IEC 61788-15

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INTERNATIONAL STANDARD

NORME INTERNATIONALE

colour inside

**Superconductivity –
Part 15: Electronic characteristic measurements – Intrinsic surface impedance of superconductor films at microwave frequencies**

**Supraconductivité –
Partie 15: Mesures de caractéristiques électroniques – Impédance de surface intrinsèque de films supraconducteurs aux fréquences micro-ondes**

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

FDIS	Report on voting
90/280/FDIS	90/283/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, Part 2.

A list of all parts of the IEC 61788 series, published under the general title *Superconductivity,* can be found on the IEC website.

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INTRODUCTION

Since the discovery of high T_C superconductors (HTS), extensive research has been performed worldwide on electronic applications and large-scale applications with HTS filter subsystems based on $YBa_2Cu_3O_{7-\delta}$ (YBCO) having already been commercialized [1][1].

The merits of using HTS films for microwave devices such as resonators, filters, antennas, delay lines, etc., include i) possibility of microwave losses from HTS films being extremely low and ii) no signal dispersion on transmission lines made of HTS films due to extremely low microwave surface resistance (R_S) [2] and frequency-independent penetration depth (λ) of HTS films, respectively.

In this regard, when it comes to designing HTS-based microwave devices, it is important to measure the surface impedance (Z_S) of HTS films with $Z_S = R_S + jX_S$ and $X_S = \omega\mu_0\lambda$ (here ω and μ_0 denote the angular frequency and the permeability of vacuum, respectively, X_S, the surface reactance, and $X_S = \omega\mu_0\lambda$ is valid at temperatures not too close to the critical temperature T_C of HTS films).

Various reports have been made on measuring the R_S of HTS films at microwave frequencies with the typical R_S of HTS films as low as 1/100 - 1/50 of that of oxygen-free high-purity copper (OFHC) at 77 K and 10 GHz. The R_S of conventional superconductors such as niobium (Nb) could be easily measured by using Nb cavities by converting the resonator quality factor (Q) to the R_S of Nb. However, such conventional measurement method could no longer be applied to HTS films grown on dielectric substrates, with which it is basically impossible to make all-HTS cavities. Instead, for measuring the R_S of HTS films, several other methods have been useful, which include the microstrip resonator method [3], the coplanar microstrip resonator method [4], the parallel plate resonator method [5] and the dielectric resonator method [7-10]. Among the stated methods, the dielectric resonator method has been very useful due to that the method enables to measure the R_S in a non-invasive way and with accuracy. In 2002, the International Electrotechnical Commission (IEC) published the dielectric resonator method as a measurement standard [11].

The test method given in this standard enables measurement not only of the intrinsic surface resistance but also the intrinsic surface reactance of HTS films, regardless of the film's thickness, by using a single sapphire resonator that differs from the existing IEC standard (IEC 61788-7:2006), which is limited to measuring the surface resistance of superconductor films having a thicknesses of more than 3λ at the measured temperature by using two sapphire resonators. In fact, the measured surface resistances of HTS films with different thicknesses of less than 3λ mean effective values instead of intrinsic values, which cannot be used for directly comparing the microwave properties of HTS films among one another [12, 13]. Use of a single sapphire resonator as suggested in this standard also makes it possible to reduce uncertainty in the measured surface resistance that might result from using two sapphire resonators with sapphire rods of even slightly different quality.

The test method given in this standard can also be applied to HTS coated conductors, HTS bulks and other superconductors having established models for the penetration depth.

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 has been discussed at the VAMAS (Versailles Project on Advanced Materials and Standards) TWA-16 meeting.

[1] Numerals in square brackets refer to the Bibliography.

SUPERCONDUCTIVITY –

Part 15: Electronic characteristic measurements – Intrinsic surface impedance of superconductor films at microwave frequencies

1 Scope

This part of IEC 61788 describes measurements of the intrinsic surface impedance (Z_S) of HTS films at microwave frequencies by a modified two-resonance mode dielectric resonator method [13, 14][2]. The object of measurement is to obtain the temperature dependence of the intrinsic Z_S at the resonant frequency f_0.

The frequency and thickness range and the measurement resolution for the intrinsic Z_S of HTS films are as follows:

- frequency: up to 40 GHz;
- film thickness: greater than 50 nm;
- measurement resolution: 0,01 mΩ at 10 GHz.

The intrinsic Z_S data at the measured frequency, and that scaled to 10 GHz, assuming the f^2 rule for the intrinsic surface resistance R_S (f < 40 GHz) and the f rule for the intrinsic surface reactance X_S for comparison, shall be reported.

2 Normative references

The following referenced documents are indispensible 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 60050-815:2000, *International Electrotechnical Vocabulary – Part 815: Superconductivity*

IEC 61788-7:2006, *Superconductivity – Part 7: Electronic characteristic measurements – Surface resistance of superconductors at microwave frequencies*

3 Terms, definitions and general concepts

3.1 Terms and definitions

For the purposes of this document, the definitions given in IEC 60050-815, one of which is repeated here for convenience, apply.

3.1.1
surface impedance
impedance of a material for high frequency electromagnetic wave which is constrained to the surface of the material in case of metals and superconductors

NOTE The surface impedance governs the thermal losses of superconducting RF cavities.

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2 Numerals in square brackets refer to the Bibliography.

(IEC 60050-815:2000, 815-04-62)

3.2 General concepts

3.2.1 Intrinsic surface impedance

In general, the surface impedance Z_S of conductors, including superconductors, is defined as the ratio of the tangential component of the electric field (E_t) and that of the magnetic field (H_t) at a conductor surface:

$$Z_S = \frac{E_t}{H_t} = R_S + jX_S. \tag{1}$$

Here R_S denotes the surface resistance and X_S, the surface reactance. If the thickness of the conductor (or the superconductor) under test is sufficiently greater than the penetration depth of electromagnetic fields, Z_S is expressed by

$$Z_S = \left(\frac{\mu}{\varepsilon}\right)^{\frac{1}{2}} = \left(\frac{j\mu_0\omega}{\sigma}\right)^{\frac{1}{2}} \tag{2}$$

with ε and μ denoting the permittivity and the permeability of the conductor (or the superconductor) under test, respectively, μ_0, the permeability of vacuum, σ, the conductivity of the conductor (or the superconductor), and ω, the measured angular frequency, and is called the intrinsic surface impedance. σ is real for the conductor and complex for the superconductor.

3.2.2 Effective surface impedance

If the thickness of the conductor (or the superconductor) under test is not sufficiently greater than the penetration depth of electromagnetic fields, Z_S as defined by Equation (1) in 3.2.1 becomes significantly different from that defined by Equation (2) in 3.2.1. In this case, Z_S as defined by Equation (1) is called the effective surface impedance Z_{Se} with

$$Z_{Se} = \frac{E_t}{H_t} = R_{Se} + jX_{Se} \tag{3}$$

Here R_{Se} denotes the effective surface resistance and X_{Se}, the effective surface reactance.

4 Requirements

The Z_S of HTS films shall be measured by applying a microwave signal to a dielectric resonator with the superconductor 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 uncertainty of this method is less than 10 % at temperatures of 30 K to 80 K.

It is the responsibility of the user of this standard to consult and establish 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 exposure to human bodies can cause an immediate burn.

5 Apparatus

5.1 Measurement equipment

Figure 1 shows a schematic diagram of the equipment required for the microwave measurement. The equipment consists of a network analyzer system for transmission measurements, a measurement apparatus, and thermometers for monitoring the temperature of HTS films under test.

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.

For measuring the Z_S of HTS films, a vector network analyzer is recommended because it has better measurement accuracy than a scalar network analyzer due to its wider dynamic range.

5.2 Measurement apparatus

Figure 2 shows a schematic diagram of a typical measurement apparatus for the Z_S of HTS films deposited on a substrate with a flat surface. The lower HTS film is pressed down by a spring, which is made of beryllium copper. Use of a plate type spring is recommended for the improvement of measurement uncertainty. This type of spring reduces the friction between the spring and the other part of the apparatus, and enables smooth motion of HTS films in the course of thermal expansion/contraction of the dielectric-loaded cavity. The upper HTS film is glued to the Cu plate at the top using adhesives with good thermal conductivity.

The R_S is measured with the upper HTS film being in contact with the top of the Cu cavity. During measurements of the R_S, the whole resonator is first cooled down to the lowest temperature with the cryocooler turned on and then warmed up to higher temperatures with the cryocooler turned off. Meanwhile, the X_S is measured with a small gap between the upper HTS film and the top of the Cu cavity. The gap distance shall be set to a value predetermined at the room temperature by using either a micrometer or a step motor connected to the upper superconductor film through a polytetrafluoroethylene (PTFE) rod. The real gap distances would be a little longer at cryogenic temperatures than the corresponding predetermined ones due to thermal contraction of the PTFE rod. The gap distance should be small enough not to cause significant radiation loss and large enough to enable control of the temperature of the upper superconductor film. More detailed descriptions on a dielectric resonator with a movable top plate, a switch block for thermal connection, and the dielectric resonator assembled with the switch block are given in Figures 3 to 5, respectively. Procedures for controlling the temperature of the upper HTS film for measurements of the X_S are described in 6.6.

Each of the two semi-rigid cables shall have a small loop at the end as shown in Figure 3. The plane of the loop shall be set parallel to that of the HTS films in order to suppress the unwanted TM_{mn0} modes. The coupling loops shall be carefully checked prior to the measurements to keep the good coupling conditions. These cables can move to the right or to the 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 not only reduces the high-*Q* value of the TE mode resonator but also increases uncertainty in the measured resonant frequency of the TE mode resonator, making it difficult to measure changes in the resonant frequency vs. temperature data with accuracy.

For suppressing the parasitic coupling, dielectric resonators shall be designed in such a way that the frequencies of the resonance modes of interest are well separated from those of nearby parasitic modes. The dielectric rod should be fixed at the center of the bottom superconductor film by using low-loss epoxy.

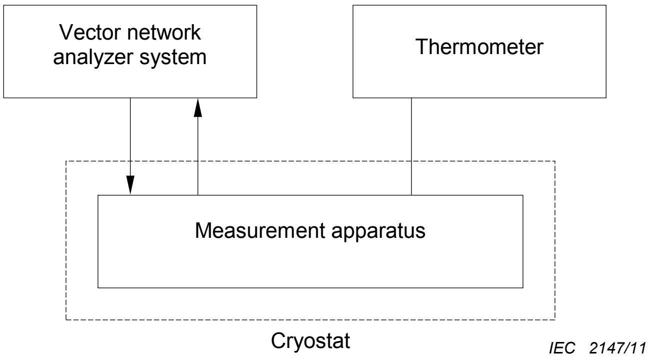
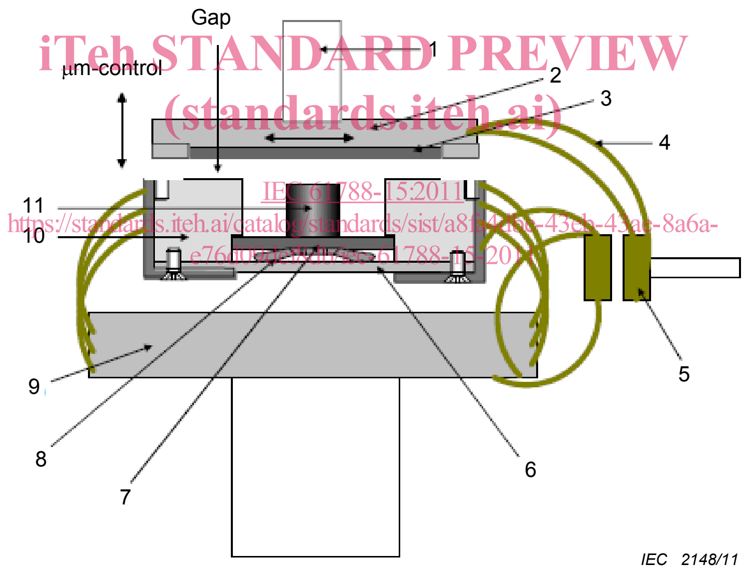


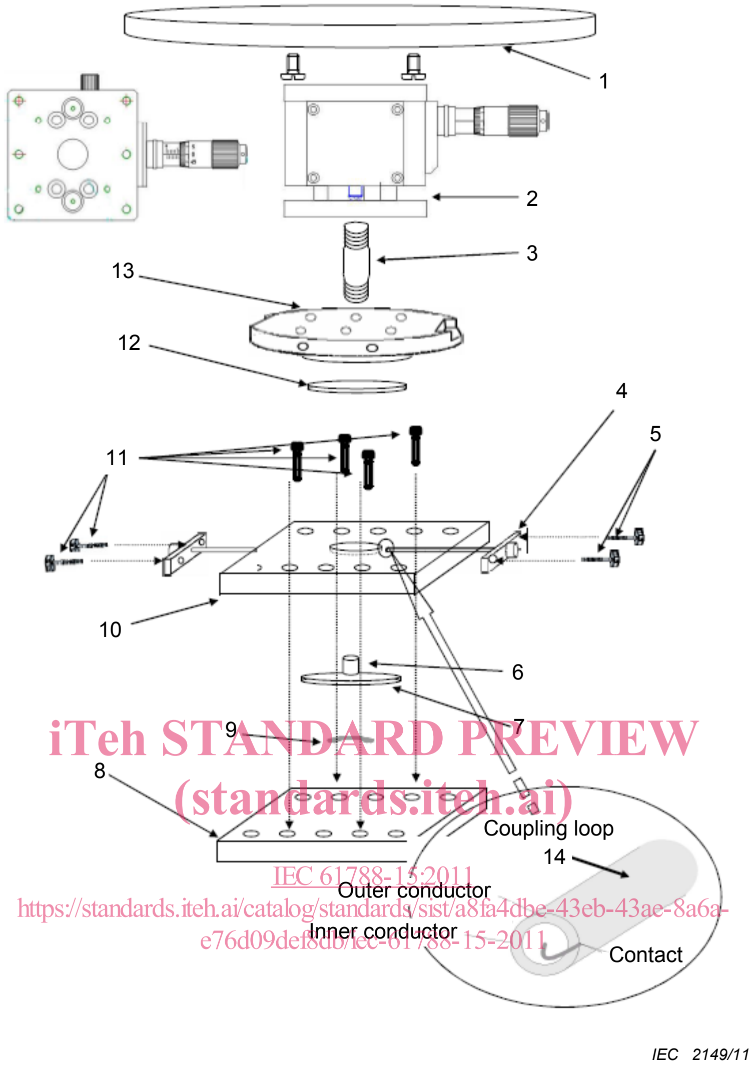
Figure 1 – Schematic diagram for the measurement equipment for the intrinsic Z_S of HTS films at cryogenic temperatures



Key

1	polytetrafluoroethylene (PTFE) rod	7	superconductor (or metal) film
2	Cu plate	8	Be-Cu spring
3	superconductor (or metal) film	9	cold finger
4	Cu wire	10	Cu cavity
5	switch for thermal connection	11	dielectric rod
6	Cu plate		

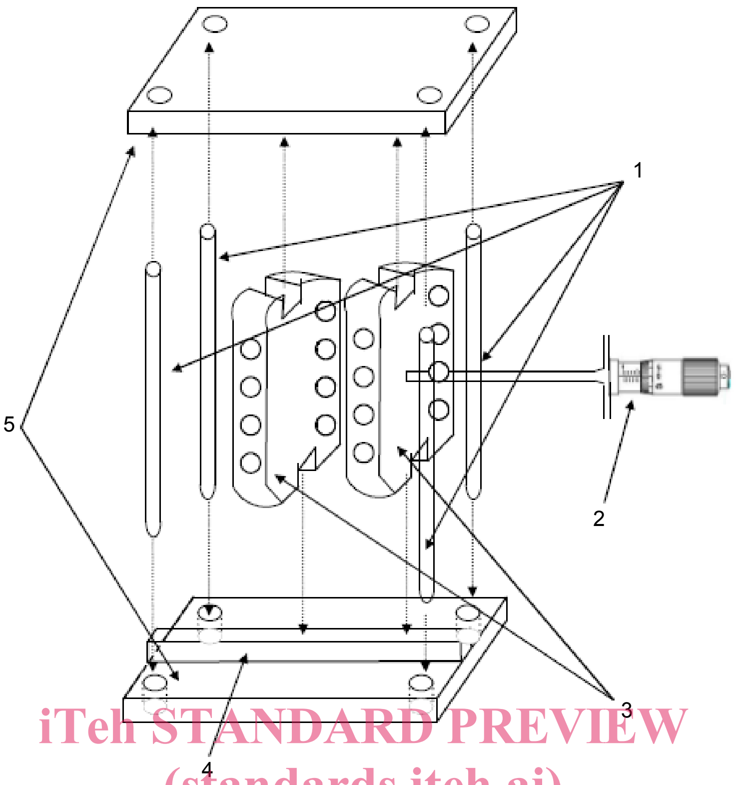
Figure 2 – Schematic diagram of a dielectric resonator with a switch for thermal connection



Key

1 acryl plate
2 z-axis stage
3 polytetrafluoroethylene (PTFE) screw
4 connector
5 screw
6 dielectric rod
7 superconductor film
8 Cu plate
9 Be-Cu spring
10 Cu plate
11 screw
12 superconductor film
13 Cu plate
14 semi-rigid coaxial cable

Figure 3 – Typical dielectric resonator with a movable top plate



Key

1 SUS rod

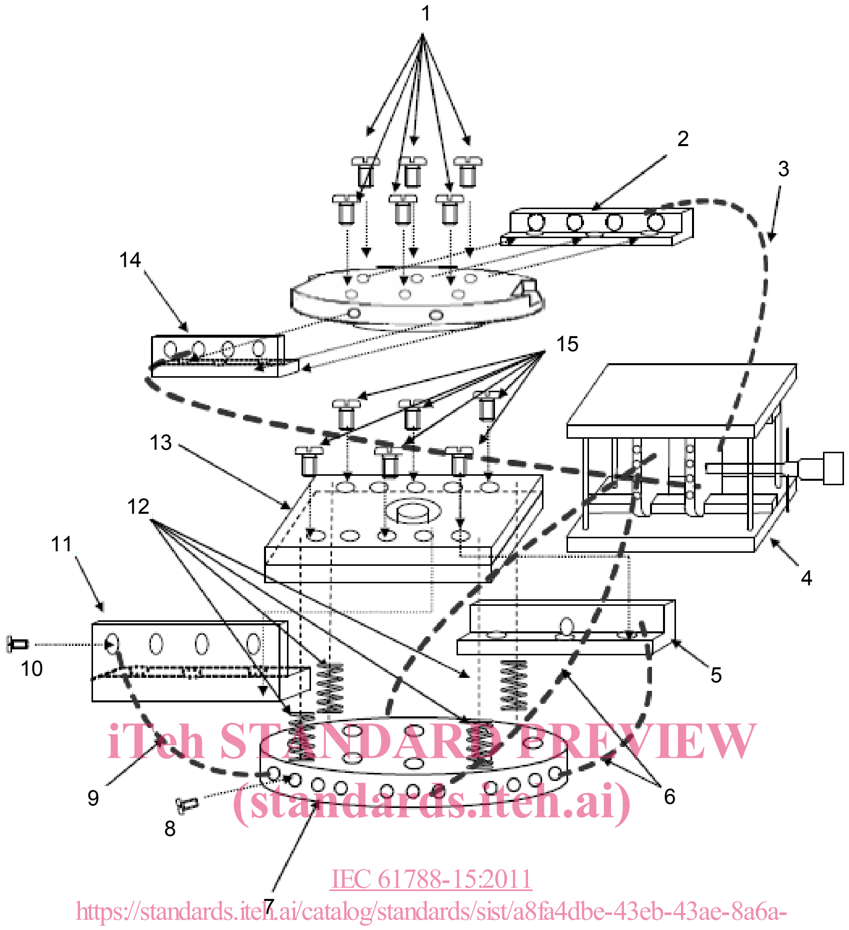
2 micrometer

3 Cu block

4 sliding guide

5 polytetrafluoroethylene (PTFE) plate

Figure 4 – Switch block for thermal connection



Key

1 screw
2 Cu block
3 Cu braid
4 thermal switch block
5 Cu block
6 Cu braid
7 Cu plate
8 screw
9 Cu braid
10 screw
11 Cu block
12 spring
13 Cu cavity block
14 Cu block
15 screw

Figure 5 – Dielectric resonator assembled with a switch block for thermal connection

5.3 Dielectric rods

Dielectric resonators shall be designed in such a way that the TE_{021} and the TE_{012} modes appear next to each other without being coupled to the other TM or HE modes. Furthermore, the resonant frequencies of the two modes shall be close enough for reducing the measurement uncertainty in Z_S and far enough not to cause any coupling between them. The difference between the resonant frequencies of the TE_{021} and the TE_{012} modes shall be less than 400 MHz, a value corresponding to ~ 1% of each resonant frequency, and more than 80 MHz considering reduced resonator *Q* at higher temperatures.

The dielectric rods shall have low tan δ and low temperature variation of the dielectric constants to achieve the requisite measurement accuracy in R_S and X_S, respectively. In this regard, *c*-cut sapphire rods are recommended for measuring the Z_S with accuracy (the relative permittivity along the a-b plane $\varepsilon_{a\text{-}b}'$ = 9,28 at 77 K for sapphire).

Designing schemes for the standard sapphire rod are described in Annex A.4 and A.5. Table 1 shows typical dimensions of the standard sapphire rod used for 40 GHz TE_{021}-mode sapphire resonator. The resonant frequencies become lower if the dimensions are greater, for