IEC 61788-7

Edition 3.0 2020-03
REDLINE VERSION

# INTERNATIONAL STANDARD

colour inside

## Superconductivity –
## Part 7: Electronic characteristic measurements – Surface resistance of high-temperature superconductors at microwave frequencies



IEC 61788-7:2020-03 RLV (en)

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

Tel.: +41 22 919 02 11
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 corrigendum or an amendment might have been published.

**IEC publications search - webstore.iec.ch/advsearchform**
The advanced search enables 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 It also gives information on projects, replaced and withdrawn publications.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 online and once a month by email.

**IEC 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: sales@iec.ch.

**Electropedia - www.electropedia.org**
The world's leading online dictionary on electrotechnology, containing more than 22 000 terminological entries in English and French, with equivalent terms in 16 additional languages. Also known as the International Electrotechnical Vocabulary (IEV) online.

**IEC Glossary - std.iec.ch/glossary**
67 000 electrotechnical terminology entries in English and French extracted from the Terms and Definitions clause of IEC publications issued since 2002. Some entries have been collected from earlier publications of IEC TC 37, 77, 86 and CISPR.

# IEC 61788-7

Edition 3.0 2020-03
REDLINE VERSION

# INTERNATIONAL STANDARD

## Superconductivity –
## Part 7: Electronic characteristic measurements – Surface resistance of high-temperature superconductors at microwave frequencies



INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

ICS 17.220.20; 29.050 ISBN 978-2-8322-7917-5

**Warning! Make sure that you obtained this publication from an authorized distributor.**

CONTENTS

INTERNATIONAL ELECTROTECHNICAL COMMISSION

---

# SUPERCONDUCTIVITY –

# Part 7: Electronic characteristic measurements – Surface resistance of high-temperature 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.

**This redline version of the official IEC Standard allows the user to identify the changes made to the previous edition. A vertical bar appears in the margin wherever a change has been made. Additions are in green text, deletions are in strikethrough red text.**

International Standard IEC 61788-7 has been prepared by IEC technical committee 90: Superconductivity.

This third edition cancels and replaces the second edition, published in 2006. This edition constitutes a technical revision.

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

a) informative Annex B, relative combined standard uncertainty for surface resistance measurement has been added;
b) precision and accuracy statements have been converted to uncertainty;
c) reproducibility in surface resistant measurement has been added.

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

| FDIS | Report on voting |
|---|---|
| 90/447/FDIS | 90/452/RVD |

Full information on the voting for the approval of this International Standard can be found in the report on voting indicated in the above table.

This document has been drafted in accordance with the ISO/IEC Directives, Part 2.



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

The committee has decided that the contents of this document will remain unchanged until the maintenance result date indicated on the IEC web site under "http://webstore.iec.ch" in the data related to the specific publication. At this date, the document 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 some Perovskite-type Cu-containing oxides, extensive research and development (R & D) work on high-temperature ~~oxide~~ superconductors (HTS) has been, and is being, done worldwide, and its application to high-field magnet machines, low-loss power transmission, electronics and many other technologies is in progress.

In various fields of electronics, especially in telecommunication fields, microwave passive devices such as filters using ~~oxide superconductors~~ HTS are being developed and are undergoing on-site testing [1][2] [1].

Superconductor materials for microwave resonators [3], filters [4],, antennas [5] and delay lines [6] have the advantage of very low loss characteristics. The parameters of superconductor materials needed for the design of microwave low loss components are the surface resistance, ($R_s$) and the temperature dependence of the $R_s$. Knowledge of this parameter is of primary importance for the development of new materials on the supplier side and for the design of superconductor microwave components on the customer side.

~~Recent advances in high Tc superconductor (HTS) thin films with $R_s$~~ $R_s$ of high quality HTS films is generally several orders of magnitude lower than that of normal metals [7] [8] [9] [10], ~~have~~ which has increased the need for a reliable characterization technique to measure this property ~~[3,4]~~. Traditionally, the $R_s$ of niobium or any other low-temperature superconducting material was measured by first fabricating an entire three-dimensional resonant cavity and then measuring its $Q$-value [11]. The $R_s$ could be calculated by solving the electro-magnetic field (EM) distribution inside the cavity. Another technique involves placing a small sample inside a larger cavity. This technique has many forms but usually involves the uncertainty introduced by extracting the loss contribution due to the HTS films from the experimentally measured total loss of the cavity.



The best HTS samples are epitaxial films grown on flat crystalline substrates and no high-quality films have been grown on any curved surface so far. What is needed is a technique that: can use these small flat samples; requires no sample preparation; does not damage or change the film; is highly repeatable; has great sensitivity (down to 1/1 000 the $R_s$ of copper); has great dynamic range (up to the $R_s$ of copper); can reach high internal powers with only modest input powers; and has broad temperature coverage (4,2 K to 150 K).



The dielectric resonator method is selected among several methods ~~[5,6,7]~~ to determine the surface resistance at microwave frequencies because it is considered to be the most popular and practical at present. Especially, the sapphire resonator is an excellent tool for measuring the $R_s$ of HTS materials ~~[8,9]~~ [12] [13] [14].

The test method given in this document can also be applied to other superconductor bulk plates including low $T_c$ materials.

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 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 7: Electronic characteristic measurements – Surface resistance of high-temperature superconductors at microwave frequencies**

## 1 Scope

This part of IEC 61788 describes measurement of the surface resistance ($R_s$) of superconductors at microwave frequencies by the standard two-resonator method. The object of measurement is the temperature dependence of $R_s$ at the resonant frequency.

The applicable measurement range of $R_s$ for this method is as follows:

– Frequency: 8 GHz < $f$ < 30 GHz

– Measurement resolution: 0,01 mΩ at 10 GHz

The $R_s$ data at the measured frequency, and that scaled to 10 GHz, assuming the $f^2$ rule for comparison, is 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, *International Electrotechnical Vocabulary (IEV) – Part 815: Superconductivity*

## 3 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC 60050-815 apply.

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

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

~~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 $R_s$ of a superconductor film shall be measured by applying a microwave signal to a dielectric resonator with the superconductor film 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 ~~precision~~ relative combined standard uncertainty of this method ~~is a coefficient of variation (standard deviation divided by the average of the surface resistance determinations) that~~ is less than 20 % for the measurement temperature range from ~~30~~ 20 K to 80 K.

It is the responsibility of the user of this document to ~~consult and~~ establish appropriate 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 RF generator is also essential to measure high-frequency properties of materials. If its power is too high, direct contact to human bodies can cause an immediate burn.

# 5 Apparatus



## 5.1 Measurement system

Figure 1 shows a schematic diagram of the system required for the microwave measurement. The system consists of a network analyzer system for transmission measurement, a measurement apparatus, and a thermometer for monitoring the measuring temperature.



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

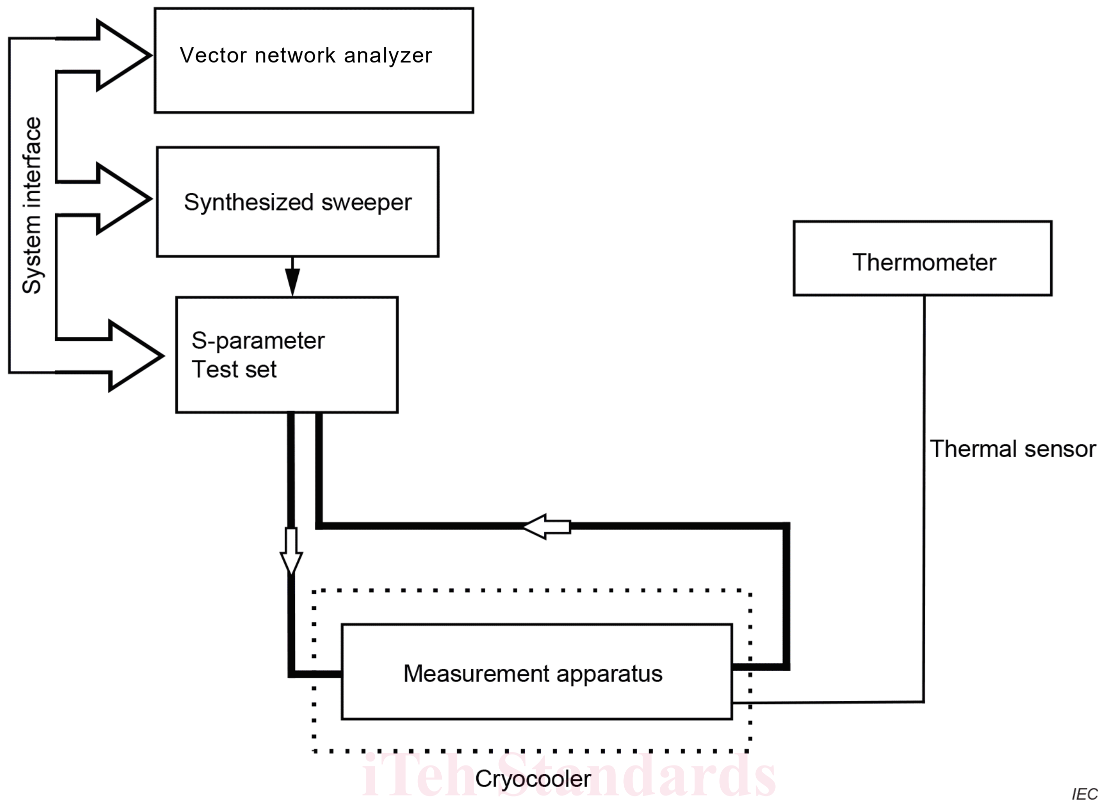




**Figure 1 – Schematic diagram of measurement system for temperature dependence of $R_s$ using a cryocooler**

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



For the measurement of $R_s$ for superconductor films, a vector network analyzer is recommended. A vector network analyzer has better measurement accuracy than a scalar network analyser due to its wide dynamic range. The performance requirements of the vector network analyzer are specified in 7.1.

### 5.2 Measurement apparatus for $R_s$

Figure 2 shows a schematic of a typical measurement apparatus (closed type resonator) for the $R_s$ of ~~superconductor~~ HTS films deposited on a substrate with a flat surface. The upper ~~superconductor~~ HTS film is pressed down by a spring, which is made of phosphor bronze. The plate type spring ~~is recommended to~~ should be used for the improvement of measurement ~~accuracy~~ uncertainty. This type of spring reduces the friction between the spring and the other part of the apparatus, and allows the smooth movement of superconductor films due to the thermal expansion of the dielectric rod. In order to minimize the measurement ~~error~~ uncertainty, the sapphire rod and the copper ring shall be ~~set in coaxial~~ arranged coaxially.

Two semi-rigid cables for measuring transmission characteristics of the resonator shall be attached on both sides of the resonator in an axial symmetrical position ($\phi$ = 0 and $\pi$, where $\phi$ is the rotational angle around the central axis of the sapphire rod). Each of the two semi-rigid cables shall have a small loop at the ends. The plane of the loop shall be set parallel to that of the superconductor films in order to suppress the unwanted Transverse Magnetic Wave Modes ($TM_{mn0}$ 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 cavity modes to the interested dielectric resonance mode shall be suppressed. Unwanted, parasitic coupling to the other modes reduces the high $Q$-value of the Transverse Electro-Magnetic Mode (TE mode) resonator. For suppressing the parasitic coupling, special attention shall be paid to designing high-$Q$ resonators. Two other types of resonators along with the closed type shown in Figure 2 can be used. They are explained in A.4.

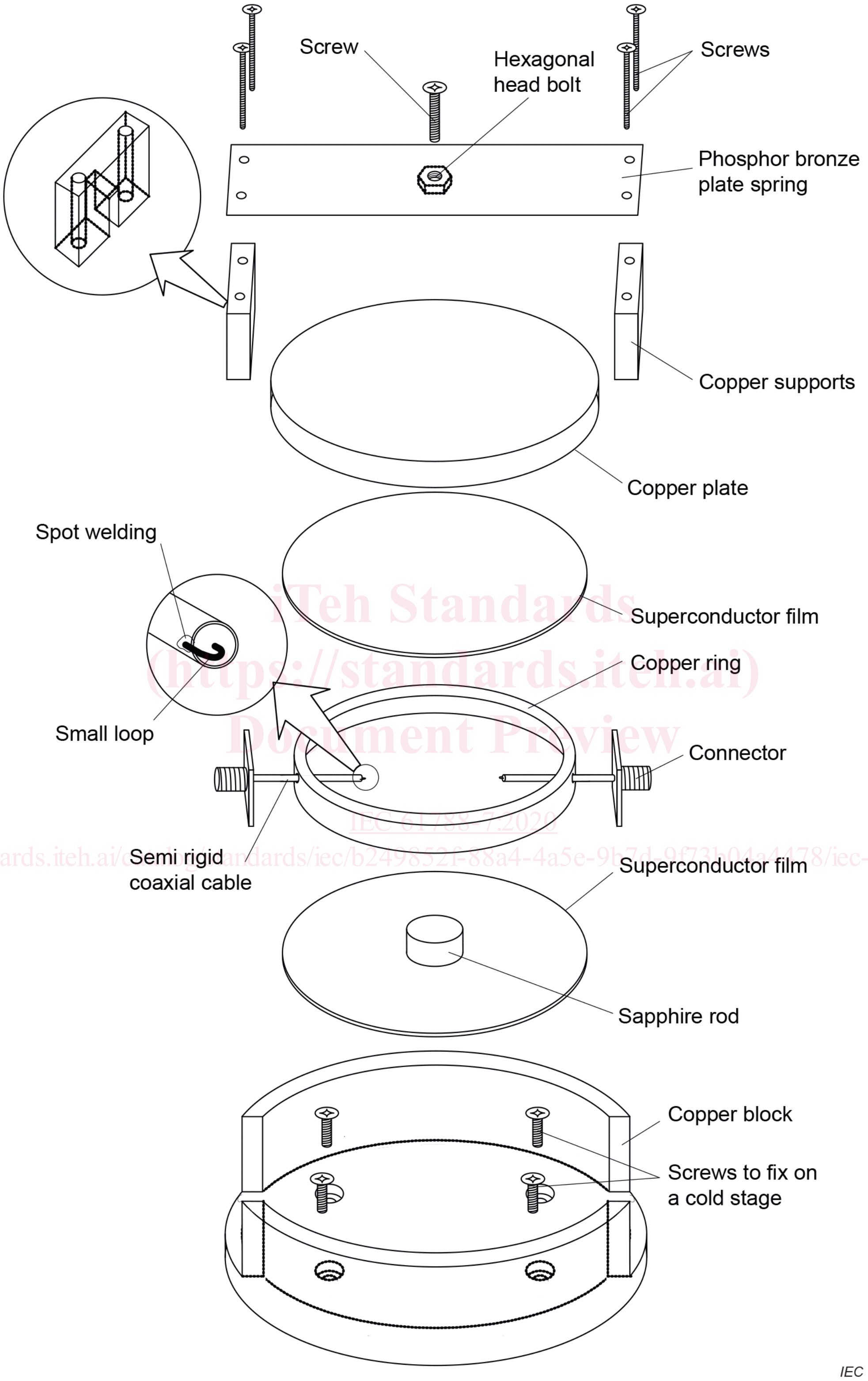




**Figure 2 – Typical measurement apparatus for $R_s$**

A reference line made of a semi-rigid cable shall be used to measure the full transmission power level, i.e. the reference level. This cable has a length equal to the sum of the two cables of the measurement apparatus. Semi-rigid cable with an outer diameter of 1,20 mm is recommended.

In order to minimize the measurement ~~error~~ uncertainty, two superconductor films shall be set to be parallel to each other. To ensure that the two superconductor films remain in tight contact with the ends of the sapphire rod, without any air gap, both of the surfaces of the films and the ends of the rod shall be cleaned carefully.

### 5.3 Dielectric rods

Two dielectric rods with the same relative permittivity, $\varepsilon'$, and loss factor, tan $\delta$, preferably cut from one cylindrical dielectric rod, are required. These two rods, standard dielectric rods, shall have the same diameter but different heights: one ~~has a~~ shall have height three times longer than the other.

It is preferable to use ~~standard~~ dielectric rods with low tan $\delta$ to achieve the requisite measurement ~~accuracy~~ uncertainty on $R_s$. Recommended dielectric rods are single-crystal sapphire rods with tan $\delta$ less than ~~$10^{-6}$~~ $2 \times 10^{-7}$ at 77 K. Specifications on the sapphire rods are described in 7.1. In order 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 for the sapphire rods are given in Clause 7.

The diameter and the heights of the standard sapphire rods shall be carefully designed so that the $TE_{011}$ and $TE_{013}$ modes do not couple to other TM, HE and EH modes, since the coupling between TE mode and other modes causes the degradation of unloaded $Q$. A design guideline for the standard sapphire rods is described in Clause A.5. Table 1 shows typical examples of dimensions of the standard sapphire rods for 12 GHz, 18 GHz, and 22 GHz resonance. ~~At higher frequencies the unloaded $Q$ value will be lower, which makes the measurement easier, and the error will be lower.~~ In the $R_s$ measurement at 22 GHz, the required film diameter can be set to 20 mm, and the measured $Q_L$ is small, therefore the effect of the dielectric loss of sapphire rod can be reduced.



**Table 1 – Typical dimensions of pairs of ~~standard~~ single-crystal sapphire rods for 12 GHz, 18 GHz and 22 GHz**

| ~~Frequency~~ ~~GHz~~ | | ~~Diameter~~ ~~$d$~~ ~~mm~~ | ~~Height~~ ~~$h$~~ ~~mm~~ |
|---|---|---|---|
| ~~12~~ | ~~Short rod ($TE_{011}$ resonator)~~ | ~~11,4~~ | ~~5,7~~ |
| | ~~Long rod ($TE_{013}$ resonator)~~ | ~~11,4~~ | ~~17,1~~ |
| ~~18~~ | ~~Short rod ($TE_{011}$ resonator)~~ | ~~7,6~~ | ~~3,8~~ |
| | ~~Long rod ($TE_{013}$ resonator)~~ | ~~7,6~~ | ~~11,4~~ |
| ~~22~~ | ~~Short rod ($TE_{011}$ resonator)~~ | ~~6,2~~ | ~~3,1~~ |
| | ~~Long rod ($TE_{013}$ resonator)~~ | ~~6,2~~ | ~~9,3~~ |

| **Frequency** GHz | | **Diameter, $d$** mm | **Height, $h$** mm |
|---|---|---|---|
| 12 | Short rod ($TE_{011}$ resonator) | 11,40 ± 0,05 | 5,70 ± 0,05 |
| | Long rod ($TE_{013}$ resonator) | 11,40 ± 0,05 | 17,10 ± 0,05 |
| 18 | Short rod ($TE_{011}$ resonator) | 7,60 ± 0,05 | 3,80 ± 0,05 |
| | Long rod ($TE_{013}$ resonator) | 7,60 ± 0,05 | 11,40 ± 0,05 |
| 22 | Short rod ($TE_{011}$ resonator) | 6,20 ± 0,05 | 3,10 ± 0,05 |
| | Long rod ($TE_{013}$ resonator) | 6,20 ± 0,05 | 9,30 ± 0,05 |