyze data as well as to calculate R_S simultaneously. The dimensions of the sapphire rod are 5 mm x 5 mm for the diameter and height, respectively, with the diameter of the cavity of 15 mm. The gap between the sapphire rod and the top plate is set to 0.5 mm. The TE_{011} mode resonant frequency (f_0) of the resonator appeared to be about 19.6 GHz at temperatures of 30 - 90 K. More experimental details are described below.

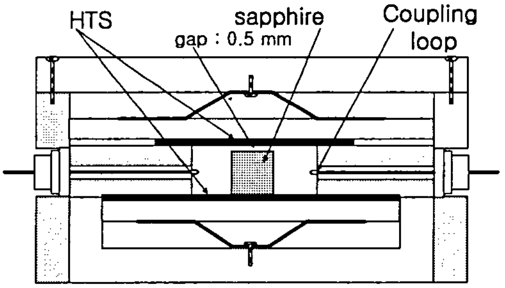


Fig. 1. A cross-sectional view of the open-ended sapphire-loaded cavity. Note the small gap between the sapphire rod and the top HTS film.

i) Measurement procedures for Q and R_S

The data acquisition program consists of a part for collecting raw data, a part for data fitting for Q and a part for calculating R_S. The raw data from the network analyzer are S_{21} values of the DR resonator, with each data set consisting of 801 data points. The data, collected by computer using the GPIB interface, were used to obtain Q from fitting of S_{21} data to the following equation [16].

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

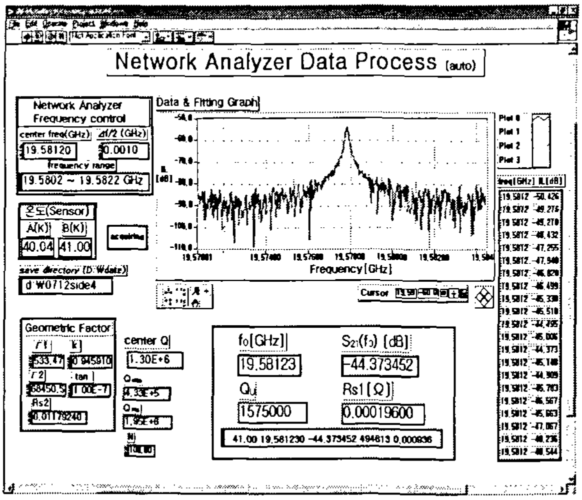
Here f and f_0 denote the measured and the resonant frequency, respectively, $\Delta(f) = 1 - \frac{f_0^2}{f^2}$, and Q_L, the loaded Q. During measurements, cares were taken to maintain the DR resonator weakly coupled to the input/output line, when $Q_L \sim Q_0$. Once we get Q_0, R_S of HTS films can be calculated using the following equation for the DR resonator with YBCO endplates, which is

$$\frac{1}{Q_0}=\frac{R_S^{YBCO}}{\Gamma_E}+\frac{R_S^{Cu}}{\Gamma_S}+k\tan\delta \qquad (2)$$

Here R_S^{YBCO} denotes the surface resistance of the YBCO films at the top and bottom of the cavity, R_S^{Cu}, the surface resistance of the cavity side wall made of OFHC, and Γ_E, Γ_S for the respective geometric factor related with the top and bottom endplates, and the cavity side wall. Also, k denotes the filling factor, i.e., the ratio of the stored energy inside the sapphire rod to that inside the whole cavity, and $\tan\delta$, the loss tangent of sapphire. It is noted that the geometric factors and the filling factor can be calculated using the electric and magnetic field distributions inside the cavity resonator, which are $\Gamma_E = 526\ \Omega$, $\Gamma_S = 68552\ \Omega$ and $k = 0.9463$. we used $\tan\delta = 10^{-6}$ for sapphire at 30 K – 90 K.

ii) Preparation of a measurement program for R_S

A commercial GPIB application software, called LabVIEW, was used in making the measurement program for R_S. It is noted that the same program can be prepared using high level languages such as C or BASIC. Fig. 2 shows some characteristics of our program, which include i) automatic variation of the measurement frequency span for locating the resonance peak at the center of the selected frequency interval regardless of the temperature change, ii) simultaneous display of S_{21} raw data and their fitted data, iii) functions to collect the temperature-dependent resonant frequency and the insertion loss, iv) functions to obtain Q from a fit to the raw data and to calculated R_S from the measured Q, v) functions to collect temperature-dependent Q and R_S up to the temperature very near to T_C, and vi) functions to display the temperature-dependent f_0, IL, Q, and R_S simultaneously on the same screen.



Network Analyzer Frequency control
center freq(GHz) 19.58120
Δf/2 (GHz) 0.0010
frequency range 19.5802 ~ 19.5822 GHz
온도(Sensor) A(K) 40.04 B(K) 41.00
save directory (D:Wdata) d:W0712side4
Geometric Factor
Γ1 533.47 k 0.945910
Γ2 68450.5 tan 1.00E-7
Rs2 0.01179240
center Q 1.30E+6
Qmin 4.33E+5
Qmax 1.95E+8
N 100.00
f0[GHz] 19.58123
S21(f0) [dB] -44.373452
QU 1575000
Rs1 [Ω] 0.00019600
41.00 19.581230 -44.373452 494613 0.000836

Fig. 2. A capture from the computer screen displaying the resonance peak, data for f_0 and IL, the fitted Q, and the calculated R_S.

III. Results and Discussion

Figure 3 shows the measured f_0, IL, and Q of the sapphire-loaded resonator as well as the surface resistance of the YBCO films used as the endplates of the resonator, which are simultaneously displayed as functions of the temperature. Since R_S of the HTS films can be measured at the same time with other parameters of the resonator, this method can be applied to investigate the homogeneity in R_S of a large HTS films in-situ. As a preliminary study, we investigated the homogeneity in R_S of a YBCO film with 1 x 1 inch^2 in size. Fig. 4 (a) shows each position of the sapphire rod on the YBCO film placed at the top of the cavity during each measurement, for which the resonator Q was measured. Later, R_S was calculated from the measured Q, with the calculated value meaning the average R_S of a part of the two YBCO films enclosed inside the top and the bottom of the cavity resonator. In Figs. 4(b) and 4(c), the temperature dependent Q of the resonator and the

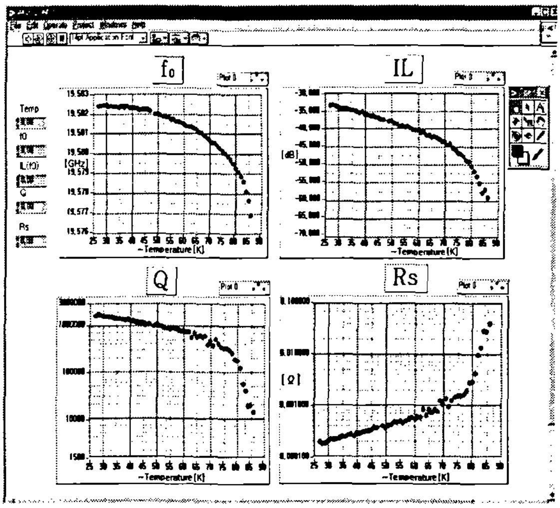


Fig. 3. A capture from the computer screen showing simultaneous display of temperature-dependent f_0, IL, Q and R_S.

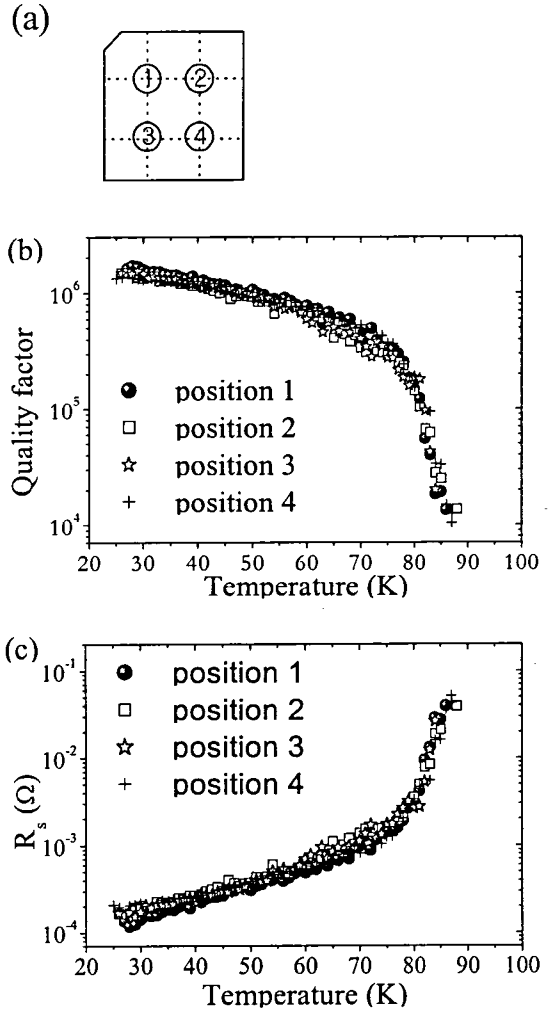


Fig. 4(a). Locations of the sapphire rod on the YBCO film with the number representing the order in which experiments were performed. (b) Q vs T data and (c) R_S vs T data at $f_0 \sim$ 19.6 GHz with the sapphire rod placed at various positions of 1 ~ 4 on the YBCO film at the top of the sapphire-loaded cavity.

average R_S of each numbered part on the YBCO film are shown. In the figure, the average R_S appeared to be 140 μΩ, 180 μΩ, 180 μΩ, 210 μΩ at 30 K, 510 μΩ, 560 μΩ, 610 μΩ, and 540 μΩ at 60 K and 1.7 mΩ, 1.8 mΩ, 2.0 mΩ, and 1.6 mΩ at 77 K at positions 1~4, respectively, at 19.6 GHz, showing about 20 % difference in R_S depending on the position on the YBCO film. Considering $R_S \propto f^2$, R_S of the YBCO film corresponds to 430 μΩ, 460 μΩ ,

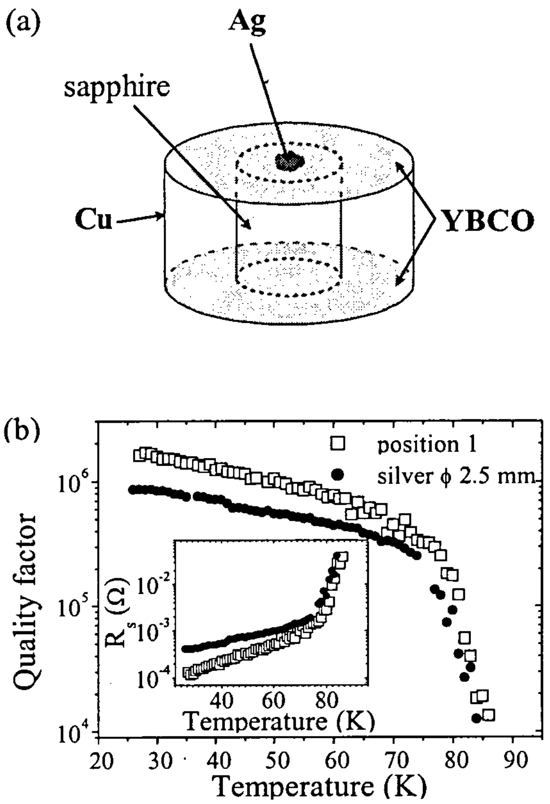


Fig. 5(a) A diagram with a YBCO film covered with disk-shaped Ag film placed at the top of the cavity. (b) Q vs T data of the TE_{011} mode sapphire-loaded resonator with the sapphire rod placed at position 1 of the YBCO film at the top of the cavity and 0.5 μm -thick Ag film with the diameter of 1 mm deposited at the center of position 1. Inset : R_S vs T data calculated from the measured Q. The resonant frequency was 19.6 GHz.

530 μΩ, 420 μΩ at 77 K at positions 1~4, respectively, at 10 GHz, The resonator Q with the sapphire rod placed at position 1 was also compared with that with 0.5 μm-thick Ag film deposited at the center of the position "1" of the top YBCO film. Fig. 5(a) shows a diagram with a YBCO film covered with disk-shaped Ag film placed at the top of the cavity. The diameter of the Ag film was 2.5 mm. From the measured TE_{011} mode Q, average R_S of the YBCO film at position 1 was also calculated. Figure 5(b) shows that the temperature dependence of the Q and R_S with the average R_S being 440μΩ, 1.0mΩ, and 3.4mΩ at 30 K, 60 K and 77 K, respectively, at 19.6 GHz, which were significantly larger than the R_S

without the Ag film. From the measured Q of the resonator with a Ag/YBCO endplate, we could calculated the effective surface resistance of the Ag/YBCO film. For the calculation, we used the following equation (3).

$$\frac{1}{Q_0} = \frac{R_S^{YBCO}}{\Gamma_1} + \frac{R_S^{Ag/YBCO}}{\Gamma_{Ag}} + \frac{R_S^{YBCO}}{\Gamma_2'} + \frac{R_S^{Cu}}{\Gamma_S} + k \tan\delta \quad (3)$$

Here Γ_1 (=1052 Ω), Γ_{Ag} (=129191 Ω), Γ_2' (=1061 Ω), and Γ_S (= 68552 Ω) denote the geometric factor associated with the bottom endplate, the Ag-deposited area at the top plate, the area at the top with pure YBCO and the side wall of the cavity, respectively. The calculated effective R_S of Ag/YBCO film ($R_S^{Ag/YBCO}$) was 2.60mΩ , 9.2 mΩ, and 11.8 mΩ at 30 K, 60 K, and 77 K with the values smaller than the theoretical R_S of Ag (R_S^{Ag}), which are 4.62 mΩ , 11.17 mΩ and 14.41 mΩ at 30 K, 60 K, and 77 K, respectively. The fact that Ag film is only 0.5 μm-thick and electromagnetic field can penetrate into the YBCO film covered by the Ag film explains why the calculated effective $R_S^{Ag/YBCO}$ is smaller than R_S^{Ag}

It is noted that our measurement system for R_S of HTS films can be easily upgraded to measure the homogeneity in the microwave properties of larger HTS films with the size of more than 2 inches. If a proper moving stage for large HTS films is prepared and can be computer-controlled, our measurement system would work as an automated measurement system for large HTS films, which can be very useful for controlling the quality of large HTS films.

IV. Summary

An automated measurement system for R_S of HTS films was set up with a sapphire-loaded cavity resonator with YBCO endplates and its usefulness was successfully tested by measurement of R_S of YBCO films. The measurement system made it possible to obtain R_S of HTS films very fast with high sensitivity, which are important to investigate the homogeneity in R_S of large HTS films prepared for microwave applications. The measurement system can be upgraded to an automated measurement system for large HTS films, that can be used for controlling the quality of large HTS films.

Acknowledgment

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