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

Supraleitfähigkeit - Teil 15: Messungen der elektronischen Charakteristik - Oberflächenimpedanz von Supraleiterschichten bei Mikrowellenfrequenzen

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

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29.050	Superprevodnost in prevodni materiali	Superconductivity and conducting materials

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TITLE:

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

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

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

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FOREWORD

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

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

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

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a) Informative Annex B, combined relative standard uncertainty in the intrinsic surface impedance is added;

146

b) The terms, 'precision and accuracy', are replaced with uncertainty;

147

c) Results from a round robin test are added.

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

FDIS

Report on voting

90/XXX/FDIS	90/XXX/RVD
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150

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

153 The language used for the development of this international standard is English.

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

157 The committee has decided that the contents of this amendment and the base publication will remain unchanged
158 until the stability date indicated on the IEC web site under "http://webstore.iec.ch" in the data related to the specific
159 document. At this date, the publication will be

- 160 • reconfirmed,
- 161 • withdrawn,
- 162 • replaced by a revised edition, or
- 163 • amended.

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INTRODUCTION

167 Since the discovery of high T_C superconductors (HTS), extensive researches have been
168 performed worldwide on electronic applications and large-scale applications with HTS filter
169 subsystems based on $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ (YBCO) having already been commercialized [1].

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

174 In this regard, when it comes to designing of HTS-based microwave devices, it is important to
175 measure the intrinsic surface impedance (Z_s) of HTS films with $Z_s = R_s + jX_s$ and $X_s = \omega \mu_0 \lambda$
176 (Here ω and μ_0 denote the angular frequency and the permeability of vacuum, respectively,
177 X_s , the intrinsic surface reactance, and $X_s = \omega \mu_0 \lambda$ is valid at temperatures not too close to
178 the critical temperature T_C of HTS films).

179 Various reports have been made on measuring the R_s of HTS films at microwave frequencies
180 with the typical R_s of HTS films as low as 1/100 - 1/50 of that of oxygen-free high-purity copper
181 (OFHC) at 77 K and 10 GHz. The R_s of conventional superconductors such as niobium (Nb)
182 could be easily measured by using Nb cavities by converting the resonator quality factor (Q) to
183 the R_s of Nb. However, such conventional measurement method could no longer be applied to
184 HTS films grown on dielectric substrates, with which it is basically impossible to make all-HTS
185 cavities. Instead, for measuring the R_s of HTS films, several other methods have been useful,
186 which include microstrip resonator method [3], coplanar microstrip resonator method [4],
187 parallel plate resonator method [5] and dielectric resonator method [7-11]. Among the stated
188 methods, the dielectric resonator method has been very useful due to the fact that the method
189 enables to measure the microwave surface resistance in a non-invasive way and with accuracy.
190 In 2002, International Electrotechnical Commission (IEC) published the dielectric resonator
191 method as a measurement standard [12].

192 The test method given in this standard enables to measure not only the R_s but also the X_s of
193 HTS films regardless of the film's thickness by using single sapphire resonator, which differs
194 from the existing IEC standard (IEC 61788-7:2020) that is limited to measure the surface
195 resistance of superconductor films having the thicknesses of more than 3λ at the measured
196 temperature by using two sapphire resonators. In fact, the measured surface resistances of
197 HTS films with different thicknesses of less than 3λ mean effective values instead of intrinsic
198 values, which cannot be used for directly comparing the microwave properties of HTS films
199 among one another [13, 14]. Use of single sapphire resonator as suggested in this standard
200 also enables to reduce uncertainty in the measured surface resistance that might result from
201 using two sapphire resonators with sapphire rods of different quality.

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

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

206 The test method covered in this standard has been discussed at the VAMAS (Versailles Project
207 on Advanced Materials and Standards) TWA-16 meeting.

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212 SUPERCONDUCTIVITY –

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214 **Part 15: Electronic characteristic measurements – Intrinsic surface** 215 **impedance of superconductor films at microwave frequencies**

216

217 **1 Scope**

218 This part of IEC 61788 describes measurements of the intrinsic surface impedance (Z_s) of HTS
 219 films at microwave frequencies by a modified two-resonance mode dielectric resonator method
 220 [14, 15]. The object of measurement is to obtain the temperature dependence of the intrinsic
 221 surface impedance, Z_s , at the resonant frequency f_0 .

222 The frequency and thickness range and the measurement resolution for the Z_s of HTS films are
 223 as follows:

- 224 – frequency: Up to 40 GHz;
- 225 – film thickness: Greater than 50 nm;
- 226 – measurement resolution: 0,01 m Ω at 10 GHz.

227 The Z_s data at the measured frequency, and that scaled to 10 GHz, assuming the f^2 rule for the
 228 intrinsic surface resistance, R_s ($f < 40$ GHz), and the f rule for the intrinsic surface reactance,
 229 X_s , for comparison, shall be reported.

230 **2 Normative references**

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

234 IEC 60050-815:2000, *International Electrotechnical Vocabulary – Part 815: Superconductivity*

235 IEC 61788-15:2011, *Superconductivity – Part 15: Electronic characteristic measurements –*
 236 *Intrinsic surface impedance of superconductor films at microwave frequencies*

237 IEC 61788-7:2020, *Superconductivity – Part 7: Electronic characteristic measurements –*
 238 *Surface resistance of high-temperature superconductors at microwave frequencies*

239 **3 Terms and definitions**

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

241 **3.1**

242 **Surface impedance**

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

244 **3.2**

245 **Intrinsic surface impedance**

246 In general, for conductors (or superconductors) having the thicknesses sufficiently greater than
 247 the skin depth (or the penetration depth) of electromagnetic fields, Z_s is defined as the ratio of
 248 the tangential component of the electric field (E_t) and that of the magnetic field (H_t) at a
 249 conductor or a superconductor surface:

$$250 \quad Z_s = E_t/H_t = R_s + jX_s. \quad (1)$$

251 Here R_s denotes the intrinsic surface resistance and X_s is the intrinsic surface reactance if the
 252 thickness of the conductor (or the superconductor) under test is sufficiently greater than the
 253 penetration depth of electromagnetic fields. In this case, Z_s is expressed by

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

254

255 with ε and μ denoting the permittivity and the permeability of the conductor (or the
 256 superconductor) under test, respectively, μ_0 , the permeability of vacuum, $\sigma (= \sigma_1 - j\sigma_2)$, the
 257 conductivity of the conductor (or the superconductor), and ω , the measured angular frequency.
 258 σ is real for normal conductors with $\sigma_2 = 0$ and complex for superconductors in the
 259 superconducting state¹.

260 3.3

261 Effective surface impedance

262 If the thickness of the conductor (or the superconductor) under test is not sufficiently greater
 263 than the penetration depth of electromagnetic fields, Z_s as defined by Equation (1) in 3.2
 264 becomes significantly different from that defined by Equation (2) in 3.2. In this case, Z_s as
 265 defined by Equation (1) becomes the effective surface impedance, Z_{se} , with

$$266 \quad Z_{se} = E_t/H_t = R_{se} + jX_{se}. \quad (3)$$

267 Here R_{se} denotes the effective surface resistance and X_{se} is the effective surface reactance.

268 4 Requirements

269 The Z_s of HTS films shall be measured by applying a microwave signal to a dielectric resonator
 270 with the superconductor specimen and then measuring the attenuation of the resonator at each
 271 frequency. The frequency shall be swept around the resonant frequency as the centre, and the
 272 attenuation - frequency characteristics as well as the scattering parameters shall be recorded
 273 to obtain the Q-value, which corresponds to the loss.

274 The target relative uncertainty of this method is less than 20 % at temperatures of 30 K to 60
 275 K.

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

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

284 5 Apparatus

285 5.1 Measurement equipment

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

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

¹ σ_2 is a parameter associated with the appearance of Cooper pairs in superconductors at temperatures below the critical temperature.

293 The measurement apparatus is fixed in a temperature-controlled cryocooler. For the penetration
294 depth measurements, vibrations from the cryocooler should be dampened by using dampers
295 between the vacuum chamber and the cryocooler.

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

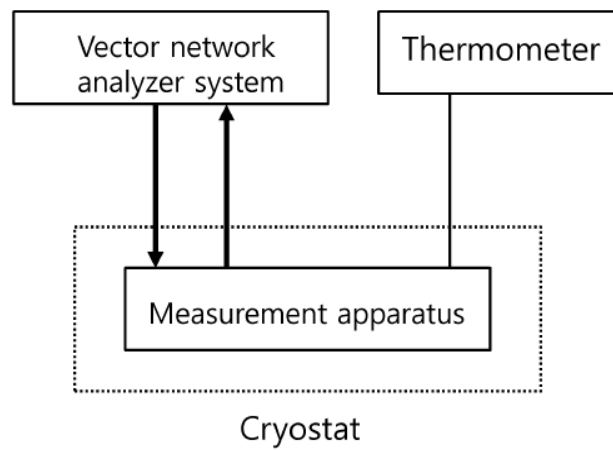
298 5.2 Measurement apparatus

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

306 The R_{se} is measured with the upper HTS film being in contact with the top of the Cu cavity.
307 During measurements of the R_{se} , the whole resonator is first cooled down to the lowest
308 temperature with the cryocooler turned on and then warmed up to higher temperatures with the
309 cryocooler turned off. Meanwhile, the X_{se} is measured with a small gap between the upper HTS
310 film and the top of the Cu cavity. The gap distance shall be set to a value predetermined at the
311 room temperature by using either a micrometer or a step motor connected to the upper
312 superconductor film through a Teflon rod. The real gap distances would be a little longer at
313 cryogenic temperatures than the corresponding predetermined ones due to thermal contraction
314 of the Teflon rod. The gap distance should be small enough not to cause significant radiation
315 loss and large enough to enable control of the temperature of the upper superconductor film.
316 More detailed descriptions on a dielectric resonator with a movable top plate, a switch block for
317 thermal connection, and the dielectric resonator assembled with the switch block are given in
318 Figures 3 to 5, respectively. Procedures for controlling the temperature of the upper HTS film
319 for measurements of the X_s are described in 6.6.

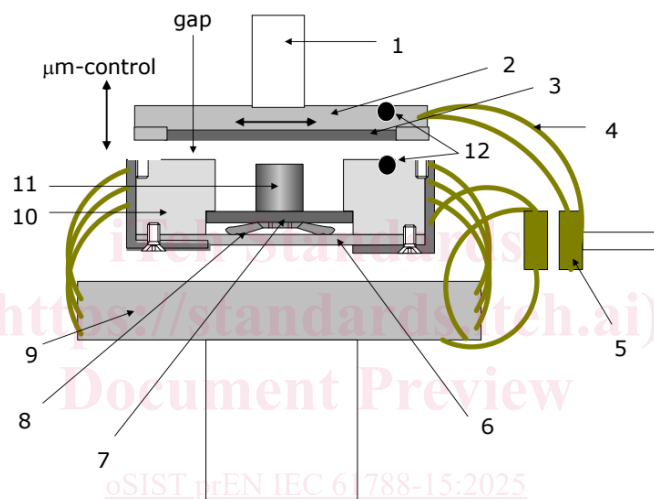
320 Each of the two semi-rigid cables shall have a small loop at the end as shown in Figure 3. The loop,
321 shaped like a semicircle, is affixed to the cross-sectional part of the outer conductor via soldering
322 at its terminal point. The plane of the loop shall be set parallel to that of the HTS films in order to
323 suppress the unwanted TM_{mn0} modes. The coupling loops shall be carefully checked prior to the
324 measurements to keep the good coupling conditions. For measuring the Q values as a function of
325 temperature, these cables can be moved to the right or to the left to maintain the insertion
326 attenuation (IA) slightly higher than 20 dB at the lowest temperature, with the vertical position of
327 each loop fixed in the middle of the sapphire rod. The distance between the loop and the sapphire
328 rod should be adjusted to a smaller value if the resonant signal gets too noisy at higher temperatures.
329 In this adjustment, coupling of unwanted cavity modes to the interested dielectric resonance mode
330 shall be suppressed. Unwanted, parasitic coupling to the other modes not only reduces the high- Q
331 value of the TE mode resonator but also increases uncertainty in the measured resonant frequency
332 of the TE mode resonator, making it difficult to measure changes in the resonant frequency vs.
333 temperature data with accuracy. For collecting the temperature dependence of the resonant
334 frequency data, the distance between the loop and the sapphire rod should not be changed during
335 measurements. In this case, IA at the lowest temperature can be lower than 20 dB.

336 For suppressing the parasitic coupling, dielectric resonators shall be designed in such a way
337 that the frequencies of the resonance modes of interest are well separated from those of nearby
338 parasitic modes. The dielectric rod should be fixed at the center of the bottom superconductor
339 film by using low-loss glue. It is noted that effects of glue on the measured Q -value should be
340 negligible.



341

342 **Figure 1 – Schematic diagram for the measurement equipment for the intrinsic Z_s of**
 343 **HTS films at cryogenic temperatures**



344

345 Key

346 1 Teflon rod

347 2 Cu plate

348 3 superconductor (or metal) film

349 4 Cu wire

350 5 switch for thermal connection

351 6 Cu plate

352 7 superconductor (or metal) film

353 8 Be-Cu spring

354 9 cold finger

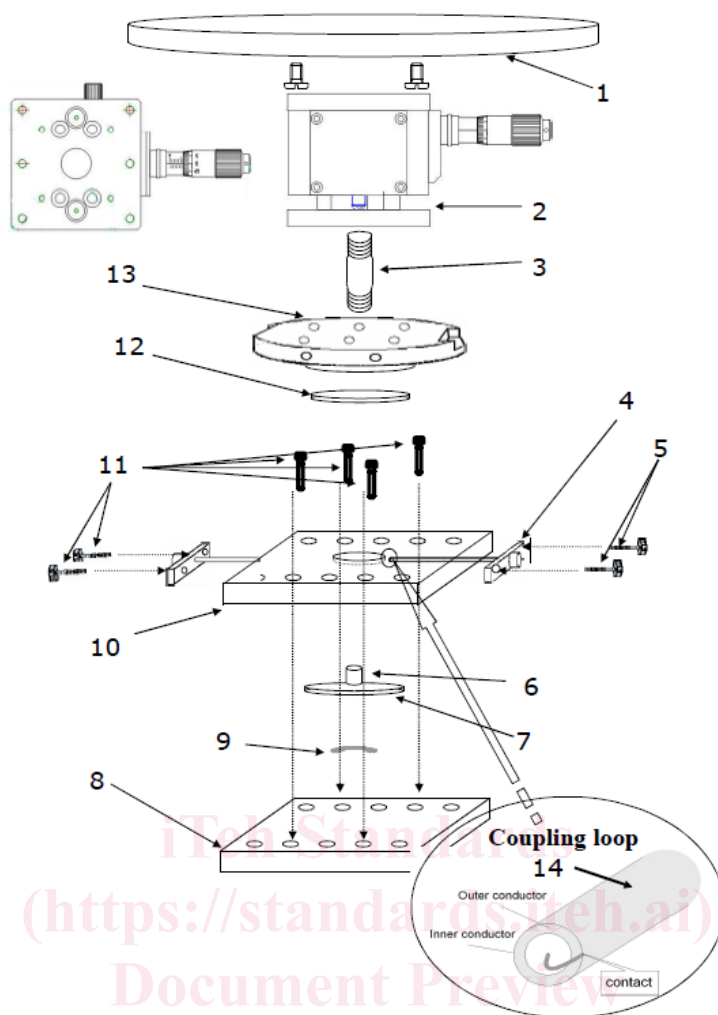
355 10 Cu cavity

356 11 dielectric rod

357 12 temperature sensor

358 **Figure 2 – Schematic diagram of a dielectric resonator with a switch**359 **for thermal connection**

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

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Figure 3 – Typical dielectric resonator with a movable top plate

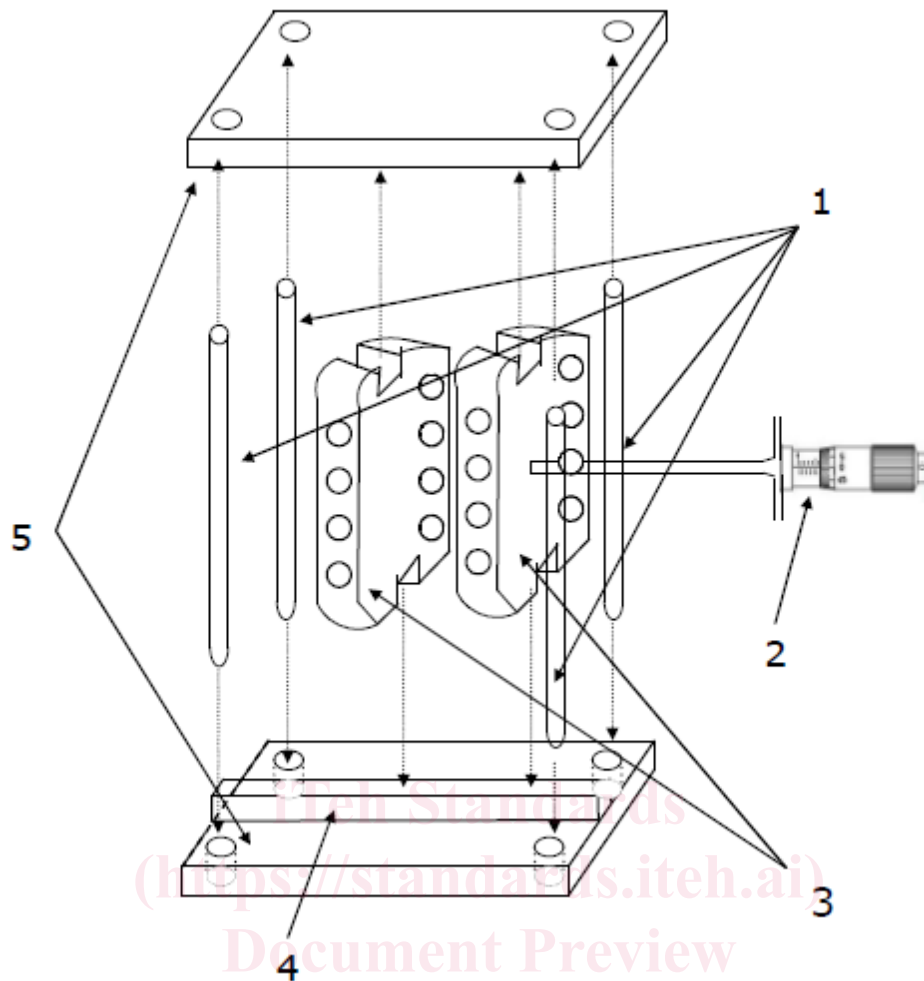
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370 Key

371 1 stainless steel rod

372 2 micrometer

373 3 Cu block

374 4 sliding guide

375 5 Teflon plate

376

Figure 4 – Switch block for thermal connection

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