IEC 61788-16

Edition 1.0 2013-01

INTERNATIONAL STANDARD

NORME INTERNATIONALE

colour
inside

Superconductivity –
Part 16: Electronic characteristic measurements – Power-dependent surface resistance of superconductors at microwave frequencies

Supraconductivité –
Partie 16: Mesures de caractéristiques électroniques – Résistance de surface des supraconducteurs aux hyperfréquences en fonction de la puissance

IEC Central Office
3, rue de Varembé
CH-1211 Geneva 20
Switzerland

Tel.: +41 22 919 02 11
Fax: +41 22 919 03 00
info@iec.ch
www.iec.ch

About the IEC

The International Electrotechnical Commission (IEC) is the leading global organization that prepares and publishes International Standards for all electrical, electronic and related technologies.

About IEC publications

The technical content of IEC publications is kept under constant review by the IEC. Please make sure that you have the latest edition, a corrigenda or an amendment might have been published.

Useful links:

IEC publications search - www.iec.ch/searchpub

The advanced search enables you to find IEC publications by a variety of criteria (reference number, text, technical committee,…).
It also gives information on projects, replaced and withdrawn publications.

IEC Just Published - webstore.iec.ch/justpublished

Stay up to date on all new IEC publications. Just Published details all new publications released. Available on-line and also once a month by email.

Electropedia - www.electropedia.org

The world's leading online dictionary of electronic and electrical terms containing more than 30 000 terms and definitions in English and French, with equivalent terms in additional languages. Also known as the International Electrotechnical Vocabulary (IEV) on-line.

Customer Service Centre - webstore.iec.ch/csc

If you wish to give us your feedback on this publication or need further assistance, please contact the Customer Service Centre: csc@iec.ch.

A propos de la CEI

La Commission Electrotechnique Internationale (CEI) est la première organisation mondiale qui élabore et publie des Normes internationales pour tout ce qui a trait à l'électricité, à l'électronique et aux technologies apparentées.

A propos des publications CEI

Le contenu technique des publications de la CEI est constamment revu. Veuillez vous assurer que vous possédez l'édition la plus récente, un corrigendum ou amendement peut avoir été publié.

Liens utiles:

Recherche de publications CEI - www.iec.ch/searchpub

La recherche avancée vous permet de trouver des publications CEI en utilisant différents critères (numéro de référence, texte, comité d'études,…).
Elle donne aussi des informations sur les projets et les publications remplacées ou retirées.

Just Published CEI - webstore.iec.ch/justpublished

Restez informé sur les nouvelles publications de la CEI. Just Published détaille les nouvelles publications parues. Disponible en ligne et aussi une fois par mois par email.

Electropedia - www.electropedia.org

Le premier dictionnaire en ligne au monde de termes électroniques et électriques. Il contient plus de 30 000 termes et définitions en anglais et en français, ainsi que les termes équivalents dans les langues additionnelles. Egalement appelé Vocabulaire Electrotechnique International (VEI) en ligne.

Service Clients - webstore.iec.ch/csc

Si vous désirez nous donner des commentaires sur cette publication ou si vous avez des questions contactez-nous: csc@iec.ch.

IEC 61788-16

Edition 1.0 2013-01

INTERNATIONAL STANDARD

NORME INTERNATIONALE

colour
inside

Superconductivity –
Part 16: Electronic characteristic measurements – Power-dependent surface resistance of superconductors at microwave frequencies

Supraconductivité –
Partie 16: Mesures de caractéristiques électroniques – Résistance de surface des supraconducteurs aux hyperfréquences en fonction de la puissance

INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

COMMISSION
ELECTROTECHNIQUE
INTERNATIONALE

PRICE CODE
CODE PRIX **V**

ICS 17.220.20; 29.050 ISBN 978-2-83220-582-2

Warning! Make sure that you obtained this publication from an authorized distributor.
Attention! Veuillez vous assurer que vous avez obtenu cette publication via un distributeur agréé.

CONTENTS

INTERNATIONAL ELECTROTECHNICAL COMMISSION

SUPERCONDUCTIVITY –

Part 16: Electronic characteristic measurements – Power-dependent surface resistance of superconductors 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 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, IEC publishes International Standards, Technical Specifications, Technical Reports, Publicly Available Specifications (PAS) and Guides (hereafter referred to as "IEC Publication(s)"). 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. 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 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 IEC 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) Attention is drawn to the possibility that some of the elements of this IEC Publication may be the subject of patent rights. IEC shall not be held responsible for identifying any or all such patent rights.

International Standard IEC 61788-16 has been prepared by IEC technical committee 90: Superconductivity.

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

FDIS	Report on voting
90/309/FDIS	90/318/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 the 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 publication will remain unchanged until the stability date indicated on the IEC web site under "http://webstore.iec.ch" in the data related to the specific publication. At this date, the publication will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

IMPORTANT – The 'colour inside' logo on the cover page of this publication indicates that it contains colours which are considered to be useful for the correct understanding of its contents. Users should therefore print this document using a colour printer.

INTRODUCTION

Since the discovery of high-T_c superconductors (HTS), extensive researches have been performed worldwide for electronic applications and large-scale applications.

In the fields of electronics, especially in telecommunications, microwave passive devices such as filters using HTS are being developed and testing is underway on sites [1,2,3,4][1].

Superconductor materials for microwave resonators, filters, antennas and delay lines have the advantage of ultra-low loss characteristics. Knowledge of this parameter is vital for the development of new materials on the supplier side and the design of superconductor microwave components on the customer side. The parameters of superconductor materials needed to design microwave components are the surface resistance R_s and the temperature dependence of the R_s. Recent advances in HTS thin films with R_s, several orders of magnitude lower than normal metals has increased the need for a reliable characterization technique to measure this property [5,6]. Among several methods to measure the R_s of superconductor materials at microwave frequencies, the dielectric resonator method [7,8,9] has been useful due to that the method enables to measure the R_s nondestructively and accurately. In particular, the sapphire resonator is an excellent tool for measuring the R_s of HTS materials [10]. 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 of the power-dependent surface resistance of superconductors at microwave frequencies. For high power microwave device applications such as those of transmitting devices, not only the temperature dependence of R_s but also the power dependence of R_s is needed to design the microwave components. Based on the measured power dependence, the RF current density dependence of the surface resistance can be evaluated. The simulation software to design the device gives the RF current distribution in the device. The results of the power dependence measurement can be directly compared with the simulation and allow the power handling capability of the device to be evaluated.

The test method given in this standard can be also applied to other superconductor bulk plates including low-T_c material.

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

The test method covered in this standard 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 16: Electronic characteristic measurements – Power-dependent surface resistance of superconductors at microwave frequencies

1 Scope

This part of IEC 61788 involves describing the standard measurement method of power-dependent surface resistance of superconductors at microwave frequencies by the sapphire resonator method. The measuring item is the power dependence of R_s at the resonant frequency.

The following is the applicable measuring range of surface resistances for this method:

Frequency: $f \sim 10$ GHz

Input microwave power: $P_{in} < 37$ dBm (5 W)

The aim is to report the surface resistance data at the measured frequency and that scaled to 10 GHz using the $R_s \propto f^2$ relation for comparison.

2 Normative references

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60050 (all parts), *International Electrotechnical Vocabulary* (available at: <http://www.electropedia.com>)

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

3 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
surface impedance

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

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

Note 2 to entry: In general, surface impedance Z_s for conductors including superconductors is defined as the ratio of the electric field E_t to the magnetic field H_t, tangential to a conductor surface:

$Z_s = E_t / H_t = R_s + jX_s$,

where R_s is the surface resistance and X_s is the surface reactance.

4 Requirements

The surface resistance R_s of a superconductor film shall be measured by applying a microwave signal to a sapphire resonator with the superconductor film specimen and then measuring the insertion attenuation of the resonator at each frequency. The frequency shall be swept around the resonant frequency as the center and the insertion 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 the coefficient of variation (standard deviation divided by the average of the surface resistance determinations), which is less than 20 % for a measurement temperature range from 30 K to 80 K.

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

Hazards exist in such measurement. The use of a cryogenic system is essential to cool the superconductors and 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 the high-frequency properties of materials. If its power is excessive, direct contact to human bodies could cause immediate burns.

5 Apparatus

5.1 Measurement system

5.1.1 Measurement system for the tan δ of the sapphire rod

Figure 1 shows a schematic diagram of the system required for the tan δ measurement. The system consists of a network analyzer system for transmission measurements, a measurement apparatus in which a sapphire resonator with superconductor films is fixed, and a thermometer for monitoring the measuring temperature.

The incident power generated from a suitable microwave source such as a synthesized sweeper is applied to the sapphire 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.

To measure the tan δ of the sapphire rod, a vector network analyzer is recommended, since its measurement accuracy is superior to a scalar network analyzer due to its wide dynamic range.

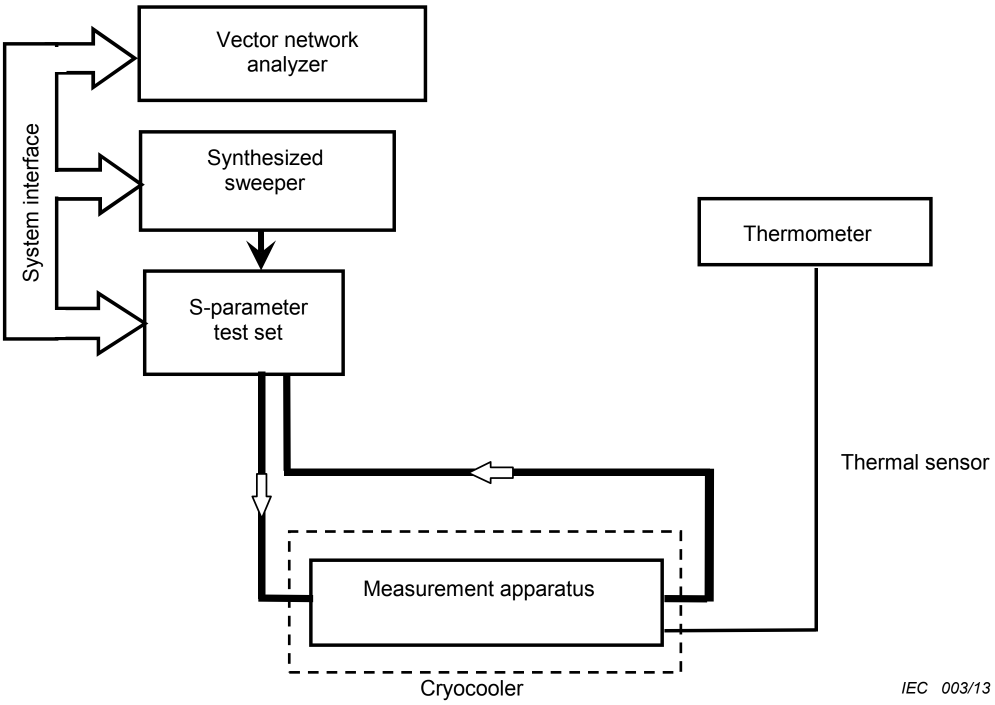


Figure 1 – Measurement system for tan δ of the sapphire rod

5.1.2 Measurement system for the power dependence of the surface resistance of superconductors at microwave frequencies

Figure 2 shows the measurement system for the power dependence of the surface resistance of superconductors using a sapphire resonator. A travelling wave tube (TWT) power amplifier with a maximum output power of around 40 dBm is inserted at the input into the resonator. The maximum input power into the resonator is around 37 dBm in this measurement system shown in Figure 2. The typical maximum input power of a network analyzer is in the order of 0 dBm, so a measurement circuit shall be designed to avoid direct exposure of high powered microwaves to the network analyzer, and also by using a circulator and an attenuator, significant reflection from the sapphire resonator should not affect the TWT amplifier.

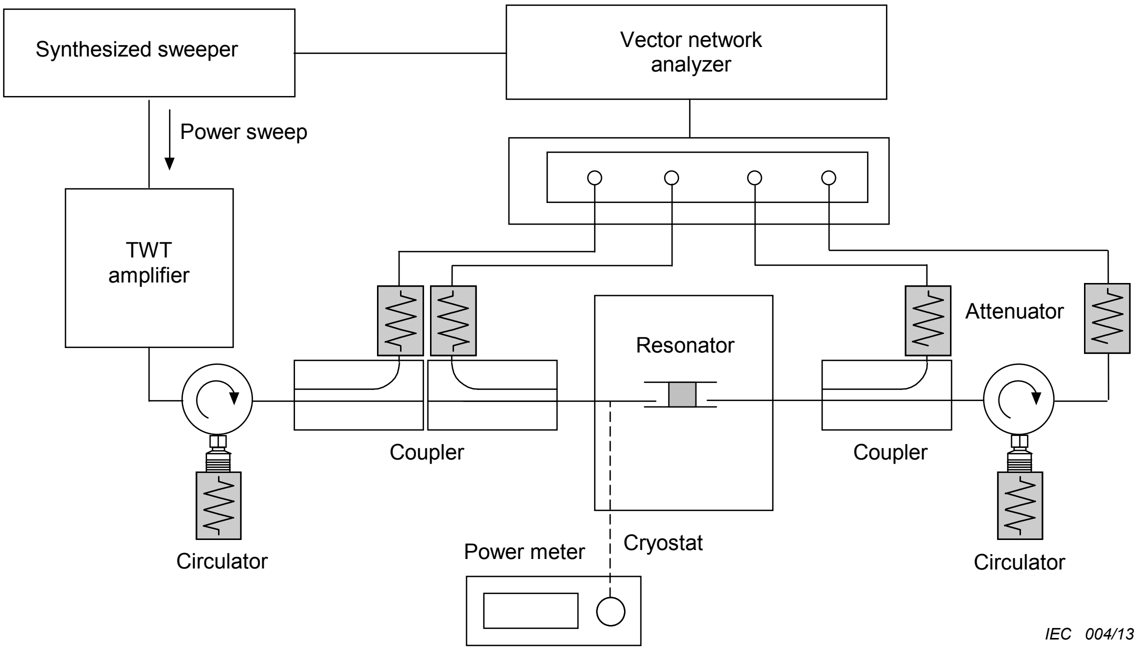


Figure 2 – Measurement system for the microwave power dependence of the surface resistance

Incident microwave power to the resonator is calibrated using a power meter before the measurement (dotted line in Figure 2). The incident power of the microwave is swept by changing the input power of the TWT amplifier.

5.2 Measurement apparatus

5.2.1 Sapphire resonator

Figure 3 shows a schematic diagram of a typical sapphire resonator (open type resonator) used to measure R_s of superconductor films and tan δ of the sapphire rod [9]. In the sapphire resonator, a sapphire rod was sandwiched between two superconducting films. The upper superconductor film is pressed down by a spring, which is made of phosphor bronze. The use of a plate type spring is recommended to improve measurement accuracy. This type of spring reduces the friction between the spring and the rest of the apparatus, and facilitates the movement of superconductor films during the thermal expansion of the sapphire rod.

Two semi-rigid cables for measuring transmission characteristics of the resonator shall be attached on both sides of the resonator in axially symmetrical positions ($\phi = 0$ and π, where ϕ is the rotational angle around the central axis of the sapphire rod). A semi-rigid cable with an outer diameter of 3,50 mm is recommended. Each of the two semi-rigid cables shall have a small loop at the end. The plane of the loop shall be set parallel to that of the superconductor films in order to suppress the unwanted 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 modes to the interested resonance mode shall be suppressed. Unwanted coupling to the other modes reduces the high Q value of the TE mode resonator. To suppress the unwanted coupling, special attention shall be paid to designing high Q resonators. Two other types of resonators usable along with the open type shown in Figure 3 are explained in A.1.

A reference line made of a semi-rigid cable shall be used to measure the full transmission power level, i.e. the reference level. The cable length equals to the sum of the two cables of the measurement apparatus.

To minimize the measurement error, two superconductor films shall be set in parallel. To ensure that the two superconductor films remain in tight contact with the ends of the sapphire rod, without any air gap, the surface of the two films and both ends of the rod shall be cleaned carefully.

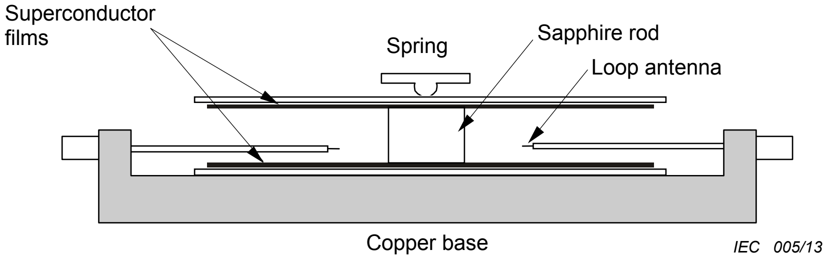


Figure 3 – Sapphire resonator (open type) to measure the surface resistance of superconductor films

5.2.2 Sapphire rod

A high-quality sapphire rod with low tan δ is required to achieve the requisite measurement accuracy on R_s. A recommended sapphire rod is expected to have a tan δ less than 10^{-6} at 77 K. 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 of the sapphire rods are described in 7.1.

The diameter and height of the sapphire rod shall be carefully designed to ensure the TE_{011}, TE_{021} and TE_{012} modes do not couple to other TM, HE and EH modes, since coupling between TE mode and other modes causes the unloaded Q to deteriorate. The design guideline for the sapphire rod is described in A.2. Table 1 shows typical dimensions of the sapphire rod for a TE_{011}–mode resonant frequency of about 10 GHz.

Table 1 – Typical dimensions of the sapphire rod

Resonance Mode	**Frequency** GHz	**Diameter**	**Height**
		d mm	h mm
TE_{011}	10,6	11,8	6,74
TE_{021}	17,0		
TE_{012}	17,0		

5.2.3 Superconductor films

The diameter of the superconductor films shall be about three times larger than that of the sapphire rods. In this configuration, the increased uncertainty of R_s due to the radiation loss can be considered negligible, given the target relative combined standard uncertainty of 20%.

The film thickness shall be more than three times larger than the London penetration depth value at each temperature. If the film thickness is less than three times the London penetration depth, the measured R_s should mean the effective surface resistance.

6 Measurement procedure

6.1 Set-up

All the components of the sapphire resonator, such as the sapphire rod, superconductor films, and so on, shall be kept in a clean and dry state such as in a dry box or desiccator, as high humidity may degrade the unloaded Q-value.

The sapphire resonator shall be fixed in a specimen chamber inside the temperature-controlled cryocooler. The specimen chamber shall be generally evacuated. The temperatures of the superconductor films and sapphire rod shall be measured by a diode thermometer, or a thermocouple. The temperatures of the upper and lower superconductor films, and the sapphire rod must be kept as close as possible. This can be achieved by covering the sapphire resonator with aluminum foil, or filling the specimen chamber with helium gas.

6.2 Measurement of the tan δ of the sapphire rod

6.2.1 General

To measure the surface resistance of the superconductor films precisely using a sapphire resonator, the tan δ of the sapphire rod shall be known. The two-resonance mode dielectric resonator method [12,13], which uses the TE_{021} and TE_{012} modes of the same sapphire resonator shall be adopted to measure the tan δ of the sapphire rod. The measurement procedure of the tan δ is as follows:

6.2.2 Measurement of the frequency response of the TE_{021} mode

The temperature dependence of the resonant frequency f_0 and unloaded quality factor Q_u for TE_{021} resonance mode shall be measured as follows:

a) Connect the measurement system as shown in Figure 1. Fix the distance between the sapphire rod and each of the loops of the semi-rigid cables to be equal, so that this transmission-type resonator can be under-coupled equally to both loops. The coupling shall be adjusted to be weak enough not to excite unwanted resonance modes such as TM, HE and EH modes but strong enough to be able to excite TE_{021} mode. The input power to the resonator shall be below 10 dBm (typically 0 dBm). Confirm that the insertion attenuation of this mode is larger than 20 dB from the reference level. Evacuate and cool down the specimen chamber to below the critical temperature.

b) Measure S_{21} as a function of frequency where S_{21} is the transmission scattering parameter. Find the TE_{021} mode $|S_{21}|$ resonance peak of this resonator at a frequency nearly equal to the designed value of the resonant frequency f_0.

c) Narrow the frequency span on the display so that only the $|S_{21}|$ resonance peak of TE_{021} mode can be shown.

d) Collect both real and imaginary parts of the S_{21} , S_{11} and S_{22} as a function of frequency ($S_{21}(f)$, $S_{11}(f)$ and $S_{22}(f)$) where S_{11} and S_{22} are reflection scattering parameters.

e) Resonant frequency f_0 and loaded Q-value Q_L are obtained by fitting the experimentally measured data $S_{21}(f)$ to the Equation (1), where f_0 and Q_L are fitting parameters.

$$S_{21}(f) = \frac{S_{21}(f_0)}{1 + \mathrm{j}Q_\mathrm{L}\Delta(f)} \qquad (1)$$

where f is frequency and $\Delta(f)$ is defined as

$$\Delta(f) = 1 - \frac{f_0^2}{f^2} \qquad (2)$$

This fitting technique is called the “Circle fit technique”, the details of which are described in A.3.

f) The unloaded Q-value, Q_U, shall be extracted from the Q_L by the following Equation (3):

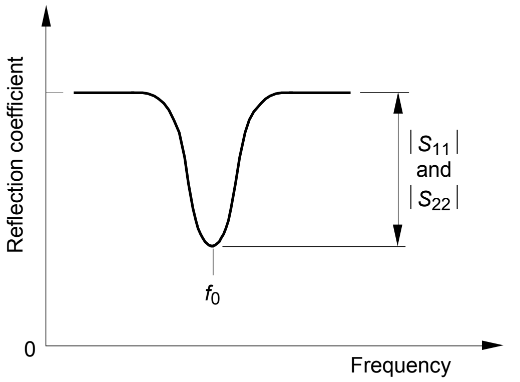
$$Q_\mathrm{U} = Q_\mathrm{L}(1 + \beta_1 + \beta_2) \qquad (3)$$

where β_1 and β_2 are the coupling coefficients and defined as

$$\beta_1 = \frac{1 - |S_{11}|}{|S_{11}| + |S_{22}|} \qquad (4)$$

$$\beta_2 = \frac{1 - |S_{22}|}{|S_{11}| + |S_{22}|} \qquad (5)$$

where $|S_{11}|$ and $|S_{22}|$ are dips in the reflection scattering parameters at f_0 as shown in Figure 4, and measured in linear units of power rather than relative dB.



IEC 006/13

Figure 4 – Reflection scattering parameters (|S_{11}| and |S_{22}|)

g) The f_0 and Q_U measured for this TE_{021} mode are denoted as f_{021} and Q_{U021}. By slowly changing the temperature of the cryocooler, the temperature dependence of f_{021} and Q_{U021} shall be measured.

6.2.3 Measurement of the frequency response of the TE_{012} mode

The temperature dependence of the resonant frequency f_0 and unloaded quality factor Q_U for the TE_{012} resonance mode shall be measured similarly to the TE_{021} resonance mode. The procedure is as follows:

a) After measuring the TE_{021} mode, cool down the specimen chamber below the critical temperature again.

b) Measure S_{21} as a function of frequency. Find the TE_{012} mode |S_{21}| resonance peak of this resonator at a frequency nearly equal to the designed value of the resonant frequency f_0.

c) Narrow the frequency span on the display so that only the |S_{21}| resonance peak of TE_{012} mode can be shown.

d) Follow step 6.2.2 d) to g) to measure the temperature dependence of the resonant frequency f_0 and the unloaded Q value Q_U for this TE_{012} mode. They are denoted as f_{012} and Q_{U012}.

6.2.4 Determination of tan δ of the sapphire rod

Using the measured value of f_{021}, Q_{U021}, f_{012} and Q_{U012}, the surface resistance of the superconductor films R_s and tan δ of the sapphire rod are given by the following simultaneous equations:

$$\left.\begin{aligned} R_s(f_{012}) &= \frac{1}{B_{012}}\left\{\frac{A_{012}}{Q_{U012}} - \tan\delta(f_{012})\right\} \\ R_s(f_{021}) &= \frac{1}{B_{021}}\left\{\frac{A_{021}}{Q_{U021}} - \tan\delta(f_{021})\right\} \end{aligned}\right\} \tag{6}$$

where A_{012}, B_{012}, A_{021} and B_{021} are geometric factors of TE_{012} and TE_{021}, respectively, and given by

$$A = 1 + \frac{W}{\varepsilon'} \tag{7}$$

$$B = p^2\left(\frac{\lambda_0}{2h}\right)^3 \frac{1+W}{30\pi^2\varepsilon'}, \quad p = 1,2,\cdots, \tag{8}$$