INVITED PAPER *Special Section on Measurement Technologies for Microwave Materials, Devices and Circuits*

Standardization of Measurement Methods of Low-Loss Dielectrics and High-Temperature Superconducting Films

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SUMMARY The present state of IEC and JIS standards is reviewed on measurement methods of low-loss dielectric and high-tempera-ture superconductor (HTS) materials in the microwave and millimeter wave range. Four resonance methods are discussed actually, that is, a two-dielectric resonator method for dielectric rod measurements, a two-sapphire resonator method for HTS film measurements, a cavity resonator method for microwave measurements of dielectric plates and a cutoff circular waveguide method for millimeter wave measurements of dielectric plates. These methods realize the high accuracy sufficient for measurements of temperature dependence of material properties.

key words: *microwave, millimeter wave, standardization, low-loss dielectric, high-temperature superconductor*

1. Introduction

In order to develop new materials and to design passive and active circuits in microwave and millimeter wave region, standardization on measurement methods of material properties increases the importance in the globalization of economy.

It is well known that the measurement methods are classified into a guided wave method and a resonance method. In the guided wave method, a dielectric test sample is placed in a waveguide such as a rectangular waveguide or a coaxial line. The values of the relative permittivity ε_r and the loss tangent $\tan\delta$ are determined from the transmission or reflection coefficients measured. This method is commonly used to measure the frequency dependences of ε_r and $\tan\delta$. However this method has a disadvantage, that is, air gaps between the conductor and the sample affects the measurement adversely.

In the resonance method, on the other hand, the sample is placed in a cavity. The values of ε_r and $\tan\delta$ are determined from the resonant frequency and the unloaded Q measured. This method is available for accurate measurements of low-loss materials, even of high ε_r materials, because a resonant mode, which has not the electric field on the conductor surface, is used and the air-gap effect can be eliminated. Thus we can measure the temperature dependences accurately, but must prepare cavities and samples of different sizes in the frequency dependence measurements.

In this paper, the present state of the IEC (International Electrotechnical Commission) and JIS (Japanese Industrial Standards) standards is reviewed on four resonance methods; that is, a two-dielectric resonator method to evaluate dielectric rod samples, a two-sapphire resonator method to evaluate the surface resistance of high-temperature superconducting films, a cavity resonator method to evaluate dielectric plate samples in the microwave range and a cutoff circular waveguide method to evaluate dielectric plate samples in the millimeter wave range.

In the practical use, the high accuracy in these methods can be achieved by a computer-aided measurement based on a rigorous field analysis and the high speed treatment can be realized by an automatic measurement system controlled with a personal computer.

2. Two-Dielectric Resonator Method

In 1960, a novel method to measure ε_r and $\tan\delta$ of a dielectric rod in the millimeter-wave region was proposed by B.W. Hakki and P.D. Coleman [1], which is well-known as the Hakki-Coleman method.

In this method a dielectric rod resonator shown in Fig. 1(a) is used, where a dielectric rod having diameter D and length L is placed in the center between two parallel copper plates having the same values of surface resistance R_s, which is expressed by $R_s = (\omega\mu/2\sigma)^{1/2}$ where $\sigma = \sigma_0\sigma_r$, $\sigma_0 = 58 \times 10^6$ (S/m) is the conductivity of the standard copper, σ_r is the relative conductivity, and μ is the permeability of copper. A circularly-symmetric TE_0 mode is used to avoid an air-gap effect between the end plates and the rod. The resonator is excited by a rectangular waveguide as a reaction type cavity. The ε_r value of the rod is calcu-

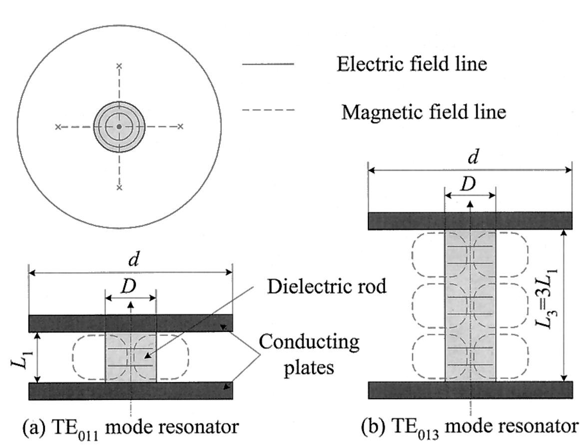

Fig. 1 Two-dielectric resonator method.

Manuscript received January zz, 2003.
Manuscript revised January zz, 2003.
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lated from f_0 measured for the TE_{011} mode. The $\tan\delta$ value is calculated from the measured Q_u on the assumption of $\sigma_r = 100\%$ for copper. As a result, this $\tan\delta$ value is higher than a true value because the actual σ_r value is usually less than 100% due to the influence of oxidization and roughness on a copper surface. This method was applied also to high ε_r measurements by W.E. Courtney [2], where the resonator was excited electrically by monopole semi-rigid coaxial cables as a transmission type cavity.

In order to evaluate $\tan\delta$ and R_s separately and accurately, a two-dielectric resonator method was proposed by Y. Kobayashi, et al. [3], [4]. In this method, two dielectric rods having the same diameter D are used, where a short length L_1 is for a TE_{011} mode resonator and a long length L_3=3L_1 is for a TE_{013} mode resonator, as shown in Fig. 1. A stable and fine control of the excitation due to a magnetic coupling can be realized by using a small loop fabricated at the top of a semi-rigid coaxial cable as shown in Fig. 2 [3], [4]. Also, mode charts of the dielectric resonator including all resonance modes were calculated on the basis of the rigorous analysis using the mode matching techniques [5]. They are useful for precise resonator designs and the mode identification in the measurement.

High accuracy of this method was verified by the round robin tests [6], which were performed by 10 groups in Japan coordinated by Japan Fine Ceramics Association (JFCA) and funded by the Ministry of International Trade and Industry of Japan. Based on this result, a Japanese draft for JIS was prepared and this method was established as JIS in 1996 [7]. In the same time, an English draft for IEC was prepared as a part of activities of the National Committee of IEC/ TC49/ WG10 and this method was established also as the IEC standard in 1999 [8].

Recently, another two-dielectric resonator method was proposed to apply it in the millimeter-wave range by A. Nakayama, et al. [9]. In this method dielectric resonators are excited by NRD-guides. An IEC draft for this method is prepared presently by the IEC/ TC49/ WG10 National Committee, together with one for the cutoff circular waveguide method described in Sect. 5.

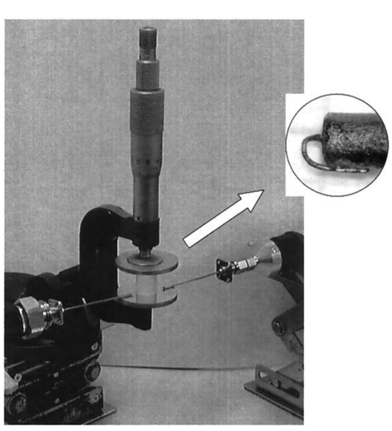

Fig. 2 Measurement apparatus.

3. Two-Sapphire Resonator Method for Surface Resistance Measurements

The two-dielectric resonator method using two ceramic rods was applied to R_s measurements of high-temperature superconductor (HTS) bulk plates, where the temperature dependence was measured every 1 K by an automatic measurement system with a personal computer [10]. For HTS films having low R_s values such as 0.1 mΩ at 10 GHz, however, low-loss sapphire rod resonators were used instead of ceramic rods with higher $\tan\delta$ values [11]. It will be called a two-sapphire resonator method.

On the other hand, the Hakki-Coleman method using a sapphire rod has been applied also to R_s measurements of HTS films on the assumption of $\tan\delta$=0 because of low loss characteristics of sapphire or $LaAlO_3$ [12]–[14]. Recently it was reported that R_s of 0.1 mΩ measured at 12 GHz by the Hakki-Coleman method includes the error of 4%, compared with one measured by the two-sapphire resonator method [15].

In 1996, the National Committee of IEC/ TC90/ WG8 was organized to discuss the R_s measurement methods by the IEC/ TC90 Superconductivity Committee (Office: International Superconductivity Technology Center, ISTEC). The WG8 National Committee adopted the two-sapphire resonator method as a most suitable method for R_s measurements of HTS films. Then the National Technical Working Group was organized by Electrotechnical Laboratory to perform the round robin tests and prepare an IEC draft based on this result. It was established as the IEC standard in 2001 [16].

In this standard, resonator structures of three types have been proposed, that is, an open-type, a cavity-type and a

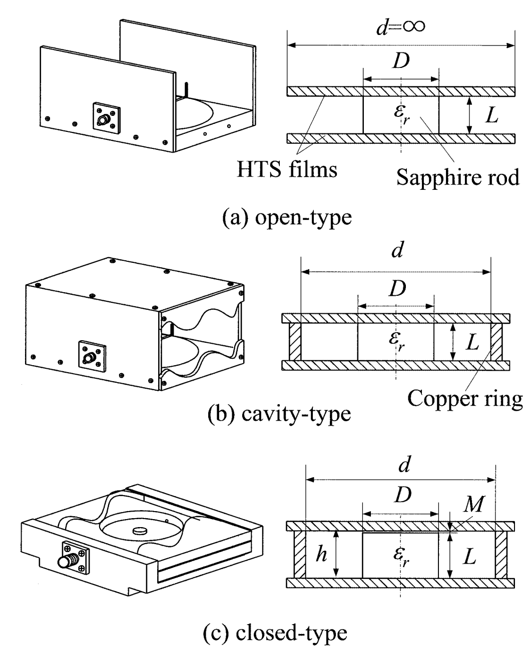

Fig. 3 Two-sapphire resonator method.

closed-type, as shown in Fig. 3. Recently, precise designs for these resonator structures were performed theoretically and experimentally [15], [17]. In addition, a novel measurement technique of R_s was proposed by T. Hashimoto and Y. Kobayashi [18]–[20]. In this method, R_s measurements at 3 different frequencies can be realized by using 4 resonant modes in a sapphire resonator. This method also can be expected as one of prospective measurement methods.

4. Cavity Resonator Method for Microwave Measurements of Dielectric Plates

In 1956, a resonance method using a circular cavity was proposed to measure accurate complex permittivity of a dielectric circular disk by S. Saito and K. Kurokawa [21]. In this method a circular disk sample is placed coaxially into a TE_{011} mode circular cavity. The TE_{011} mode having only the electric field component tangential to the plane of the disk is used to measure ε_r and $\tan\delta$ tangential to the plane. However, it is not easy to set the sample in the cavity, if a disk is thin.

In order to fix a plate sample in a cavity easily and measure any size of the sample nondestructively, a cavity resonator method was proposed by Y. Kobayashi and J. Sato [22]. In this method a circular cavity with diameter D and height H is cut into two halves in the middle of the height, as shown in Fig. 4. A dielectric plate with thickness t is placed between these two halves and clamped by three clips. A fringing effect at the plate-cavity interface is evaluated accurately from the rigorous analysis based on the Ritz-Galerkin method. Mode charts presented in [23] are useful to identify the TE_{011} mode and the other resonance modes. As a result, the values of ε_r and $\tan\delta$ can be obtained accurately from the measured values of f_0 and Q_u for the TE_{011} mode. Moreover, an automatic measurement system is useful to measure their temperature dependence [23]–[25].

High accuracy of the cavity resonator method was verified by the round robin test and the JIS draft was prepared by Session 8 Subcommittee, one of 10 sub-committees for measurement standardization organized by JFCA during 1995 to 1998. It was established as the JIS standard in 2002 [26].

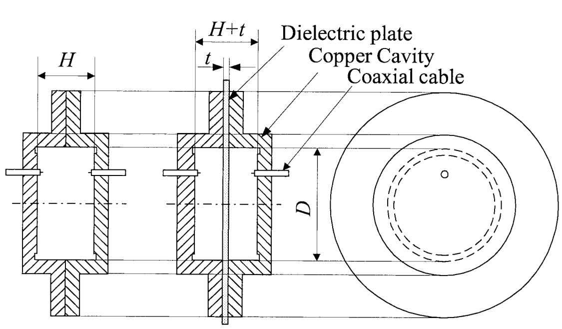

Fig. 4 Cavity resonator method.

5. Cutoff Circular Waveguide Method for Millimeter-Wave Measurements of Dielectric Plates

In 1966, a TE_{011} mode circular waveguide method was proposed by S.B. Cohn and K.C. Kelly [27]. In this method a circular disk sample is inserted in a TE_{01} mode cutoff circular waveguide. This method with a waveguide excitation was applied to the millimeter wave measurement [28]. A novel resonator structure shown in Fig. 5 was proposed by Y. Kobayashi and J. Sato [22], where a dielectric plate sample was placed between two copper circular cylinders. A similar method was presented independently by G. Kent [29], although it was found that an equation for ε_r correction of the fringe effect presented by Kent is not correct [30]. This structure is suitable in the millimeter wave range, because cavities are too small to machine over 40 GHz. The temperature dependence can be measured by the automatic measurement system [31]–[33]. This method is called a cutoff circular waveguide method.

An IEC draft for this method is presently prepared by the IEC/ TC49/ WG10 National Committee.

6. Measurement Precisions and Application Scopes

The measurement precisions and application scopes of the measurement methods described above are summarized in Tables 1 and 2.

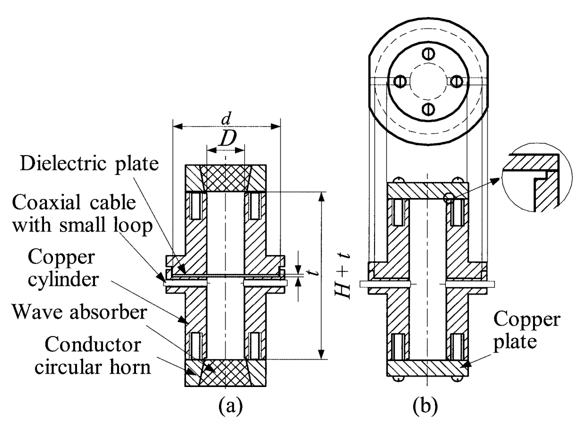

Fig. 5 Cutoff circular waveguide method. (a) Circular cylindrical resonator clamping a dielectric plate. (b) Circular empty cavity.

Table 1 Measurement precisions of complex permittivity measurements.

Methods	f_0 (GHz)	ε_r $\frac{\Delta\varepsilon_r}{\varepsilon_r}$(%)	tanδ $\frac{\Delta\tan\delta}{\tan\delta}$(%)
Two-dielectric resonator method	2∼40	2∼1000 ±0.2∼0.5	10^{-3}∼10^{-7} ±5∼20
Cavity resonator method	2∼40	1.1∼50 ±0.2∼0.5	10^{-3}∼10^{-6} ±5∼10
Cutoff circular waveguide method	30∼100	1.1∼50 ±0.2∼1.0	10^{-3}∼10^{-6} ±5∼10

Table 2 Measurement precisions of R_s measurements.

Method	f_0 (GHz)	R_s (mΩ) at 12 GHz	$\frac{\Delta R_s}{R_s}$(%)
Hakki-Coleman method	5~30	> 0.1	±10~50
Two-sapphire resonator method	10~30	> 0.06	< ±10

7. Conclusions

The present state of IEC and JIS standards was reviewed on four resonance methods to measure the complex permittivity of dielectric materials and R_s of HTS. A similar report in Japanese has been given in [34]. These standards are needed to be revised every 5 years. Recently the National Committee of IEC/SC46F was organized by the IEICE Standard Activities, to promote the IEC standardization of microwave devices.

Acknowledgments

The author would like to thank Mr. T. Hashimoto who is a Dr. course student in Saitama University, for assisting the preparation of the manuscript.

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