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

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~~[1] In this Annex A, numerals in square brackets refer to Clause A.8, Reference documents.~~

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

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IEC 61788-15 has been prepared by IEC technical committee 90: Superconductivity. It is an International Standard.

This second edition cancels and replaces the first edition published in 2011. This edition constitutes a technical revision.

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

a) informative Annex B, combined relative standard uncertainty in the intrinsic surface impedance is added;
b) the terms, 'precision and accuracy', are replaced with uncertainty;
c) results from a round robin test are added.

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

Draft	Report on voting
90/550/FDIS	90/556/RVD

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

The language used for the development of this International Standard is English.

This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available at www.iec.ch/members_experts/refdocs. The main document types developed by IEC are described in greater detail at www.iec.ch/publications.

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

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under webstore.iec.ch in the data related to the specific document. At this date, the document will be

– reconfirmed,
– withdrawn, or
– revised.

INTRODUCTION

Since the discovery of high T_C superconductors (HTS), extensive researches have 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][2].

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

In this regard, when it comes to designing of HTS-based microwave devices, it is important to measure the intrinsic 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 intrinsic 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 to 1/50 of that of oxygen-free high ~~purity~~ conductivity 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 microstrip resonator method [3], coplanar microstrip resonator method [4], parallel plate resonator method [5] and dielectric resonator method ([6] to [11]). Among the stated methods, the dielectric resonator method has been very useful due to the fact that the method enables to measure the ~~R_S~~ microwave surface resistance in a non-invasive way and with accuracy. In 2002, the International Electrotechnical Commission (IEC) published the dielectric resonator method as a measurement standard [12].

The test method given in this document enables to measure not only the ~~intrinsic surface resistance~~ R_S but also the ~~intrinsic surface reactance~~ X_S of HTS films regardless of the film's thickness by using single sapphire resonator, which differs from the existing IEC standard (IEC 61788-7~~:2006~~) that is limited to measure the surface resistance of superconductor films having the 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 [13], [14]. Use of a single sapphire resonator as suggested in this document also enables to reduce uncertainty in the measured surface resistance that ~~might~~ can result from using two sapphire resonators with sapphire rods of ~~even slightly~~ different quality.

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

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

2 Numbers in square brackets refer to the Bibliography.

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 [14], [15]. The object of measurement is to obtain the temperature dependence of the intrinsic surface impedance, 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.

It is crucial that the ~~intrinsic~~ Z_S data at the measured frequency, and that scaled to 10 GHz be reported for comparison, 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 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:~~2000~~2024, *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 and definitions ~~and general concepts~~

~~3.1 Terms and definitions~~

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

ISO and IEC maintain terminology databases for use in standardization at the following addresses:

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

3.1
surface impedance
~~impedance of a material for highfrequency electromagnetic wave which is constrained to the surface of the material in case of metals and superconductors~~

impedance of a metallic material or a superconductor when a high-frequency electromagnetic wave is constrained to the surface

Note 1 to entry: The surface impedance governs the thermal losses of superconducting RF cavities.

Note 2 to entry: This entry was numbered 815-13-60 in IEC 60050-815:2015.

[SOURCE: IEC 60050-815:2024~~2000~~, ~~815-04-62~~ 815-22-33]

~~**3.2 General concepts**~~

3.2
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:~~

~~$$Z_S = \frac{E_t}{H_t} = R_S + jX_S \quad (1)$$~~

~~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~~

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

~~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.~~

impedance of conductors (or superconductors) having the thicknesses sufficiently greater than the skin depth (or the penetration depth), with the intrinsic surface impedance Z_S 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 or a superconductor surface:

$$Z_S = E_t / H_t = R_S + jX_S \quad (1)$$

3.3
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~~

~~$$Z_{Se} = \frac{E_t}{H_t} = R_{Se} + jX_{Se} \quad (3)$$~~

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

impedance of conductors (or superconductors) having the thicknesses not sufficiently greater than the skin depth (or the penetration depth) as defined by

$$Z_{Se} = E_t / H_t = R_{Se} + jX_{Se} \quad (2)$$

with Z_{Se} being significantly different from Z_S in Formula (1).

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 as well as the scattering parameters shall be recorded to obtain the Q-value, which corresponds to the loss.

The target relative uncertainty of this method is less than ~~10~~ 20 % at temperatures of 30 K to ~~80~~ 60 K.

It is the responsibility of the user of this document 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 analyser 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 analyser.

The measurement apparatus is fixed in a temperature-controlled cryostat. The cryostat consists of a vacuum chamber and a cryocooler, the cold finger of which the measurement apparatus is connected to. For the penetration depth measurements, vibrations from the cryocooler should be dampened by using dampers between the vacuum chamber and the cryocooler. During collection of resonance data as a function of temperature, the resonance signal should remain stable at each temperature.

For measuring the Z_S of HTS films, a vector network analyser is recommended because it has better measurement accuracy than a scalar network analyser 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~~ (by the copper cavity) against 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~~ R_{Se} is measured with the upper HTS film being in contact with the top of the Cu cavity. During measurements of the ~~R_S~~ R_{Se}, 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~~ X_{Se} 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 micrometre or a step motor connected to the upper superconductor film through a polytetrafluoroethylene rod. The real gap distances would be a little longer at cryogenic temperatures than the corresponding predetermined ones due to thermal contraction of the polytetrafluoroethylene 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 are given in Figure 3, with Figure 4 and Figure 5 displaying a switch block for thermal connection and the dielectric resonator assembled with the switch block, 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 loop, shaped like a semicircle, is affixed to the cross-sectional part of the outer conductor via soldering at its terminal point. 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. For measuring the Q values as a function of temperature, these cables can ~~move~~ be moved to the right or to the left to ~~adjust~~ maintain the insertion attenuation (IA) slightly higher than 20 dB at the lowest temperature, with the vertical position of each loop fixed in the middle of the sapphire rod. The distance between the loop and the sapphire rod should be adjusted to a smaller value if the resonant signal gets too noisy at higher temperatures. 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 collecting the temperature dependence of the resonant frequency data, the distance between the loop and the sapphire rod should not be changed during measurements. In this case, IA at the lowest temperature can be lower than 20 dB.

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 centre of the bottom superconductor film by using low-loss ~~epoxy~~ glue. A small drop of glue applied to the surface of the bottom superconductor is enough to attach the film to the dielectric rod. It is noted that effects of glue on the measured Q-value should be negligible.

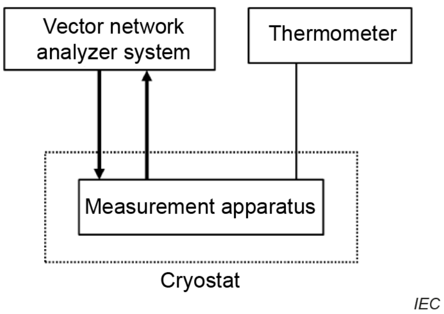
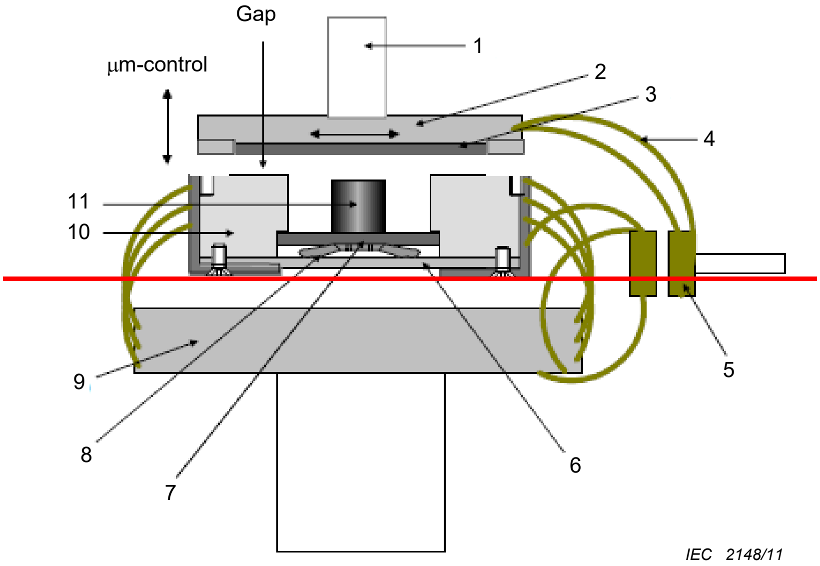
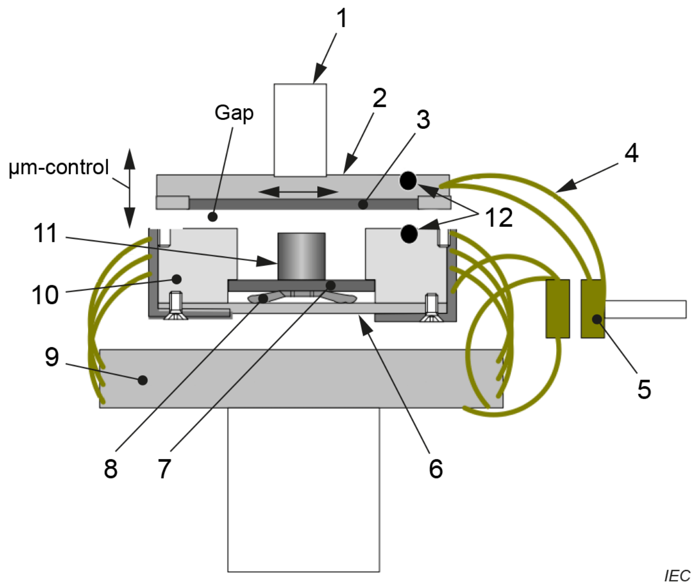


Figure 1 – Schematic diagram for the measurement equipment for the intrinsic Z_S of HTS films at cryogenic temperatures



Key

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



Key

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

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