IEICE TRANS. ELECTRON., VOL.E85–C, NO.3 MARCH 2002

PAPER *Special Issue on Superconductive Electronics*

# Development of a Millimeter-Wave Coaxial Cable Measurement System at Cryogenic Temperature and Measurement of the Surface Resistance of High-$T_c$ Superconductor Films

**Toru HASHIMOTO**[†a)], ***Regular Member and*** **Yoshio KOBAYASHI**[†], ***Fellow***

**SUMMARY** A coaxial cable measurement system applicable up to 60 GHz in the cryogenic temperature is developed by using V-connectors. In this system, the fine location of coupling loop antennas can be adjusted by three-dimensional mechanical stages in the low temperature region. In order to verify usefulness of this system, the temperature dependence of surface resistance ($R_s$) of Y-Ba-Cu-O (YBCO) films was measured at 30 GHz by the two-dielectric resonator method using $\mathrm{TE}_{011}$- and $\mathrm{TE}_{013}$-mode sapphire rod resonators. The measured result of $R_s$ was 0.5 mΩ at 30 GHz and 20 K, which was 1/40, compared with those of copper plates.

***key words:*** *millimeter-wave, cryogenic temperatures, surface resistance, high-$T_c$ superconductors*

## 1. Introduction

Many high-$T_c$ superconductor (HTS) filters with low-loss and sharp skirt characteristics have been developed to be applied to mobile telecommunications and satellite communications in the microwave region [1]. However, in the millimeter-wave region, as far as we know, we cannot find any papers for HTS filters but for an amplifier in the cryogenic temperature [2]. Therefore, we developed a coaxial cable measurement system applicable up to 60 GHz in the cryogenic temperature to measure the surface resistance $R_s$ of HTS films and the characteristics of HTS filters.

This paper discusses usefulness of this system. The temperature dependence of $R_s$ of Y-Ba-Cu-O (YBCO) films is measured at 30 GHz by the two-dielectric resonator method using this system.

## 2. Automatic Measurement System

A block diagram of a coaxial cable measurement system applicable up to 60 GHz in the cryogenic temperature is shown in Fig. 1. In this system, HP-8510C Vector Network Analyzer up to 50 GHz is used. Moreover, it was found that this system using HP-8757D Scalar Network Analyzer was applicable up to 60 GHz. A photograph of this system is shown in Fig. 2. A sapphire rod resonator described in Sect. 3.1 is set on a cold head stage in the cryocooler and is connected to the analyzer, which is controlled by a Windows (R) computer through the GP-IB cable. A thermal sensor is attached

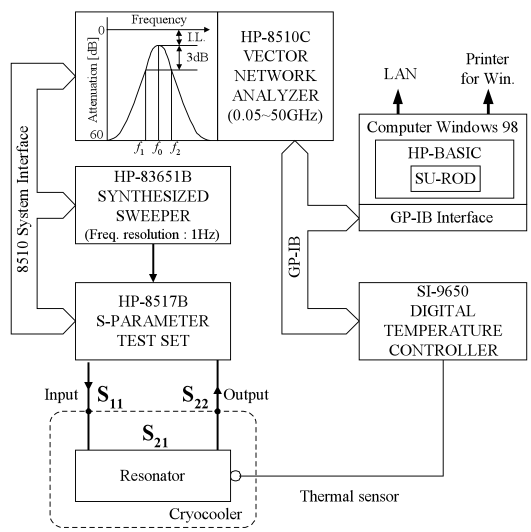


**Fig. 1** Automatic measurement system.


**Fig. 2** Photograph of measurement system.

Manuscript received July 31, 2001.
Manuscript revised September 19, 2001.
[†]The authors are with the Faculty of Engineering, Saitama University, Saitama-shi, 338-8570 Japan.
a) E-mail: toru@reso.ees.saitama-u.ac.jp

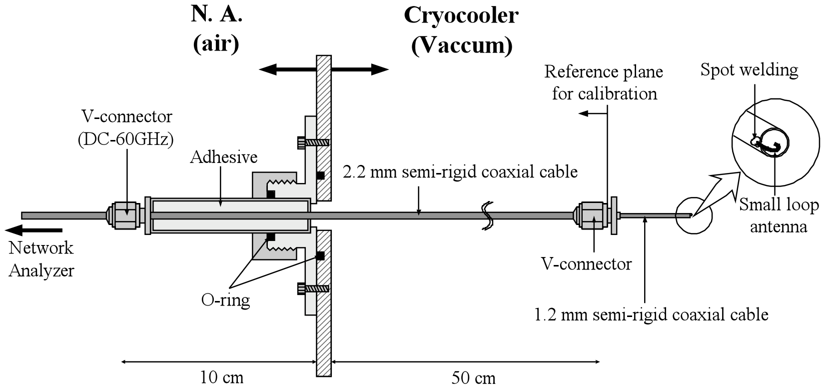


**Fig. 3** Hermetic structure of a coaxial cable.

on the resonator and a digital temperature controller is connected to the computer. Then, the temperature dependence of $R_s$ of HTS films is measured automatically by the computer. Advantages of this system will be described below.

(1) GM-type cryocooler

A GM-type cryocooler with low mechanical vibration (AISIN SEIKI Co., Ltd.), where the vibration is suppressed to 1/40, compared with conventional one of the same company, was used to prevent displacement of a sapphire rod due to mechanical vibration and to eliminate fixing of the rod by adhesive. In particular, this cryocooler was very useful to evaluate $R_s$ of a HTS film without damage by the image-type dielectric resonator method [3].

(2) V-connectors and small loop antennas

In order to apply this system to the millimeter-wave region, we adopted V-connectors applicable up to 60 GHz. Although a glass bead hermetic seal applicable up to 65 GHz is known [11], we could not apply it to the present system, where V-connectors are attached at both sides of a hermetic seal. Therefore, we developed a new hermetic seal structure shown in Fig. 3. The hermetic seal was accomplished successfully by fixing the middle of a 2.2 mm semi-rigid coaxial cable having V-connectors at both ends by adhesive and using an O-ring connector. The length of the outside-cable packed by adhesive was extended to 10 cm to prevent air-leaks which occurred through the inside of the coaxial cables due to the difference of thermal expansions between Cu outer conductors and PTFE in the coaxial cable.

Both of the excitation and the detection of the resonator are performed magnetically each by a small loop fabricated at the top of a 1.2 mm semi-rigid coaxial cable as shown in Fig. 4, which shows a photograph of the resonator structure indicated in Fig. 6. For the millimeter-wave measurement, a very small loop with the spot welding technique (WAKA Manufacturing Co., Ltd.), where the loop diameter is less than $\phi = 1.0$ mm, was adopted as shown in Fig. 5, compared with a loop for a 2.2 mm semi-rigid cable.

**Fig. 4** Photograph of measurement apparatus for 12 GHz.

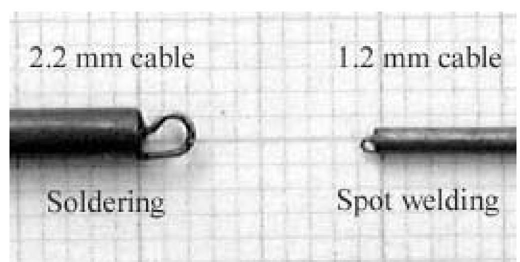


**Fig. 5** Photograph of small loop antenna.

(3) Adjustment mechanism in the low temperature

Fine adjustment of coupling strength between the resonator and the loop antenna is extremely severe in the millimeter-wave region. Therefore, an adjustment mechanism in the low temperature region was developed by using three-dimensional mechanical stages. It is important for the accurate measurement of an unloaded $Q$, $Q_u$ that the reflection coefficient $S_{11}$ and $S_{22}$ can be adjusted independently to be equal with each other, because $Q_u$ is calculated from Eq. (1) on the conditions of $S_{11} = S_{22}$ [4].

$$Q_u = \frac{Q_L}{1-a} \tag{1}$$

where

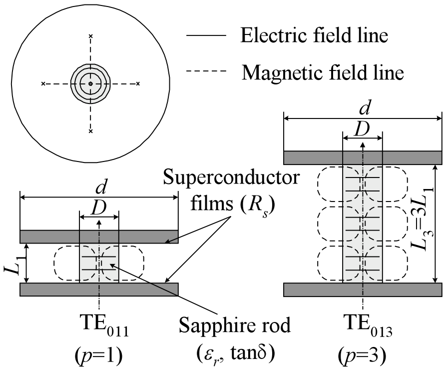


**Fig. 6** Resonator configurations in the two-dielectric resonator method.

$$Q_L = \frac{f_0}{f_2 - f_1} \quad \text{and} \quad a = 10^{-\frac{S_{21}\,(\mathrm{dB})}{20}} \tag{2}$$

Also, $Q_L$ is the loaded $Q$, $f_2 - f_1$ is a 3 dB bandwidth and $S_{21}$ (dB) is the transmission coefficient at the resonant frequency $f_0$.

## 3. Experiments

### 3.1 Measurement Principle of $R_s$ by the Two-Dielectric Resonator Method

In order to measure $R_s$ of HTS films, we use the two-dielectric resonator method, which is proposed as the standard measurement method of $R_s$ of HTS films at microwave frequencies in the IEC (International Electrotechnical Commission)/TC90/WG8 [4]–[8]. Figure 6 shows configurations of the resonators used in this method. A sapphire rod resonator for TE$_{01\mathrm{p}}$ mode ($p = 1$ or 3) having relative permittivity $\varepsilon_r$, loss tangent $\tan\delta$, diameter $D$ and length $L_p$ is placed between two parallel HTS films having $R_s$ and diameter $d$. The crystal $c$-axis of the sapphire rod with the uniaxial-anisotropic characteristic is along to the $z$-axis of the rod. On the basis of the rigorous analysis by the mode matching method, $\varepsilon_r$ of each rod can be calculated from the measured $f_0$ of each resonator. Then, $\tan\delta$ and $R_s$ can be calculated from the measured values of unloaded $Q$, $Q_{u1}$ for the TE$_{011}$ mode and $Q_{u3}$ for the TE$_{013}$ mode on the condition that two rods have the same $\tan\delta$ values [4], [9].

### 3.2 Measured Results of YBCO Film at 30 GHz

$R_s$ measurement at 30 GHz was performed to verify the usefulness of this measurement system. A TE$_{011}$ mode closed-type resonator [10] as shown in Fig. 4 was constructed by using a sapphire rod with $D = 5.48$ mm and $L_1 = 2.03$ mm ($\varepsilon_r = 9.3$, the coefficient thermal expansion $\tau_\alpha = 5.3$ ppm/K, Union Carbide Co.) and two YBCO films ($d = 51$ mm, THEVA Co.). Then, the sapphire rod was shielded by a copper (Cu) cylinder with diameter $d_c = 18.08$ mm and height $h = 2.04$ mm. The value of $d_c$ was determined so that the loss of the Cu cylinder was 1/100 lower than one of the YBCO films. Also, the value of $h$ was determined so that an air gap between the sapphire rod and the Cu cylinder was less than 5 $\mu$m at 20 K.

First, we took a calibration of this system by the full-2-ports method at room temperature using calibration kit HP 85056D. A reference plane of the calibration at each of the input and output ports is indicated in Fig. 3.

Second, taking the temperature dependence of the cable loss in the cryocooler into account, we performed a calibration of $S_{21}$. The whole cable loss including $\phi$1.2 mm through line coaxial cable of 10 cm decreased about 1.6 dB at 30 GHz by cooling down from 293 K to 20 K. As a result, $S_{21(\mathrm{meas.})}$ dB measured at $T$ K is corrected by

$$S_{21}\,(\mathrm{dB}) = S_{21(\mathrm{meas.})} + \Delta S_{21}(293 - T) \tag{3}$$

where a constant $\Delta S_{21} = 0.006$ dB/K was determined by assuming a linear temperature dependence of the cable loss.

Then, the resonator was set in the cryocooler and cooled down to 20 K. After the electric power of the cryocooler was turned off, the data of $f_0$ and $Q_u$ values could be taken in the computer automatically with the natural increase of every 1 K under the condition of no mechanical vibration. The coupling strength between the resonator and the loop antennas was adjusted finely to be $|S_{21}| = -30$ dB and $|S_{11}| = |S_{22}|$ at 20 K. Similarly, a TE$_{013}$ mode closed-type resonator was constructed by using a sapphire rod with $D = 5.48$ mm and $L_3 = 6.10$ mm, the same YBCO films as the TE$_{011}$ mode resonator and a Cu cylinder with $d_c = 18.08$ mm and $h = 6.11$ mm.

Figures 7(a) and (b) show the temperature dependences of measured $f_0$ and $Q_u$ values. Figure 7(c) shows the $\varepsilon_r$ values calculated using Fig. 7(a). Figures 7(d) and (e) show the $\tan\delta$ and $R_s$ values calculated using Figs. 7(a) to (c), respectively. For comparison, the measured $R_s$ values of copper plates are also indicated in Fig. 7(f). As a result, the measured results of these films were $R_s$ of 0.5 m$\Omega$ at 20 K, which were 1/40, compared with ones for Cu plates.

## 4. Discussions

In order to evaluate the precision of the $R_s$ measurement, the root mean square error of measured $R_s$ value $\Delta R_s$ is estimated, which is determined mainly from the following three error components [6]:

$$\Delta R_s^2 = \Delta R_s(Q_u)^2 + \Delta R_s(S)^2 + \Delta R_s(\Delta\tan\delta)^2 \tag{4}$$

where $\Delta R_s(Q_u)$ is an error due to the measured $Q_u$ value, $\Delta R_s(S)$ is an error due to the radiation loss,

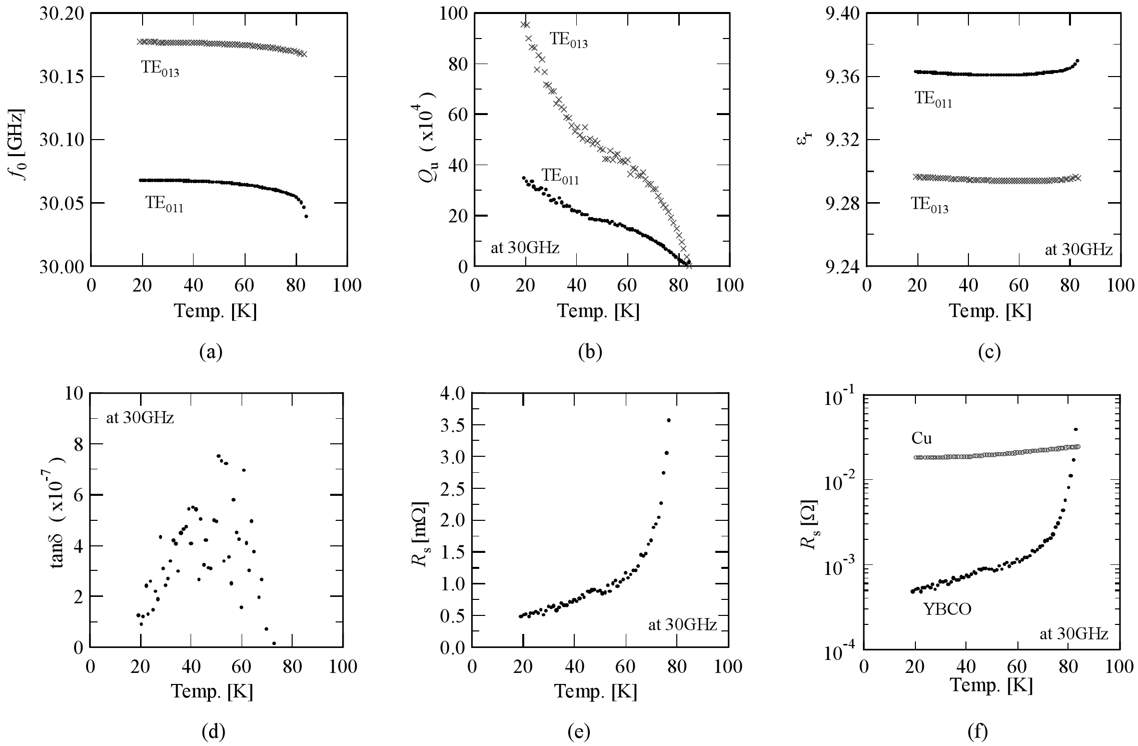


**Fig. 7** Measured results of YBCO film at 30 GHz. (a) $f_0$, (b) $Q_u$, (c) $\varepsilon_r$ of sapphire rods, (d) $\tan\delta$ of sapphire rods, (e) $R_s$ of YBCO films, (f) $R_s$ of YBCO films and Cu plates.

where $S = d/D$ is a diameter ratio, and $\Delta R_s$ ($\Delta \tan\delta$) is an error due to the difference of $\tan\delta$ between two rods. When the precision of the measured $Q_u$ value $\Delta Q_u/Q_u$ is 1 percent, the measurement precision $\Delta R_s/R_s$ has been estimated from the Eq. (4) to be 4 percents for $R_s$ of 0.6 m$\Omega$ at 30 GHz, where $\Delta R_s(Q_u)/R_s$ is 2 percents, $\Delta R_s(S)/R_s$ is 0.1 percents for $S = 3.6$ and $\Delta R_s(\Delta\tan\delta)/R_s$ is 3 percents, when $(\Delta\tan\delta)/\tan\delta$ is assumed to be 50 percents [8]. In the actual measurements, however, $\Delta Q_u/Q_u$ was 10 percents by inferior repeatability of the resonator setting. As a result, $\Delta R_s/R_s$ was estimated to be 17 percents, which was comparable to $\Delta R_s/R_s$ of 20 percents obtained from the round robin test of $R_s$ performed at 12 GHz in the IEC/TC90/WG8.

## 5. Conclusions

The measurement system applicable up to 60 GHz in the cryogenic temperature was developed. It was verified that the millimeter-wave measurement system using the coaxial cable was useful to measure the temperature dependence of $R_s$. In the future, we will discuss for the improvement of the measurement precision of $Q_u$.

## Acknowledgments

The authors would like to thank M. Kato for resonator fabrications and AISIN SEIKI Co., Ltd. for cooperative association under development of the equipment.

### References

[1] "Special issue on the microwave and millimeter wave applications of high temperature superconductivity," IEEE Trans. Microwave Theory & Tech., vol.44, no.7, pp.1193–1392, July 1996.

[2] J.M. Tanskanen, P. Kangaslahti, H. Ahtola, T. Karttaavi, M. Lahdes, J. Varis, and J. Tuovien, "Cryogenic indium-phosphide HEMT low-noise amplifiers at V-band," IEEE Trans. Microwave Theory & Tech., vol.48, no.7, pp.1283–1286, July 2000.

[3] Y. Kobayashi and T. Hashimoto, "Design of an image-type dielectric resonator to measure surface resistance of a high-$T_c$ superconductor film," IEEE MTT-S Int. Microwave Symp. Dig., pp.495–498, 2001.

[4] Y. Kobayashi and M. Katoh, "Microwave measurement of dielectric properties of low-loss materials by the dielectric rod resonator method," IEEE Trans. Microwave Theory & Tech., vol.MTT-33, no.7, pp.586–592, July 1985.

[5] Y. Kobayashi, T. Imai, and H. Kayano, "Microwave measurement of temperature and current dependence of surface impedance for high-$T_c$ superconductors," IEEE Trans. Microwave Theory & Tech., vol.39, no.9, pp.1530–1538, 1991.

[6] H. Yoshikawa, S. Okajima, and Y. Kobayashi, "Comparison between BMT ceramic one-resonator method to measure surface resistance of YBCO films," Asia-Pacific Microwave Conference Proc., pp.1083–1086, 1998.

[7] Y. Kobayashi and H. Yoshikawa, "Microwave measurements of surface impedance of high-$T_c$ superconductors using two modes in a dielectric rod resonator," IEEE Trans. Mi-

crowave Theory & Tech., vol.46, no.12, pp.2524–2530, 1998.
[8] Y. Kobayashi, H. Yoshikawa, and T. Hashimoto, "Frequency dependence of measurement precision in two dielectric resonator method for estimating surface resistance of high-$T_c$ superconductor films," Asia-Pacific Microwave Conference, pp.1564–1567, 2000.
[9] Y. Kobayashi and T. Senju, "Resonant modes in shielded uniaxial anisotropic dielectric rod resonators," IEEE Trans. Microwave Theory & Tech., vol.41, no.12, pp.2198–2205, 1993.
[10] T. Hashimoto and Y. Kobayashi, "Development of measurement apparatus for surface resistance of high-$T_c$ superconducting thin films," IEICE Technical Report, MW 2000-158, Dec. 2000.
[11] "Precision RF & microwave components/the industry leader for high frequency components," Anritsu Catalog 2001 edition, pp.9–12.

**Toru Hashimoto** was born in Tochigi, Japan on April 17, 1976. He received the B.E. and M.E. degrees in electrical engineering from Saitama University, Saitama, Japan, in 1999 and 2001, respectively. Now, he is a doctor course student at the same university. His current main interests include measurements and theory of microwave and millimeter-wave properties of high-$T_c$ superconductors. Mr. Hashimoto is an associate member of the Institute of Electronics, Information and Communication Engineers of Japan. Also, he is a student member of the Institute of Electrical and Electronics Engineers, Inc.

**Yoshio Kobayashi** was born in Japan on July 4, 1939. He received the B.E., M.E., and D.Eng. degrees in electrical engineering from Tokyo Metropolitan University, Tokyo, Japan, in 1963, 1965, and 1982, respectively. Since 1965, he has been with Saitama University, Saitama, Japan. He is now a professor at the same university. His current research interests are in dielectric resonators and filters, measurements of low-loss dielectric and high-temperature superconductive (HTS) materials, and HTS filters, in microwave and millimeter wave region. He served as the Chair of the Technical Group on Microwaves, IEICE, from 1993 to 1994, as the Chair of the Technical Group of Microwave Simulators, IEICE, from 1995 to 1997, as the Chair of Technical Committee on Millimeter-wave Communications and Sensing, IEE Japan, from 1993 to 1995, as the Chair of Steering Committee, 1998 Asia Pacific Microwave Conference (APMC'98) held in Yokohama, as the Chair of the National Committee of APMC, IEICE from 1999 to 2000, and as the Chair of the IEEE MTT-S Tokyo Chapter from 1995 to 1996. He also serves as a member of the National Committee of IEC TC49 since 1991, the Chair of the National Committee of IEC TC49 WG10 since 1999 and a member of the National Committee of IEC TC90 WG8 since 1997. Prof. Kobayashi received the Inoue Harushige Award on "Dielectric filters for mobile communication base stations" in 1995. He is a Fellow of IEEE and a member of IEE Japan.