



DPC: 24 / 30497128 DC

BSI Group Headquarters

389 Chiswick High Road London W4 4AL

Tel: +44 (0)20 8996 9000

Fax: +44 (0)20 8996 7400

www.bsigroup.com

Date: 22 July 2024
Origin: International**Latest date for receipt of comments: 7 August 2024**

Project No. 2024/02023

Responsible committee: W/- Miscellaneous Standards

Interested committees:

Title: BS EN IEC 61788-15 Superconductivity

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

Please notify the secretary if you are aware of any keywords that might assist in classifying or identifying the standard or if the content of this standard

- i) has any issues related to 3rd party IPR, patent or copyright
- ii) affects other national standard(s)
- iii) requires additional national guidance or information

**WARNING: THIS IS A DRAFT AND MUST NOT BE REGARDED OR USED AS A BRITISH STANDARD.
THIS DRAFT IS NOT CURRENT BEYOND 7 August 2024**This draft is issued to allow comments from interested parties; all comments will be given consideration prior to publication. No acknowledgement will normally be sent. **See overleaf for information on the submission of comments.**

No copying is allowed, in any form, without prior written permission from BSI except as permitted under the Copyright, Designs and Patent Act 1988 or for circulation within a nominating organization for briefing purposes. Electronic circulation is limited to dissemination by e-mail within such an organization by committee members.

Further copies of this draft may be purchased from BSI Shop <http://shop.bsigroup.com> or from BSI Customer Services, Tel: +44(0) 20 8996 9001 or email cservices@bsigroup.com. British, International and foreign standards are also available from BSI Customer Services.Information on the co-operating organizations represented on the committees referenced above may be obtained from <http://standardsdevelopment.bsigroup.com>Responsible Committee Secretary: **Committee Service Centre (BSI)**
Direct tel: **020 8996 7009**
E-mail: csc@bsigroup.com

Introduction

This draft standard is based on national and international discussions. Your comments on this draft are invited and will assist in the preparation of the consequent standard.

For international standards, comments will be reviewed by the relevant UK national committee before sending the consensus UK vote and comments to the international committee, which will then decide appropriate action. If the international standard is approved, it is usual for the text to be published as a British Standard.

For national standards, comments will be reviewed by the relevant UK national committee and the resulting standards published as a British Standard.

UK Vote

Please indicate whether you consider the UK should submit a negative (with supporting technical reasons) or positive vote on this draft. Please indicate if you are aware of any reason why this draft standard should not be published as a British Standard.

Submission of Comments

- **Annotated drafts are not acceptable and will be rejected.**
- All comments should be submitted online at <https://standardsdevelopment.bsigroup.com/>. You will need to register in order to comment.

Template for comments and secretariat observations

Date: xx/xx/20xx	Document: ISO/DIS xxxx
------------------	------------------------

1	2	(3)	4	5	(6)	7
MB	Clause No./ Subclause No./Annex (e.g. 3.1)	Paragraph/Figure/ Table/Note	Type of comment	Commend (justification for change) by the MB	Proposed change by the MB	Secretariat observations on each comment submitted
	3.1	Definition 1	ed	Definition is ambiguous and needs clarifying.	Amend to read '...so that the mains connector to which no connection...'	
	6.4	Paragraph 2	te	The use of the UV photometer as an alternative cannot be supported as serious problems have been encountered in its use in the UK.	Delete reference to UV photometer.	



90/523/CD

COMMITTEE DRAFT (CD)

PROJECT NUMBER: IEC 61788-15 ED2	
DATE OF CIRCULATION: 2024-07-12	CLOSING DATE FOR COMMENTS: 2024-09-06
SUPERSEDES DOCUMENTS:	

IEC TC 90 : SUPERCONDUCTIVITY	
SECRETARIAT: Japan	SECRETARY: Mr Jun Fujikami
OF INTEREST TO THE FOLLOWING COMMITTEES:	HORIZONTAL FUNCTION(S):
ASPECTS CONCERNED:	

This document is still under study and subject to change. It should not be used for reference purposes.

Recipients of this document are invited to submit, with their comments, notification of any relevant patent rights of which they are aware and to provide supporting documentation.

Recipients of this document are invited to submit, with their comments, notification of any local regulations or technical reasons that may exist and should be considered should this proposal proceed, recognizing that failure to address such requirements could result in the need for new or existing "In Some Countries" clauses. (SEE [AC/22/2007](#) OR [NEW GUIDANCE DOC](#)).

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

NOTE FROM TC/SC OFFICERS:

CONTENTS

1	FOREWORD.....	5
2	INTRODUCTION.....	7
3	1 Scope.....	8
4	2 Normative references	8
5	3 Terms and definitions	8
6	4 Requirements	9
7	5 Apparatus.....	9
8	5.1 Measurement equipment	9
9	5.2 Measurement apparatus	10
10	5.3 Dielectric rods	14
11	5.4 Superconductor films and copper cavity	15
12	6 Measurement procedure	15
13	6.1 Set-up	15
14	6.2 Measurement of the reference level.....	15
15	6.3 Measurement of the R_s of oxygen-free high purity copper	16
16	6.4 Determination of the effective R_s of superconductor films and $\tan\delta$ of standard dielectric rods	18
17	6.5 Determination of the penetration depth.....	19
18	6.6 Determination of the intrinsic surface impedance.....	21
19	7 Uncertainty of the test method	22
20	7.1 Measurement of unloaded quality factor	22
21	7.2 Measurement of loss tangent.....	22
22	7.3 Temperature.....	23
23	7.4 Specimen and holder support structure	23
24	7.5 Uncertainty in the intrinsic surface impedance	23
25	8 Test Report	23
26	8.1 Identification of test specimen	23
27	8.2 Report of the Z_s values.....	24
28	8.3 Report of the test conditions.....	24
29	Annex A (informative) Additional information relating to clauses 1 to 8.....	25
30	A.1 Concerning the Scope	25
31	A.2 Requirements	26
32	A.3 Theory and the measurement procedure for the intrinsic surface impedance	27
33	A.3.1 Theoretical relation between the Z_s and the Z_{se} [1] ³	27
34	A.3.2 Calculation of the geometrical factors [3]	31
35	A.3.3 Procedure for determining the intrinsic Z_s [1, 3, 4].....	32
36	A.4 Dimensions of the standard sapphire rod.....	34
37	A.5 Dimensions of the closed type resonator	35
38	A.6 Test results for type A and type B sapphire resonators	36
39	A.6.1 Test results for type A resonator.....	36
40	A.6.2 Test results for type B sapphire resonator	40
41	A.7 Uncertainty of the test results	43
42	A.8 Reference documents.....	43
43	Annex B (informative) Standard uncertainty evaluation in the test method for the intrinsic surface impedance of superconductor films at microwave frequencies	44

1	B.1	Assessment of combined uncertainty in the Z_s from uncertainties in the R_{se}	45
2		and λ	
3	B.2	Assessment of combined uncertainty in the Z_s from the measured complex	46
4		conductivity	
5	B.3	Results from the round robin test.....	47
6	B.3.1	Uncertainties in the R_{se} and f_0	47
7	B.3.2	Uncertainty in the λ	50
8	B.3.3	Uncertainties in the Z_s of the YBCO films from the round robin test	50
9	B.3.4	Effects of uncertainty in temperature on $u_r(R_{se})$ from the round robin	
10		test	51
11	B.4	Reference documents of Annex B.....	52
12			
13	Figure 1	Schematic diagram for the measurement equipment for the intrinsic Z_s of	
14		HTS films at cryogenic temperatures	11
15	Figure 2	Schematic diagram of a dielectric resonator with a switch for thermal	
16		connection	11
17	Figure 3	Typical dielectric resonator with a movable top plate	12
18	Figure 4	Switch block for thermal connection	13
19	Figure 5	Dielectric resonator assembled with a switch block for thermal connection.....	14
20	Figure 6	A typical resonance peak. Insertion attenuation IA , resonant frequency f_0	
21		and half power bandwidth Δf_{3dB} are defined	17
22	Figure 7	Reflection scattering parameters S_{11} and S_{22}	19
23	Figure 8	Definitions for terms in Table 5	23
24	Figure A.1	Schematic diagram for the measurement system	25
25	Figure A.2	A motion stage using step motors	26
26	Figure A.3	Cross-sectional view of a dielectric resonator	27
27	Figure A.4	A diagram for simplified cross-sectional view of a dielectric resonator	31
28	Figure A.5	Mode chart for type A sapphire resonator with a cavity diameter of 12 mm	35
29	Figure A.6	Frequency response of the sapphire resonator	36
30	Figure A.7	Q_U versus temperature for the TE_{021} and the TE_{012} modes of the sapphire	
31		resonator with 360 nm-thick YBCO films	37
32	Figure A.8	The resonant frequency f_0 versus temperature for the TE_{021} and TE_{012}	
33		modes of the sapphire resonator with 360 nm-thick YBCO films.....	37
34	Figure A.9	The temperature dependence of the R_{se} of YBCO films with the	
35		thicknesses of 70 nm to 360 nm measured at ~40 GHz.....	38
36	Figure A.10	The temperature dependence of $\Delta\lambda_e$ for the YBCO films with the	
37		thicknesses of 70 nm and 360 nm measured at ~40 GHz	38
38	Figure A.11	The penetration depths λ of the 360 nm-thick YBCO film measured at	
39		10 kHz by using the mutual inductance method and at ~40 GHz by using sapphire	
40		resonator	39
41	Figure A.12	The temperature dependence of the intrinsic surface resistance R_s of	
42		YBCO films with the thicknesses of 70 nm to 360 nm measured at ~40 GHz.....	39
43	Figure A.13	Mode chart used for type B sapphire resonator with a cavity diameter of	
44		15.78 mm.	40
45	Figure A.14	Frequency response of type B sapphire resonator	41
46	Figure A.15	The temperature dependence of the R_{se} for the 300 nm-thick YBCO films	
47		measured at ~38 GHz Inset-The $\tan \delta$ of the sapphire rod used for the measurements	41

1	Figure A.16 – The temperature dependence of $\Delta\lambda_e$ for the 300 nm-thick YBCO film	
2	measured at ~38 GHz Inset-The penetration depths λ of the 300 nm-thick YBCO film	
3	measured at ~38 GHz using type B sapphire resonator.....	42
4	Figure A.17 – The σ_2 vs. temperature data for the 300 nm-thick YBCO films measured	
5	at ~38 GHz Inset-The σ_1 vs. temperature data for the same YBCO films at ~38 GHz.....	42
6	Figure A.18 – The R_s vs. temperature data for the 300 nm-thick YBCO films measured	
7	at ~38 GHz Inset- The X_s for the same YBCO films at ~38 GHz.....	43
8	Figure B.1 – The measured TE ₀₂₁ -mode Q_U vs. temperature data from the round robin	
9	test. Inset: The measured TE ₀₁₂ -mode Q_U vs. temperature data from the round robin	
10	test.	47
11	Figure B.2 – The measured resonant frequencies of the TE ₀₂₁ mode as functions of	
12	temperature for the sapphire resonator under the round robin test.	48
13	Figure B.3 – The relative uncertainty in the TE ₀₂₁ mode Q_U and the TE ₀₁₂ mode Q_U as	
14	functions of temperature from the round robin test.	48
15	Figure B.4 – The relative uncertainty in the TE ₀₂₁ mode f_0 vs. temperature data from	
16	the round robin test. Inset: The uncertainty in the TE ₀₂₁ mode f_0 vs. temperature data	49
17	Figure B.5 – Comparison of the measured R_{se} at ~ 38 GHz vs. temperature data for	
18	the YBCO films under the round robin test. Inset: The measured loss tangent of	
19	sapphire vs. temperature data at ~ 38 GHz obtained simultaneously with the R_{se}	
20	values. The missing data points from KU and YU are due to the $\tan \delta$ values appearing	
21	negative.....	49
22	Figure B.6 – The relative uncertainties in the R_{se} (open square) and R_s (filled square)	
23	at ~ 38 GHz as functions of temperature for the YBCO films under the round robin test.	
24	Inset: The average R_{se} (open square) and the corresponding R_s (filled square) at ~ 38	
25	GHz as functions of temperature for the 300 nm-thick YBCO films under the round	
26	robin test.	50
27	Figure B.7 – The relative uncertainties in the TE ₀₂₁ -mode Q_U from the RRT (open	
28	circle) and that due to the presumed uncertainty of 0.5 K in the temperature (cross) at	
29	~ 38 GHz as functions of temperature for type B sapphire resonator.....	52
30		
31	Table 1 – Typical dimensions of a sapphire rod	15
32	Table 2 – Typical dimensions of OFHC cavities and HTS films.....	15
33	Table 3 – Geometrical factors and filling factors calculated for the standard sapphire	
34	resonators	18
35	Table 4 – Specifications of Vector Network Analyzer	22
36	Table 5 – Type B uncertainty for the specifications on the sapphire rod	22
37	Table B.1 – Values of ϵ_{r4} , l , t , β_4 , β_{z4} , β_h , λ and $\coth(t/\lambda)$ at 30 K.	46
38	Table B.2 – The average values for the R_{se} and the R_s of the YBCO films from the	
39	round robin test and the relative uncertainties in the R_{se} and the R_s . A relative	
40	uncertainty of 2% in the YBCO film thickness was used for obtaining the $u_r(R_s)$ values.....	51

41

42

INTERNATIONAL ELECTROTECHNICAL COMMISSION

SUPERCONDUCTIVITY –

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

FOREWORD

- 1) The International Electrotechnical Commission (IEC) 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.
- 2) The formal decisions or agreements of the IEC on technical matters express, as nearly as possible, an international consensus of opinion on the relevant subjects since each technical committee has representation from all interested National Committees.
- 3) IEC Publications have the form of recommendations for international use and are accepted by IEC National Committees in that sense. While all reasonable efforts are made to ensure that the technical content of IEC Publications is accurate, IEC cannot be held responsible for the way in which they are used or for any misinterpretation by any end user.
- 4) In order to promote international uniformity, IEC National Committees undertake to apply IEC Publications transparently to the maximum extent possible in their national and regional publications. Any divergence between any IEC Publication and the corresponding national or regional publication shall be clearly indicated in the latter.
- 5) IEC itself does not provide any attestation of conformity. Independent certification bodies provide conformity assessment services and, in some areas, access to IEC marks of conformity. IEC is not responsible for any services carried out by independent certification bodies.
- 6) All users should ensure that they have the latest edition of this publication.
- 7) No liability shall attach to IEC or its directors, employees, servants or agents including individual experts and members of its technical committees and IEC National Committees for any personal injury, property damage or other damage of any nature whatsoever, whether direct or indirect, or for costs (including legal fees) and expenses arising out of the publication, use of, or reliance upon, this IEC Publication or any other IEC Publications.
- 8) Attention is drawn to the Normative references cited in this publication. Use of the referenced publications is indispensable for the correct application of this publication.
- 9) IEC draws attention to the possibility that the implementation of the document may involve the use of a patent. IEC takes no position concerning the evidence, validity or applicability of any claimed patent rights in respect thereof. As of the date of publication of this document, IEC had not received notice of a patent, which may be required to implement this document. However, implementers are cautioned that this may not represent the latest information, which may be obtained from the patent database available at <http://patents.iec.ch> and/or www.iso.org/patents. IEC shall not be held responsible for identifying any or all such patent rights..

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

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.

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

Draft	Report on voting
XX/XX/FDIS	XX/XX/RVD

2
3 Full information on the voting for its approval can be found in the report on voting indicated in
4 the above table.

5 The language used for the development of this International Standard is **English [change**
6 **language if necessary]**.

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

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

- 14 • reconfirmed,
15 • withdrawn, or
16 • revised.

17

18

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 $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ (YBCO) having already been commercialized [1]¹⁾.

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 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 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 microstrip resonator method [3], coplanar microstrip resonator method [4], parallel plate resonator method [5] and 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, International Electrotechnical Commission (IEC) published the dielectric resonator method as a measurement standard [11].

The test method given in this standard enables to measure not only the intrinsic surface resistance but also the intrinsic surface reactance of HTS films regardless of the film's thickness by using single sapphire resonator, which differs from the existing IEC standard (IEC 61788-7:2020) 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 [12, 13]. Use of single sapphire resonator as suggested in this standard also enables 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 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 60050-815:2000, *International Electrotechnical Vocabulary – Part 815: Superconductivity*

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

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

3 Terms and definitions

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

3.1

Surface impedance

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

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:

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

²) Numerals in square brackets refer to the Bibliography.

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

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

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 with $\sigma_2 = 0$ and complex for superconductors in the superconducting state.

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 3.1 becomes significantly different from that defined by Equation (2) in 3.1. In this case, Z_s as defined by Equation (1) is called the effective surface impedance Z_{se} with

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

Here R_{se} denotes the effective surface resistance and X_{se} is 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 20 % at temperatures of 30 K to 65 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.

1 The measurement apparatus is fixed in a temperature-controlled cryocooler.

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

4 **5.2 Measurement apparatus**

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

12 The R_{se} is measured with the upper HTS film being in contact with the top of the Cu cavity.
13 During measurements of the R_{se} , the whole resonator is first cooled down to the lowest
14 temperature with the cryocooler turned on and then warmed up to higher temperatures with the
15 cryocooler turned off. Meanwhile, the X_{se} is measured with a small gap between the upper HTS
16 film and the top of the Cu cavity. The gap distance shall be set to a value predetermined at the
17 room temperature by using either a micrometer or a step motor connected to the upper
18 superconductor film through a Teflon rod. The real gap distances would be a little longer at
19 cryogenic temperatures than the corresponding predetermined ones due to thermal contraction
20 of the Teflon rod. The gap distance should be small enough not to cause significant radiation
21 loss and large enough to enable control of the temperature of the upper superconductor film.
22 More detailed descriptions on a dielectric resonator with a movable top plate, a switch block for
23 thermal connection, and the dielectric resonator assembled with the switch block are given in
24 Figures 3 to 5, respectively. Procedures for controlling the temperature of the upper HTS film
25 for measurements of the X_s are described in 6.6.

26 Each of the two semi-rigid cables shall have a small loop at the end as shown in Figure 3. The plane
27 of the loop shall be set parallel to that of the HTS films in order to suppress the unwanted TM_{mn0}
28 modes. The coupling loops shall be carefully checked prior to the measurements to keep the good
29 coupling conditions. These cables can move to the right or to the left to adjust the insertion
30 attenuation (I/A). In this adjustment, coupling of unwanted cavity modes to the interested dielectric
31 resonance mode shall be suppressed. Unwanted, parasitic coupling to the other modes not only
32 reduces the high- Q value of the TE mode resonator but also increases uncertainty in the measured
33 resonant frequency of the TE mode resonator, making it difficult to measure changes in the resonant
34 frequency vs. temperature data with accuracy.

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

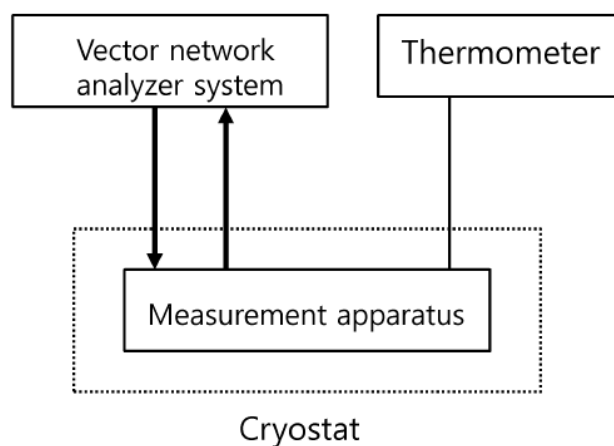
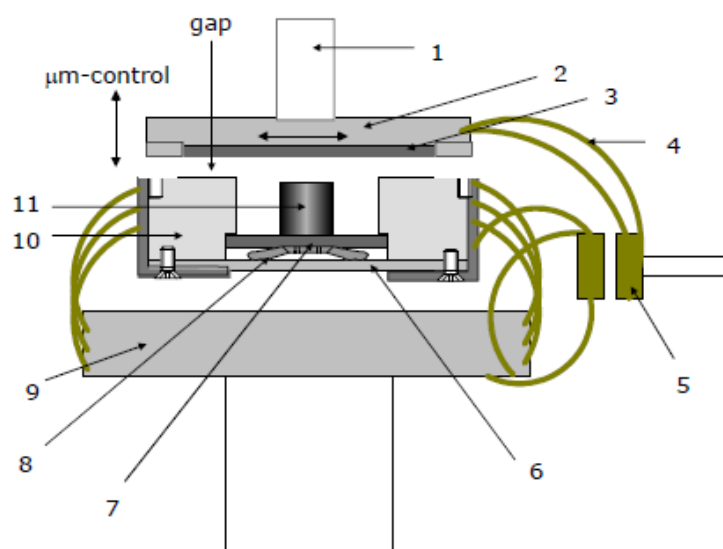


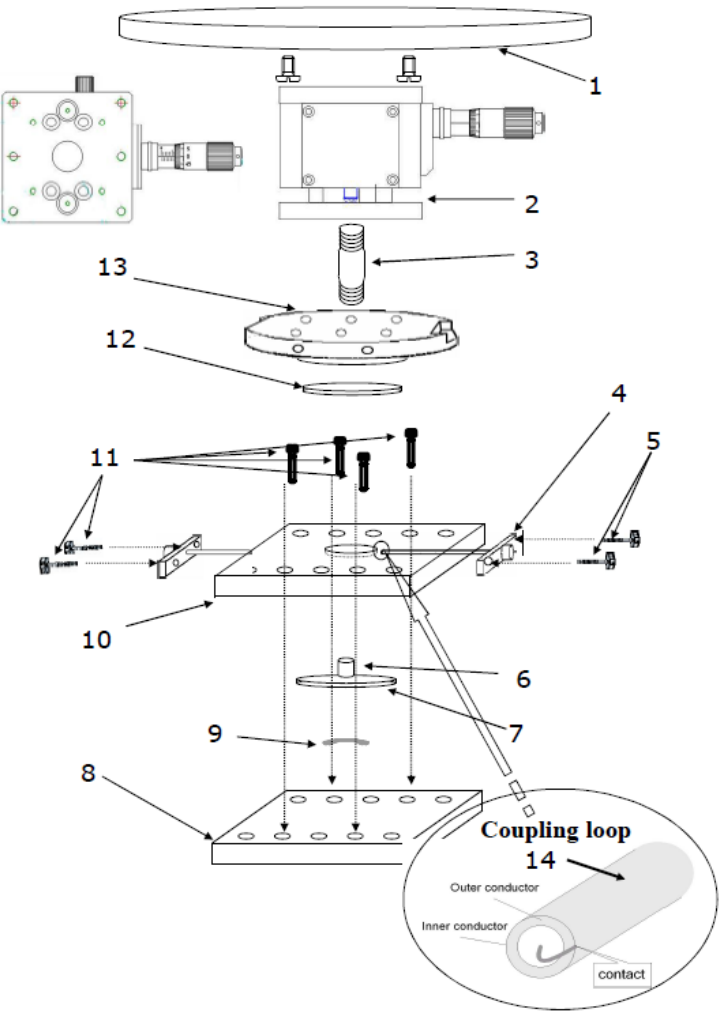
Figure 1 – Schematic diagram for the measurement equipment for the intrinsic Z_s of HTS films at cryogenic temperatures



Key

- 1 teflon 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

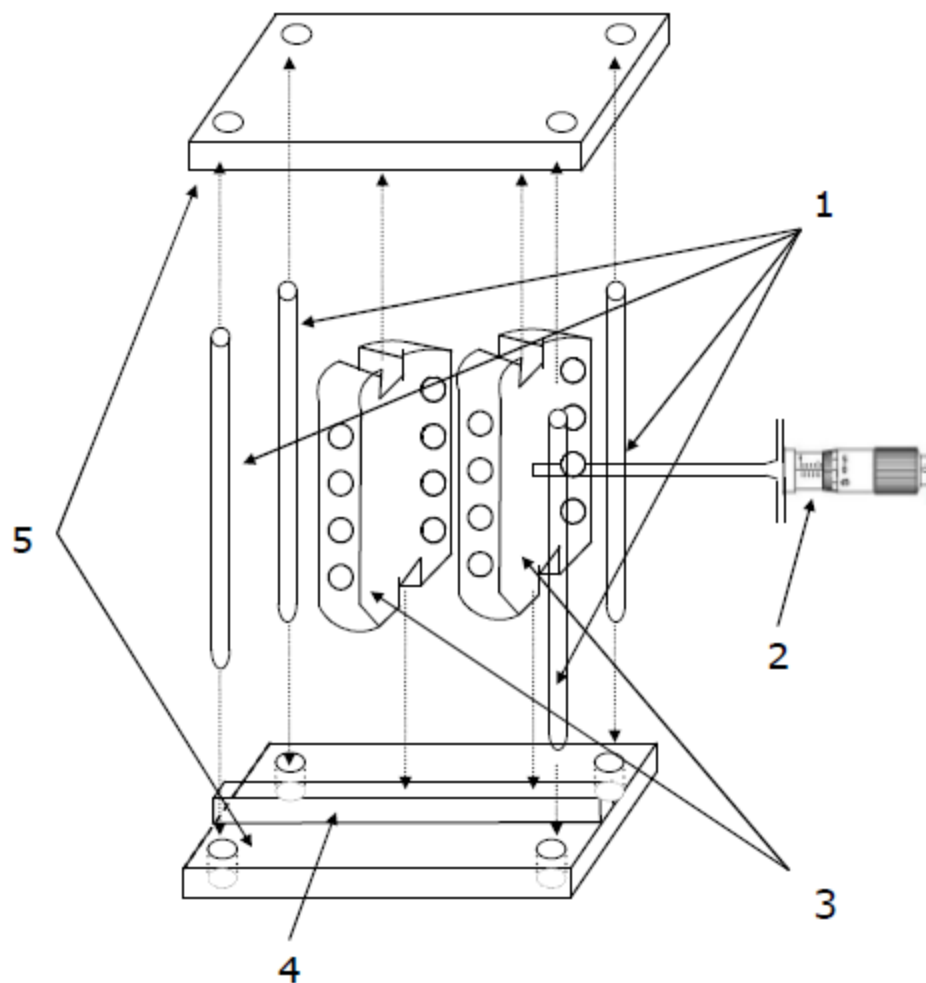
Figure 2 – Schematic diagram of a dielectric resonator with a switch for thermal connection



Key

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	

Figure 3 – Typical dielectric resonator with a movable top plate



- 1
- 2 Key
- 3 1 SUS rod
- 4 2 micrometer
- 5 3 Cu block
- 6 4 sliding guide
- 7 5 teflon plate

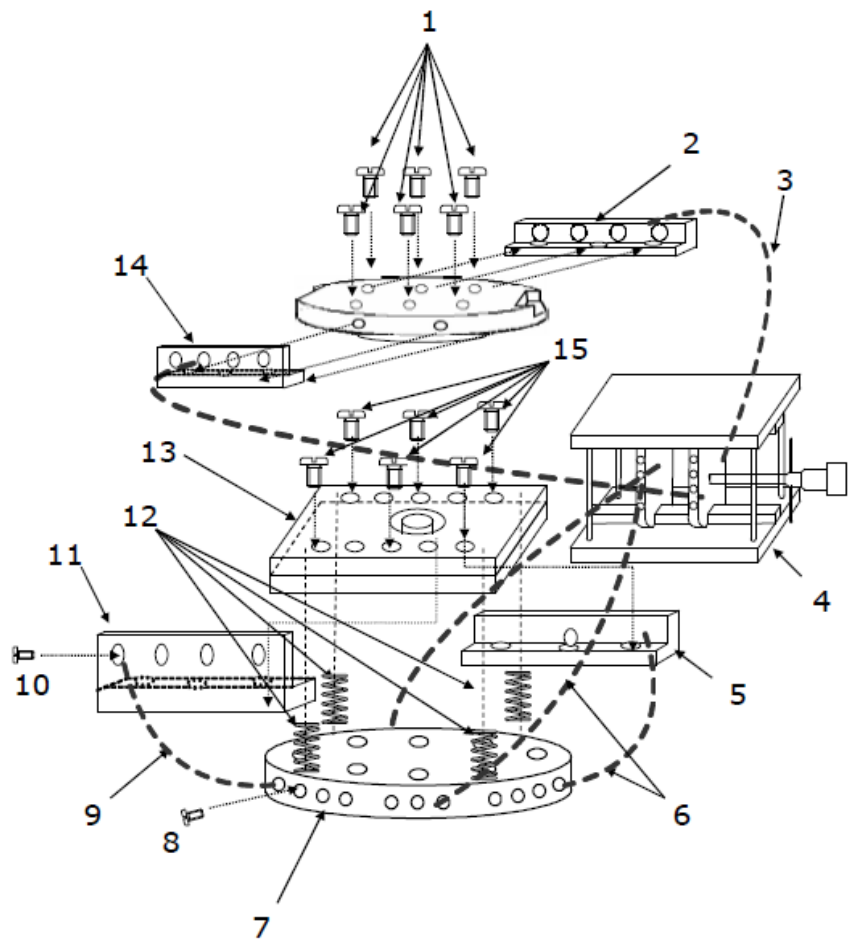
Figure 4 – Switch block for thermal connection

9

10

11

12



Key

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

The dielectric rods shall have low $\tan \delta$ 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 $\epsilon_{a-b}' = 9,28$ 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 TE₀₂₁-mode sapphire resonator. The resonant frequencies become lower if the dimensions are greater, for which, however, larger HTS films are to be used to maintain the requisite measurement uncertainty.

Table 1 – Typical dimensions of a sapphire rod

(Unit: GHz)

Resonator type	diameter (mm)	height (mm)	TE ₀₁₁ -mode frequency	TE ₀₁₂ -mode frequency	TE ₀₂₁ -mode frequency
A	5,000	2,860	25,27	40,06	39,97
B	5.258	2.993	24.10	38.23	38.05

5.4 Superconductor films and copper cavity

Oxygen-free high-purity copper (OFHC) shall be used for the surrounding wall of the dielectric resonator. The diameter of the OFHC cavity shall be determined in such a way that the requisite measurement uncertainty can be realized. Typical dimensions of OFHC cavities and HTS films suggested for the standard sapphire rod are listed in Table 2.

Table 2 – Typical dimensions of OFHC cavities and HTS films

(Unit: mm)

Resonator type	Sapphire rod		OFHC cavity		HTS films
	diameter	height	diameter	height	diameter
A	5,000	2,860	12,00	2,860	≥ 14
B	5.258	2.993	15.78	2.993	≥ 18,0

6 Measurement procedure

6.1 Set-up

The measurement equipment shall be set up as shown in Figure 1. The measurement apparatus, standard dielectric rods, and HTS films shall be kept in a clean and dry state as dust and high humidity may affect the measurement results.

6.2 Measurement of the reference level

The level of full transmission power (reference level) shall be measured prior to measurements of the resonator Q-value as a function of temperature. The measurement procedure is as follows.

- (1) Fix the output power of the synthesized sweeper at a value below 10 mW (typically 1 mW) because the measurement uncertainty depends on the measuring signal level
- (2) Connect a reference line of semi-rigid cable between the input and output connectors. The length of the reference line shall be the same as the sum of the lengths of the two semi-rigid cables with a loop at each end as described in 5.2.
- (3) Measure the transmission power level over the frequency range and temperature range of interest.