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Superconductivity – **STANDARD PREVIEW**
Part 7: Electronic characteristic measurements – Surface resistance of
high-temperature superconductors at microwave frequencies

Supraconductivité –
Partie 7: Mesurages des caractéristiques électronique – Résistance de surface
des supraconducteurs haute température critique aux hyperfréquences



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

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INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

COMMISSION
ELECTROTECHNIQUE
INTERNATIONALE

ICS 17.220.20; 29.050

ISBN 978-2-8322-7917-5

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

This third edition cancels and replaces the second edition, published in 2006. This edition constitutes a technical revision.

This edition includes the following significant technical changes with respect to the previous edition:

- a) informative Annex B, relative combined standard uncertainty for surface resistance measurement has been added;
- b) precision and accuracy statements have been converted to uncertainty;
- c) reproducibility in surface resistant measurement has been added.

The text of this International Standard is based on the following documents:

FDIS	Report on voting
90/447/FDIS	90/452/RVD

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

This document has been drafted in accordance with the ISO/IEC Directives, Part 2.

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INTRODUCTION

Since the discovery of some Perovskite-type Cu-containing oxides, extensive research and development (R & D) work on high-temperature superconductors (HTS) has been, and is being, done 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 HTS are being developed and are undergoing on-site testing [1]¹ [2].

Superconductor materials for microwave resonators [3], filters [4], antennas [5] and delay lines [6] have the advantage of very low loss characteristics. The parameters of superconductor materials needed for the design of microwave low loss components are the surface resistance, (R_s) and the temperature dependence of the R_s . 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.

R_s of high quality HTS films is generally several orders of magnitude lower than that of normal metals [7] [8] [9] [10], which has increased the need for a reliable characterization technique to measure this property. Traditionally, the R_s of niobium or any other low-temperature superconducting material was measured by first fabricating an entire three-dimensional resonant cavity and then measuring its Q -value [11]. The R_s could be calculated by solving the electro-magnetic field (EM) 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.

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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 1/1 000 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 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 [12] [13] [14]

The test method given in this document can also be applied to other superconductor bulk plates including low T_c materials.

This document 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 document is based on the VAMAS (Versailles Project on Advanced Materials and Standards) pre-standardization work on the thin film properties of superconductors.

¹ Numbers in square brackets refer to the bibliography.

SUPERCONDUCTIVITY –

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

1 Scope

This part of IEC 61788 describes measurement of the surface resistance (R_s) 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 R_s for this method is as follows:

- Frequency: 8 GHz < f < 30 GHz
- Measurement resolution: 0,01 m Ω at 10 GHz

The R_s data at the measured frequency, and that scaled to 10 GHz, assuming the f^2 rule for comparison, is reported.

2 Normative references (standards.iteh.ai)

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements 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 (IEV) – Part 815: Superconductivity*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC 60050-815 apply.

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- IEC Electropedia: available at <http://www.electropedia.org/>
- ISO Online browsing platform: available at <http://www.iso.org/obp>

4 Requirements

The 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 the Q -value, which corresponds to the loss.

The target relative combined standard uncertainty of this method is less than 20 % for the measurement temperature range from 20 K to 80 K.

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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 RF 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 Apparatus

5.1 Measurement system

Figure 1 shows a schematic diagram of the system required for the microwave measurement. The system 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. The measurement apparatus is fixed in a temperature-controlled cryocooler.

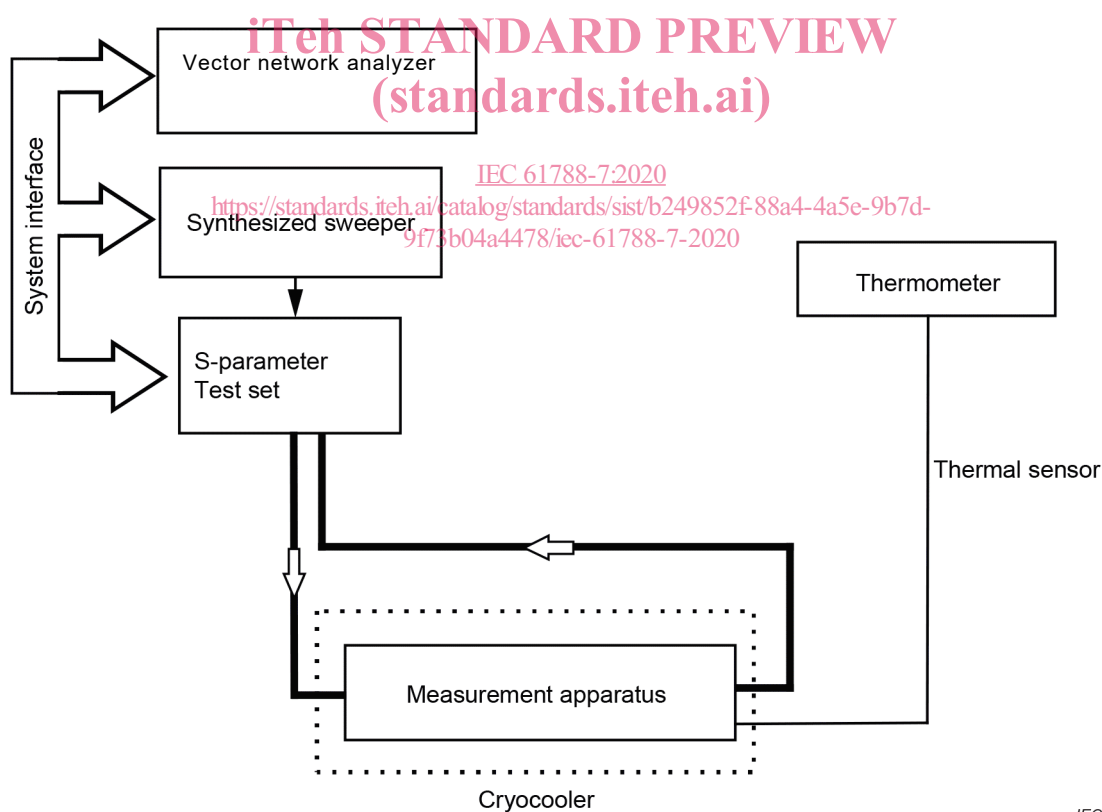


Figure 1 – Schematic diagram of measurement system for temperature dependence of R_s using a cryocooler

For the measurement of R_s for superconductor films, a vector network analyzer is recommended. A vector network analyzer has better measurement accuracy than a scalar network analyser due to its wide dynamic range. The performance requirements of the vector network analyzer are specified in 7.1.

5.2 Measurement apparatus for R_s

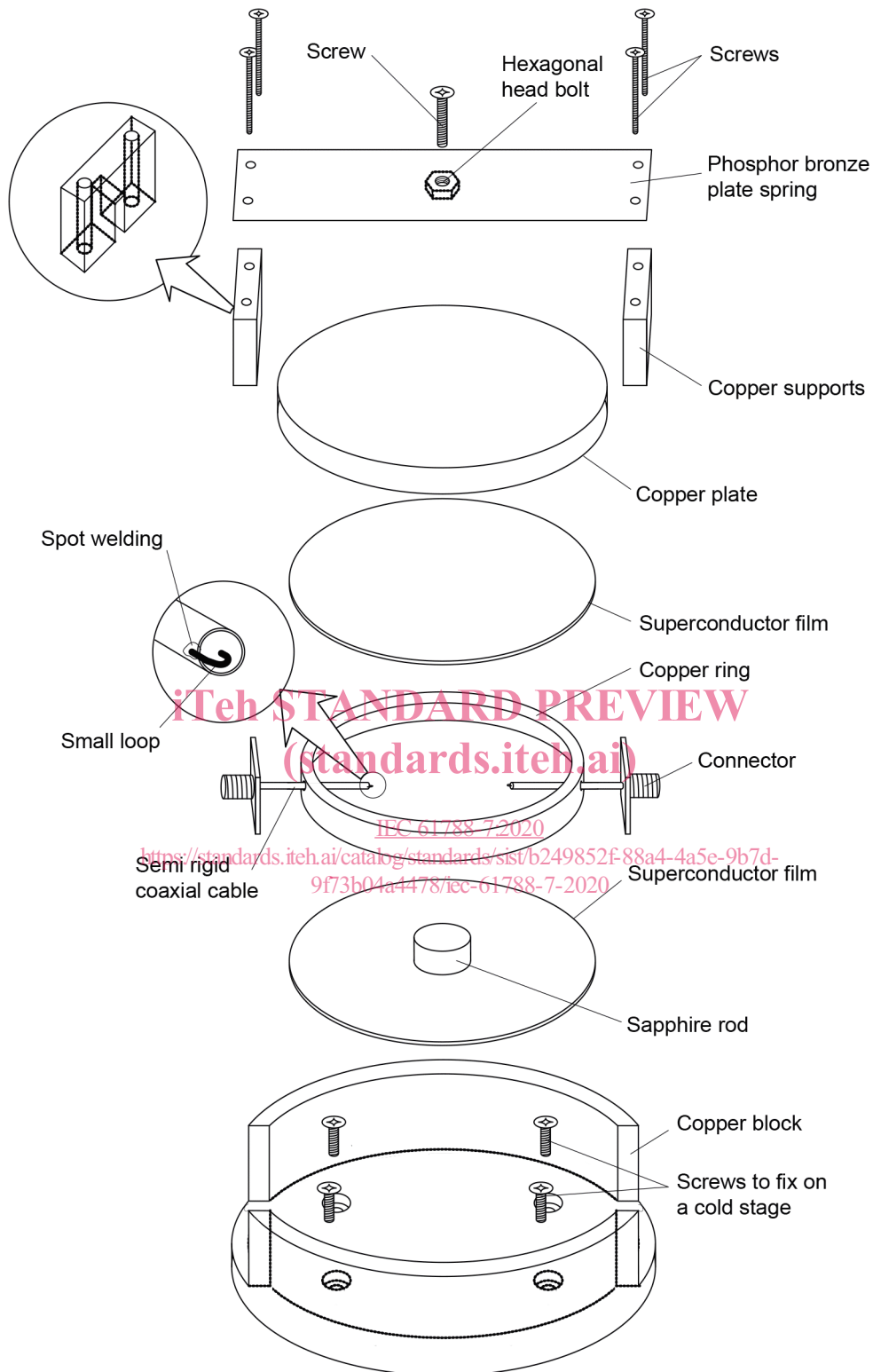
Figure 2 shows a schematic of a typical measurement apparatus (closed type resonator) for the R_s of HTS films deposited on a substrate with a flat surface. The upper HTS film is pressed down by a spring, which is made of phosphor bronze. The plate type spring should be used for the improvement of measurement uncertainty. This type of spring reduces the friction between the spring and the other part of the apparatus, and allows the smooth movement of superconductor films due to the thermal expansion of the dielectric rod. In order to minimize the measurement uncertainty, the sapphire rod and the copper ring shall be arranged coaxially.

Two semi-rigid cables for measuring transmission characteristics of the resonator shall be attached on both sides of the resonator in an axial symmetrical position ($\phi = 0$ and π , where ϕ is the rotational angle around the central axis of the sapphire rod). Each of the two semi-rigid cables shall have a small loop at the ends. The plane of the loop shall be set parallel to that of the superconductor films in order to suppress the unwanted Transverse Magnetic Wave Modes (TM_{mn0} modes). The coupling loops shall be carefully checked for cracks in the spot weld joint that may have developed upon repeated thermal cycling. These cables can move right and left to adjust the insertion attenuation (IA). In this adjustment, coupling of unwanted cavity modes to the interested dielectric resonance mode shall be suppressed. Unwanted, parasitic coupling to the other modes reduces the high Q -value of the Transverse Electro-Magnetic Mode (TE mode) resonator. For suppressing the parasitic coupling, special attention shall be paid to designing high- Q resonators. Two other types of resonators along with the closed type shown in Figure 2 can be used. They are explained in A.4.

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Figure 2 – Typical measurement apparatus for R_s

A reference line made of a semi-rigid cable shall be used to measure the full transmission power level, i.e. the reference level. This cable has a length equal to the sum of the two cables of the measurement apparatus. Semi-rigid cable with an outer diameter of 1,20 mm is recommended.

In order to minimize the measurement uncertainty, two superconductor films shall be set to be parallel to each other. To ensure that the two superconductor films remain in tight contact with the ends of the sapphire rod, without any air gap, both of the surfaces of the films and the ends of the rod shall be cleaned carefully.

5.3 Dielectric rods

Two dielectric rods with the same relative permittivity, ϵ' , and loss factor, $\tan \delta$, preferably cut from one cylindrical dielectric rod, are required. These two rods, standard dielectric rods, shall have the same diameter but different heights: one shall have height three times longer than the other.

It is preferable to use dielectric rods with low $\tan \delta$ to achieve the requisite measurement uncertainty on R_s . Recommended dielectric rods are single-crystal sapphire rods with $\tan \delta$ less than 2×10^{-7} at 77 K. Specifications on the sapphire rods are described in 7.1. In order to minimize the measurement error in R_s of the superconductor films, both ends of the sapphire rods shall be polished parallel to each other and perpendicular to the axis. Specifications for the sapphire rods are given in Clause 7.

The diameter and the heights of the standard sapphire rods shall be carefully designed so that the TE_{011} and TE_{013} modes do not couple to other TM, HE and EH modes, since the coupling between TE mode and other modes causes the degradation of unloaded Q . A design guideline for the standard sapphire rods is described in Clause A.5. Table 1 shows typical examples of dimensions of the standard sapphire rods for 12 GHz, 18 GHz, and 22 GHz resonance. In the R_s measurement at 22 GHz, the required film diameter can be set to 20 mm, and the measured Q_L is small, therefore the effect of the dielectric loss of sapphire rod can be reduced.

Table 1 – Typical dimensions of pairs of single-crystal sapphire rods for 12 GHz, 18 GHz and 22 GHz

Frequency GHz		Diameter, d mm	Height, h mm
12	Short rod (TE_{011} resonator)	$11,40 \pm 0,05$	$5,70 \pm 0,05$
	Long rod (TE_{013} resonator)	$11,40 \pm 0,05$	$17,10 \pm 0,05$
18	Short rod (TE_{011} resonator)	$7,60 \pm 0,05$	$3,80 \pm 0,05$
	Long rod (TE_{013} resonator)	$7,60 \pm 0,05$	$11,40 \pm 0,05$
22	Short rod (TE_{011} resonator)	$6,20 \pm 0,05$	$3,10 \pm 0,05$
	Long rod (TE_{013} resonator)	$6,20 \pm 0,05$	$9,30 \pm 0,05$

6 Measurement procedure

6.1 Specimen preparation

From uncertainty estimation, the film diameter shall be about three times larger than that of the sapphire rods. In this configuration, the increase in uncertainty of R_s due to the different radiation losses between TE_{011} and TE_{013} mode can be considered negligible, given the target relative combined standard uncertainty of 20 %. The film thickness shall be about two times larger than the magnetic-field penetration depth value at the maximum temperature in the measurement temperature range. If the film thickness is much less than two times the magnetic-field penetration depth, the measured R_s should mean the effective surface resistance.

Table 2 shows dimensions of the superconductor films recommended for the standard sapphire rods of 12 GHz, 18 GHz, and 22 GHz.

Table 2 – Dimensions of superconductor film for 12 GHz, 18 GHz, and 22 GHz

c-cut single-crystal sapphire rod		Superconductor film	
Frequency	Diameter, d	Diameter, d'	Thickness
GHz	mm	mm	μm
12	$11,40 \pm 0,05$	> 35	$\cong 0,5$
18	$7,60 \pm 0,05$	> 25	$\cong 0,5$
22	$6,20 \pm 0,05$	> 20	$\cong 0,5$

In case of using closed type resonators, the dimensions of the superconductor films shall also be designed taking into account the dimension of the copper cylinder between the superconductor films. A design guideline for the dimension of the copper cylinder of the closed type resonator is described in Clause A.6.

6.2 Set-up

Set up the measurement equipment as shown in Figure 1. All of the measurement apparatus, standard sapphire rods, and superconductor films shall be kept in a clean and dry state as high humidity may degrade the unloaded Q -value. The specimen and the measurement apparatus shall be fixed in a temperature-controlled cryocooler. The specimen chamber shall be totally evacuated. The temperatures of the superconductor films and standard sapphire rods shall be measured by a diode thermometer, or a thermocouple. The temperatures of the upper and lower superconductor films and standard sapphire rods shall not differ by more than 0,5 K. This can be achieved by covering the measurement apparatus with aluminium foil or filling the specimen chamber with helium gas.

6.3 Measurement of reference level

The level of full transmission power (reference level) shall be measured first. Fix the output power of the synthesized sweeper below 10 mW because the measurement uncertainty depends on the measuring signal level. Connect the reference line of semi-rigid cable between the input and output connectors. Then, measure the transmission power level over the entire measurement frequency and temperature range. The reference level can change several decibels when temperature of the apparatus is changed from room temperature to the lowest measurement temperature. Therefore, the temperature dependence of the reference level must be taken into account.