INTERNATIONAL STANDARD

IEC 61788-7

First edition
2002-01

Superconductivity –

Part 7: Electronic characteristic measurements – Surface resistance of superconductors at microwave frequencies

Supraconductivité –

Partie 7:
Mesures des caractéristiques électroniques –
Résistance de surface des supraconducteurs aux hyperfréquences

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

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FOREWORD

1) The IEC (International Electrotechnical Commission) is a worldwide organization for standardization comprising all national electrotechnical committees (IEC National Committees). The object of the IEC is to promote international co-operation on all questions concerning standardization in the electrical and electronic fields. To this end and in addition to other activities, the IEC publishes International Standards. Their preparation is entrusted to technical committees; any IEC National Committee interested in the subject dealt with may participate in this preparatory work. International, governmental and non-governmental organizations liaising with the IEC also participate in this preparation. The IEC collaborates closely with the International Organization for Standardization (ISO) in accordance with conditions determined by agreement between the two organizations.

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International Standard IEC 61788-7 has been prepared by IEC technical committee 90: Superconductivity.

The text of this standard is based on the following documents:

FDIS	Report on voting
90/111/FDIS	90/117/RVD

Full information on the voting for the approval of this standard can be found in the report on voting indicated in the above table.

This publication has been drafted in accordance with the ISO/IEC Directives.

Annex A is for information only.

The committee has decided that the contents of this publication will remain unchanged until 2006. At this date, the publication will be

- reconfirmed;
- withdrawn;
- replaced by a revised edition, or
- amended.

A bilingual version of this standard may be issued at a later date.

INTRODUCTION

Since the discovery of some Perovskite-type Cu-containing oxides, extensive R & D work on high-temperature oxide superconductors has been, and is being, made worldwide, and its application to high-field magnet machines, low-loss power transmission, electronics and many other technologies is in progress.

In various fields of electronics, especially in telecommunication fields, microwave passive devices such as filters using oxide superconductors are being developed and are undergoing on-site testing [1,2] [1].

Superconductor materials for microwave resonators, filters, antenna and delay lines have the advantage of very low loss characteristics. Knowledge of this parameter is of primary importance for the development of new materials on the supplier side and for the design of superconductor microwave components on the customer side. The parameters of superconductor materials needed for the design of microwave components are the surface resistance R_S and the temperature dependence of the surface resistance.

Recent advances in high Tc superconductor (HTS) thin films with R_S several orders of magnitude lower than that of normal metals have increased the need for a reliable characterization technique to measure this property [3,4]. Traditionally, the R_S of Nb or any other low temperature superconducting material was measured by first fabricating an entire three dimensional resonant cavity and then measuring its Q-value. The R_S could be calculated by solving the EM field distribution inside the cavity. Another technique involves placing a small sample inside a larger cavity. This technique has many forms but usually involves the uncertainty introduced by extracting the loss contribution due to the HTS films from the experimentally measured total loss of the cavity.

The best HTS samples are epitaxial films grown on flat crystalline substrates and no high quality films have been grown on any curved surface so far. What is needed is a technique that: can use these small flat samples; requires no sample preparation; does not damage or change the film; is highly repeatable; has great sensitivity (down to 1/1 000th the R_S of copper); has great dynamic range (up to the R_S of copper); can reach high internal powers with only modest input powers; and has broad temperature coverage (4,2 K to 150 K).

The dielectric resonator method is selected among several methods [5,6,7] to determine the surface resistance at microwave frequencies because it is considered to be the most popular and practical at present. Especially, the sapphire resonator is an excellent tool for measuring the R_S of HTS materials [8].

The test method given in this standard can be also applied to other superconductor bulk plates including low Tc material.

This standard is intended to provide an appropriate and agreeable technical base for the time being to engineers working in the fields of electronics and superconductivity technology.

The test method covered in this standard is based on the VAMAS (Versailles Project on Advanced Materials and Standards) pre-standardization work on the thin film properties of superconductors.

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[1] Numbers in brackets refer to the bibliography.

SUPERCONDUCTIVITY –

Part 7: Electronic characteristic measurements – Surface resistance of superconductors at microwave frequencies

1 Scope

This part of IEC 61788 describes measurement of the surface resistance of superconductors at microwave frequencies by the standard two-resonator method. The object of measurement is the temperature dependence of R_s at the resonant frequency.

The applicable measurement range of surface resistances for this method is as follows:

- – Frequency: 8 GHz < f < 30 GHz
- – Measurement resolution: 0,01 mΩ at 10 GHz

The surface resistance data at the measured frequency, and that scaled to 10 GHz, assuming the f^2 rule (f < 30 GHz) for comparison, shall be reported.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60050-815, *International Electrotechnical Vocabulary – Part 815: Superconductivity*

3 Terms and definitions

For the purposes of this standard, the definitions given in IEC 60050-815 apply.

In general, surface impedance Z_s for conductors, including superconductors, is defined as the ratio of the electric field E_t to the magnetic field H_t, tangential to a conductor surface:

$$Z_s = E_t / H_t = R_s + jX_s$$

where R_s is the surface resistance and X_s is the surface reactance.

4 Requirements

The surface resistance R_s of a superconductor film shall be measured by applying a microwave signal to a dielectric resonator with the superconductor film specimen and then measuring the attenuation of the resonator at each frequency. The frequency shall be swept around the resonant frequency as the centre, and the attenuation – frequency characteristics shall be recorded to obtain Q-value, which corresponds to the loss.

The target precision of this method is a coefficient of variation (standard deviation divided by the average of the surface resistance determinations) that is less than 20 % for the measurement temperature range from 30 K to 80 K.

It is the responsibility of the user of this standard to consult and establish appropriate safety and health practices and to determine the applicability of regulatory limitations prior to use.

Hazards exist in this type of measurement. The use of a cryogenic system is essential to cool the superconductors to allow transition into the superconducting state. Direct contact of skin with cold apparatus components can cause immediate freezing, as can direct contact with a spilled cryogen. The use of an r.f.-generator is also essential to measure high-frequency properties of materials. If its power is too high, direct contact to human bodies can cause an immediate burn.

5 Theory and calculation equations

Figure 1 shows the configuration of the TE_{0mp} mode resonator, which is used to eliminate the air-gap effects. A cylindrical dielectric rod with diameter, d, and height, h, is short-circuited at both ends by surfaces of two parallel superconductor films deposited on dielectric substrates with diameter, d', thus constituting a resonator. These superconductor films are required to have the same value of R_s. The value of R_s is calculated from the measured resonant frequency f_0 and unloaded quality factor Q_u for the TE_{0mp} resonance mode. When the two superconductor films have different values of R_s, the measured R_s value corresponds to the average value of these two films.

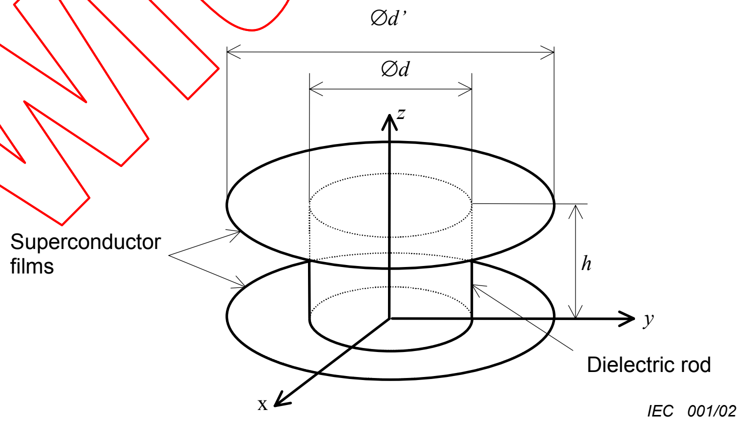

Figure 1 – Configuration of a cylindrical dielectric rod resonator short-circuited at both ends by two parallel superconductor films deposited on dielectric substrates

The value of R_s is given by

$$R_s = \frac{1}{B}\left(\frac{A}{Q_u} - \tan\delta\right) \tag{1}$$

where

$$A = 1 + \frac{W}{\varepsilon'} \tag{2}$$

$$B = p^2\left(\frac{\lambda_0}{2h}\right)^3 \frac{1+W}{30\pi^2\varepsilon'}, \quad p = 1,2,\cdots, \tag{3}$$

$$\lambda_0 = \frac{c}{f_0} \tag{4}$$

$$W = \frac{J_1^2(u)}{K_1^2(v)} \frac{K_0(v)K_2(v) - K_1^2(v)}{J_1^2(u) - J_0(u)J_2(u)} \tag{5}$$

$$v^2 = \left(\frac{\pi d}{\lambda_0}\right)^2\left[\left(\frac{p\lambda_0}{2h}\right)^2 - 1\right] \tag{6}$$

$$u\frac{J_0(u)}{J_1(u)} = -v\frac{K_0(v)}{K_1(v)} \tag{7}$$

In equations (1) and (2), ε' and $\tan\delta$ are the relative permittivity and the loss factor of the dielectric rod, respectively. In equations (3) and (4), λ_0 is the free space resonant wavelength, and c is the velocity of light in a vacuum ($c = 2{,}9979 \times 10^8$ m/s). The function W/ε' equals the ratio of electric-field energy stored outside to that stored inside the dielectric rod. If all of the electric field is concentrated inside the dielectric rod, the value W equals zero. The value u^2 is given by the transcendental equation (7) using the value of v^2, where $J_n(u)$ is the Bessel function of the first kind and $K_n(v)$ is the modified Bessel function of the second kind, respectively. For any value of v, the m-th solution u exists between u_{0m} and u_{1m}, where $J_0(u_{0m}) = 0$ and $J_1(u_{1m}) = 0$. The first solution (m = 1), which is used for easy mode identification, is shown in figure 2 by curve (A). The computed result of the W-v relation for m = 1 of TE_{0mp} resonance mode is shown in figure 2 by curve (B).

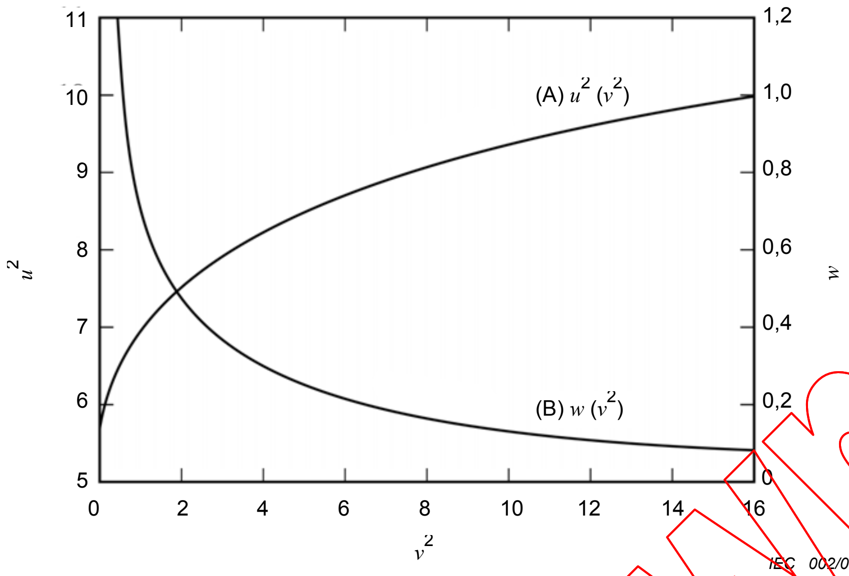

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Figure 2 – Computed results of the u-v and W-v relations for TE$_{01p}$ mode

The value of ε' is given by

$$\varepsilon' = \left(\frac{\lambda_0}{\pi d}\right)^2 \left(u^2 + v^2\right) + 1 \tag{8}$$

using the value of v^2 and u^2.

In the two-resonator method, a pair of dielectric rods, which are called "standard dielectric rods", are used. These two rods have the same diameter but have different heights. The rod heights are such that one rod is p times the height of the other; p is commonly set equal to three. They are required to have the same values of ε' and tan δ.

Figure 3 shows the configuration of the standard dielectric rods in the case of p = 3. To avoid confusion, the height of the short standard dielectric rod is denoted by h_0. Each resonator is called "TE$_{011}$ resonator" and "TE$_{013}$ resonator", respectively. The same superconductor films are used in these resonators. The values of f_0 and Q_u for the TE$_{011}$ mode are measured using the TE$_{011}$ resonator, and those for the TE$_{01p}$ mode are measured using the TE$_{01p}$ resonator. We denote the f_0 and Q_u for each resonator by using the subscripts 1 and p, respectively: f_{01} and Q_{u1} for TE$_{011}$ resonator, and f_{0p} and Q_{up} for TE$_{01p}$ resonator.

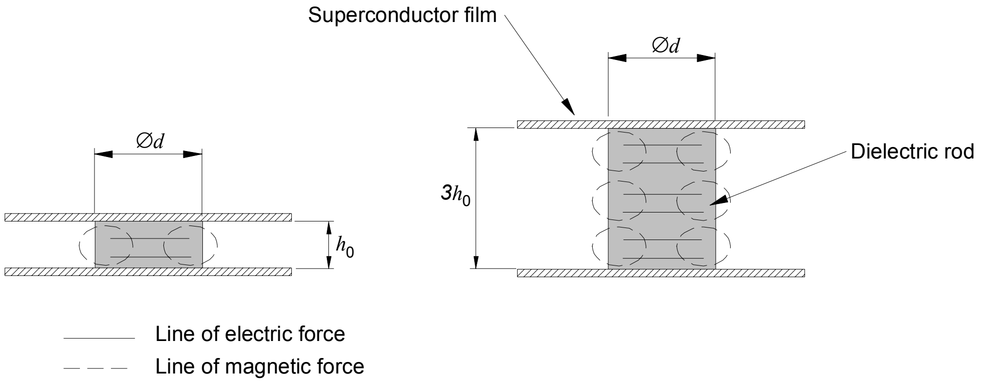

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Figure 3 – Configuration of standard dielectric rods for measurement of tan δ

The value of tan δ is given from the measured values of Q_u. When the TE$_{01p}$ resonator is precisely p times longer than the TE$_{011}$ resonator, f_{0p} coincides with f_{01}. However Q_{up} is higher than Q_{u1} according to the different magnitude of the electric field energy stored in the two resonators. Owing to the fact that both dielectric rods are short-circuited at both ends by the same superconductor films, equation (1) yields

$$\tan\delta = \frac{A}{(p-1)}\left(\frac{p}{Q_{up}} - \frac{1}{Q_{u1}}\right) \qquad (9)$$

As an alternative method, the value of R_s of superconductor films can be directly measured by

$$R_s = \frac{30\pi^2 p}{(p-1)}\left(\frac{2h_0}{\lambda_0}\right)^3 \frac{\varepsilon' + W}{1+W}\left(\frac{1}{Q_{u1}} - \frac{1}{Q_{up}}\right) \qquad (10)$$

where equation (10) is derived by substituting equation (9) into equation (1).

6 Apparatus

6.1 Measurement equipment

Figure 4 shows a schematic diagram of the equipment required for the microwave measurement. The equipment consists of a network analyzer system for transmission measurement, a measurement apparatus, and a thermometer for monitoring the measuring temperature.

An incident power generated from a suitable microwave source such as a synthesized sweeper is applied to the dielectric resonator fixed in the measurement apparatus. The transmission characteristics are shown on the display of the network analyzer.

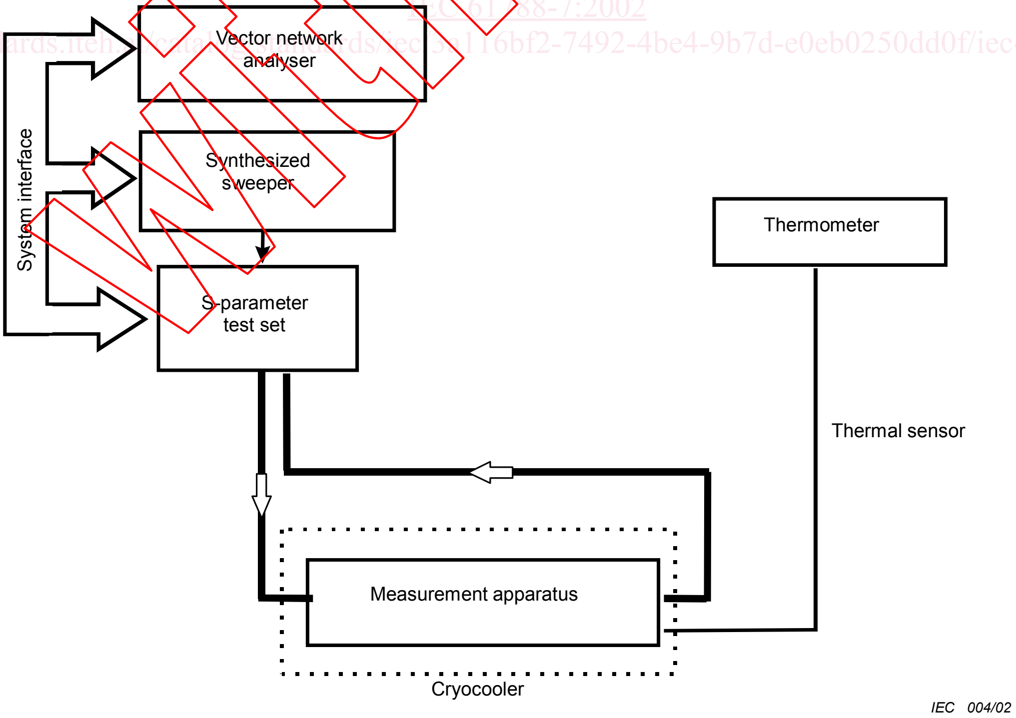

Figure 4 – Schematic diagram of measurement equipment for temperature dependence of R_s using a cryocooler