BS EN 61338-1-5:2015

BSI Standards Publication

Waveguide type dielectric resonators

Part 1-5: General information and test conditions — Measurement method of conductivity at interface between conductor layer and dielectric substrate at microwave frequency

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National foreword

This British Standard is the UK implementation of EN 61338-1-5:2015. It is identical to IEC 61338-1-5:2015. It supersedes DD IEC/PAS 61338-1-5:2010 which is withdrawn.

The UK participation in its preparation was entrusted to Technical Committee EPL/49, Piezoelectric devices for frequency control and selection.

A list of organizations represented on this committee can be obtained on request to its secretary.

This publication does not purport to include all the necessary provisions of a contract. Users are responsible for its correct application.

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Compliance with a British Standard cannot confer immunity from legal obligations.

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Date	Text affected

EUROPEAN STANDARD
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EN 61338-1-5

August 2015

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English Version

Waveguide type dielectric resonators - Part 1-5: General information and test conditions - Measurement method of conductivity at interface between conductor layer and dielectric substrate at microwave frequency (IEC 61338-1-5:2015)

Résonateurs diélectriques à modes guidés - Partie 1-5: Informations générales et conditions d'essais - Méthode de mesure de la conductivité au niveau de l'interface entre une couche conductrice et un substrat diélectrique fonctionnant aux hyperfréquences
(IEC 61338-1-5:2015)

Dielektrische Resonatoren vom Wellenleitertyp - Teil 1-5: Allgemeine Informationen und Prüfbedingungen - Messverfahren für die Leitfähigkeit an der Grenzfläche zwischen Leiterschicht und dielektrischem Träger im Mikrowellen-Frequenzbereich
(IEC 61338-1-5:2015)

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CENELEC

European Committee for Electrotechnical Standardization
Comité Européen de Normalisation Electrotechnique
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European foreword

The text of document 49/1089/CDV, future edition 1 of IEC 61338-1-5, prepared by IEC/TC 49 "Piezoelectric, dielectric and electrostatic devices and associated materials for frequency control, selection and detection" was submitted to the IEC-CENELEC parallel vote and approved by CENELEC as EN 61338-1-5:2015.

The following dates are fixed:

• latest date by which the document has to be implemented at national level by publication of an identical national standard or by endorsement	(dop)	2016-04-30
• latest date by which the national standards conflicting with the document have to be withdrawn	(dow)	2018-07-30

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Endorsement notice

The text of the International Standard IEC 61338-1-5:2015 was approved by CENELEC as a European Standard without any modification.

Annex ZA
(normative)

Normative references to international publications with their corresponding European publications

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.

NOTE 1 When an International Publication has been modified by common modifications, indicated by (mod), the relevant EN/HD applies.

NOTE 2 Up-to-date information on the latest versions of the European Standards listed in this annex is available here: www.cenelec.eu.

Publication	Year	Title	EN/HD	Year
IEC 61338-1-3	-	Waveguide type dielectric resonators -- Part 1-3: General information and test conditions - Measurement method of complex relative permittivity for dielectric resonator materials at microwave frequency	EN 61338-1-3	-
IEC 62252	-	Maritime navigation and radiocommunication equipment and systems - Radar for craft not in compliance with IMO SOLAS Chapter V - Performance requirements, methods of test and required test results	EN 62252	-

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

WAVEGUIDE TYPE DIELECTRIC RESONATORS –

Part 1-5: General information and test conditions – Measurement method of conductivity at interface between conductor layer and dielectric substrate at microwave frequency

FOREWORD

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International Standard IEC 61338-1-5 has been prepared by IEC technical committee 49: Piezoelectric, dielectric and electrostatic devices and associated materials for frequency control, selection and detection.

This first edition cancels and replaces IEC PAS 61338-1-5 published in 2010.

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

a) description of technical content related to patents (Japanese patent numbers JP3634966, JP3735501) in the Introduction;
b) changes to normative references;
c) addition to bibliography.

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

CDV	Report on voting
49/1089/CDV	49/1103/RVC

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 parts in the IEC 61338 series, published under the general title *Waveguide type dielectric resonators,* 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.

INTRODUCTION

IEC 61338 consists of the following parts, under the general title *Waveguide type dielectric resonators*:

- Part 1: Generic specification
- Part 1-3: General information and test conditions – Measurement method of complex relative permittivity for dielectric resonator materials at microwave frequency
- Part 1-4: General information and test conditions – Measurement method of complex relative permittivity for dielectric resonator materials at millimeter-wave frequency
- Part 2: Guidelines for oscillator and filter applications
- Part 4: Sectional specification
- Part 4-1: Blank detail specification

The International Electrotechnical Commission (IEC) draws attention to the fact that it is claimed that compliance with this document may involve the use of a patent concerning:

- The use of a $TE_{01\delta}$ mode dielectric rod resonator for the interface resistance and the interface conductivity measurement, given in Clause 4;
- The use of a substrate/conductor/substrate layer structure, where a conductor is formed between two dielectric substrates, for the interface resistance and interface conductivity measurement, given in Clause 5.

IEC takes no position concerning the evidence, validity and scope of this patent right.

The holder of this patent right has assured the IEC that he/she is willing to negotiate licences under reasonable and non-discriminatory terms and conditions with applicants throughout the world. In this respect, the statement of the holder of this patent right is registered with IEC. Information may be obtained from:

KYOCERA Corporation

6 Takeda Tobadono-cho, Fushimiku, Kyoto 612-8501, Japan

Attention is drawn to the possibility that some of the elements of this standard may be the subject of patent rights other than those identified above. IEC shall not be held responsible for identifying any or all such patent rights.

ISO (www.iso.org/patents) and IEC (http://patents.iec.ch) maintain on-line data bases of patents relevant to their standards. Users are encouraged to consult the data bases for the most up to date information concerning patents.

WAVEGUIDE TYPE DIELECTRIC RESONATORS –

Part 1-5: General information and test conditions – Measurement method of conductivity at interface between conductor layer and dielectric substrate at microwave frequency

1 Scope

Microwave circuits are popularly formed on multi-layered organic or non-organic substrates. In the microwave circuits, the attenuation of planar transmission lines such as striplines, microstrip lines, and coplanar lines are determined by their conductor loss, dielectric loss and radiation loss. Among them, the conductor loss is a major factor in the attenuation of the planar transmission lines. A new measurement method is standardized in this document to evaluate the conductivity of transmission line on or in the substrates such as the organic, ceramic and LTCC (low temperature co-fired ceramics) substrates. This standard describes a measurement method for resistance and effective conductivity at the interface between conductor layer and dielectric substrate, which are called interface resistance and interface conductivity.

This measurement method has the following characteristics:

- the interface resistance R_i is obtained by measuring the resonant frequency f_0 and unloaded quality factor Q_u of a $\mathrm{TE}_{01\delta}$ mode dielectric rod resonator shown in Figure 2;
- the interface conductivity σ_i and the relative interface conductivity $\sigma_\mathrm{ri} = \sigma_\mathrm{i} / \sigma_0$ are calculated from the measured R_i value, where σ_0 = 5,8 × 10^7 S/m is the conductivity of standard copper;
- the measurement uncertainty of σ_ri ($\Delta\sigma_\mathrm{ri}$) is less than 5 %.

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 61338-1-3: *Waveguide type dielectric resonators – Part 1-3: General information and test conditions – Measurement method of complex relative permittivity for dielectric resonator materials at microwave frequency*

IEC 62562: *Cavity resonator method to measure the complex permittivity of low-loss dielectric plates*

3 Measurement and related parameters

The IEC 61338-1-3 described the measurement method for the surface resistance R_s and effective conductivity σ on the surface of the conductor. The term σ is designated as σ_s in this standard, and is called surface conductivity (Figure 1). This standard describes a measurement method for resistance and effective conductivity at the interface between conductor layer and dielectric substrate designated as R_i and σ_i respectively, and are called interface resistance and interface conductivity.

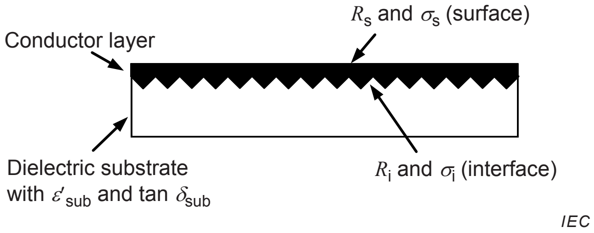

Figure 1 – Surface resistance R_s, surface conductivity σ_s, interface resistance R_i, and interface conductivity σ_i.

For the transmission line in the substrates, the electric current is concentrated at the interface between conductor layer and dielectric substrate, because the skin depth δin the conductor is the order of μm in thickness at the microwave frequencies. In microstrip lines, the current is concentrated at the interface, rather than at the open face of the conductor. Furthermore, in copper-clad organic substrates, the interface side of the copper foil has rugged structure to hold the strong adhesive strength. In LTCC substrates, the interface between the conductor and ceramics has a rough structure, depending on the co-firing process and the material compositions. The conductor loss depends on the interface conditions. Therefore, the evaluation of R_i and σ_i is important to design microwave circuit and to improve the conductor fabrication process.

The relationship between R_s and σ_s is given by

$$R_s = \sqrt{\frac{\pi f_0 \mu}{\sigma_s}}, \quad \sigma_s = \sigma_{rs}\sigma_0 \tag{1}$$

where

R_s	is the surface resistance;
f_0	is the resonance frequency;
μ	is the permeability of the conductor;
σ_s	is the surface conductivity;
σ_{rs}	is the relative surface conductivity.

Particularly, μ equals μ_0 ($\mu_0 = 4\pi \times 10^{-7}$ H/m) for nonmagnetic conductors such as copper and silver.

The relationship between R_i and σ_i is given by

$$R_i = \sqrt{\frac{\pi f_0 \mu}{\sigma_i}}, \quad \sigma_i = \sigma_{ri}\sigma_0 \tag{2}$$

where

R_i	is the interface resistance;
σ_i	is the interface conductivity;
σ_{ri}	is the relative interface conductivity.

The skin depth δ is given by

$$\delta = \sqrt{\frac{1}{\pi f \mu \sigma}} \tag{3}$$

where

f is the frequency;

σ is the conductivity of the conductor.

To obtain high accuracy in this measurement method, the relative interface conductivity σ_{ri} of the conductor is preferable to be higher than 5%, and the thickness of conductor to be three times greater than skin depth δ. The measurement frequencies are limited to be 5 GHz and 13 GHz because of the reference dielectric rods used in this standard.

4 Calculation equations for R_i and σ_i

Figure 2 shows the structure of a $TE_{01\delta}$ mode dielectric rod resonator for the R_i measurement. The resonator consists of a dielectric rod and a pair of dielectric substrates with a conductor layer at one side. The dielectric rod has diameter d, height h, relative permittivity ε'_{rod}, and loss tangent $\tan\delta_{rod}$. The pair of dielectric substrates have the same values of diameter d', thickness t, relative permittivity ε'_{sub}, and loss tangent $\tan\delta_{sub}$. To suppress the radiation loss, the diameter d' shall be three times greater than d. The conductor layers on each dielectric substrate are supposed to have the same value of R_i.

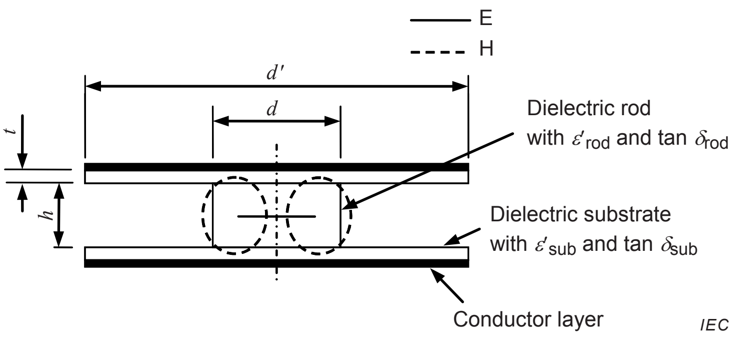

Figure 2 – $TE_{01\delta}$ mode dielectric rod resonator to measure σ_i.

In this structure, the conductive loss of the $TE_{01\delta}$ mode resonator is caused by the interface resistance R_i. The value of $1/Q_u$ is given by a sum of power losses due to R_i, $\tan\delta_{rod}$ and $\tan\delta_{sub}$:

$$\frac{1}{Q_u} = \frac{R_i}{g} + P_{rod}\tan\delta_{rod} + P_{sub}\tan\delta_{sub} \ , \tag{4}$$

where

g is the geometric factor of the resonator (Ω);

P_{rod} is the partial electric energy filling factor of the dielectric rod;

P_{sub} is the partial electric energy filling factor of the dielectric substrate.

The equation for R_i is derived from Equation (4):

$$R_i = g\left(\frac{1}{Q_u} - P_{rod}\tan\delta_{rod} - P_{sub}\tan\delta_{sub}\right) \tag{5}$$

The value σ_i is calculated from this R_i value by Equation (2).

The derivation of Equation (4) is given in Annex A, together with definitions of the parameters g, P_{rod} and P_{sub}. These parameters for the $TE_{01\delta}$ mode resonator can be calculated by using the FEM or the mode matching method. However, the calculation requires complicated and tedious works. To make the treatment simple and easy, this standard recommends to use the graphical charts that are prepared for the parameters of reference dielectric rod resonators; a sapphire single crystal and a $(Zr,Sn)TiO_4$ ceramic (Table 1). The axis of sapphire rod should be parallel to the c-axis within 0,3 degree. The $(Zr,Sn)TiO_4$ ceramic rod is provided from the Japan fine ceramics center. The parameters f_0, g, P_{rod} and P_{sub} for the reference rods were calculated by an FEM analyzed in cylindrical coordinate and are shown in Figures 3 and 4 graphically. The calculation uncertainty on the parameters is shown in Annex B.

To calculate the R_i in Equation (5), the complex permittivity values of the dielectric rod and the substrate are necessary to be given in advance. IEC 61338-1-3 shall be used to measure the values of ε'_{rod} and $\tan\delta_{rod}$. IEC 62562 shall be used to measure the values of ε'_{sub} and $\tan\delta_{sub}$.

Table 1 – Specifications of reference rods

Reference rod	f_0 GHz	ε'_{rod}	$\tan\delta_{rod}$	**diameter** d mm	**height** h mm
Sapphire single crystal	13	9,4 ± 0.1	13×10^{-6}	10,00 ± 0,05	5,00 ± 0,05
$(Zr,Sn)TiO_4$ ceramics	5	39 ± 1	$<10 \times 10^{-4}$	14,00 ± 0,05	6,46 ± 0,05

NOTE 1 The reference dielectric rod of $(Zr,Sn)TiO_4$ is provided by JFCC (Japan fine ceramics center[1]) as ER-ZST.

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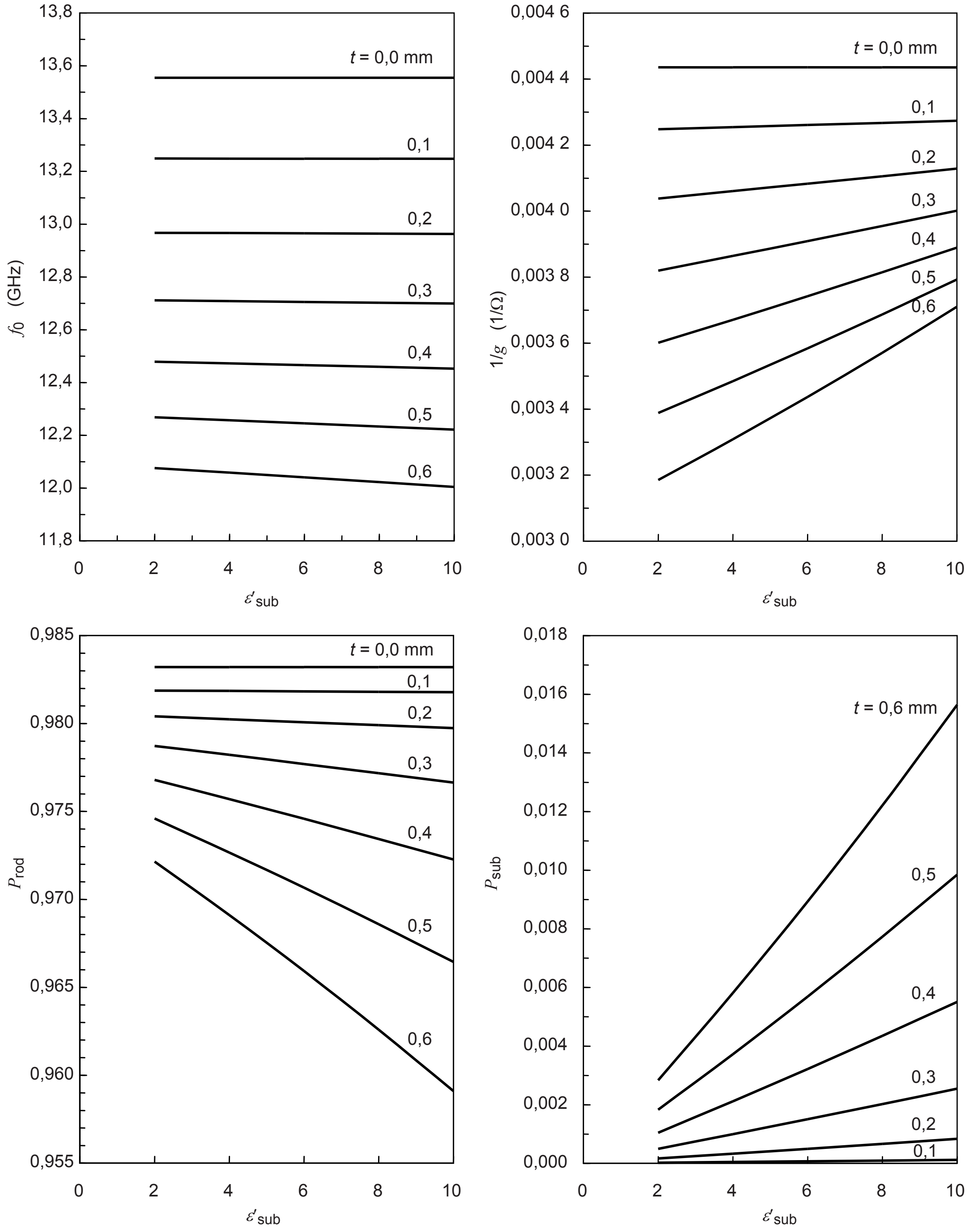
[1] Japan fine ceramics center is an example of a suitable commercial supplier. This information is given for the convenience of users of this document and does not constitute an endorsement by IEC of this supplier.

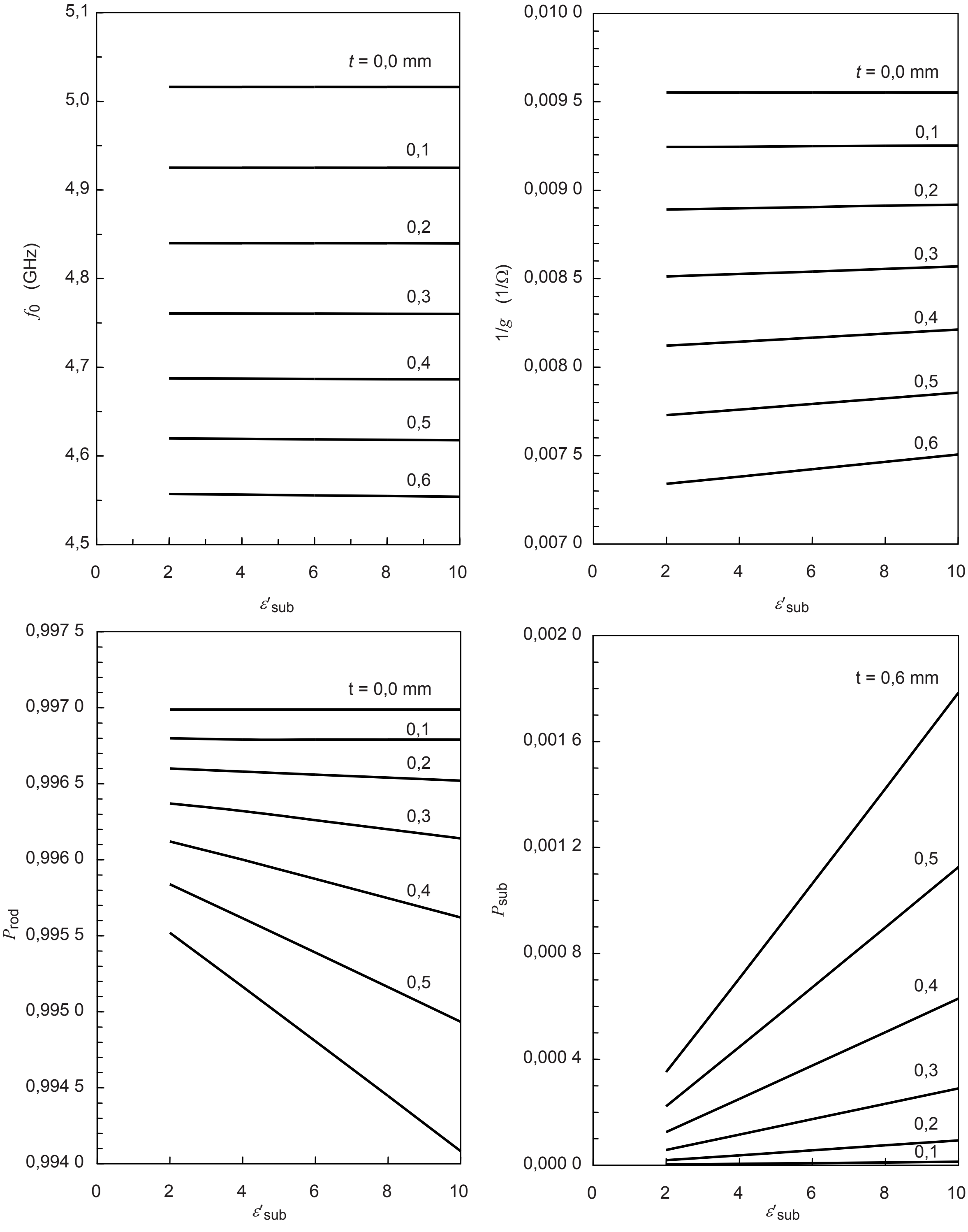


IEC

The calculation conditions are the following:

ε'_{rod} = 9,4, d = 10,00 mm and h = 5,00 mm.

Figure 3 – Parameters chart of f_0, g, P_{rod} and P_{sub} for reference sapphire rod



IEC

The calculation conditions are the following:

ε'_{rod} = 39, d = 14,00 mm and h = 6,46 mm.

Figure 4 – Parameters chart of f_0, g, P_{rod} and P_{sub} for reference (Zr,Sn)TiO$_4$ rod

5 Preparation of specimen

Two test specimens of dielectric substrates with a conductor at one side are prepared for the σ_{i} measurement. The thickness of the conductor t_{c} shall be three times greater than the skin depth δ. The values of δ is 0,9 µm for copper and 1,7 µm for tungsten at 5 GHz. The diameter d' of dielectric substrate shall be three times greater than the diameter d of the reference dielectric rod. Dielectric substrates with any shape larger than the diameter $3\times d$ is used in practical measurement. Bending of specimen causes measurement error of σ_{i}. A substrate/conductor/substrate layer structure, where a conductor is formed between two dielectric substrates, is effective to avoid the bending of specimen.

6 Measurement equipment and apparatus

6.1 Measurement equipment

Figure 5 shows a schematic diagram of two measurement systems. For the measurement of Q_{u} of the resonator to evaluate σ_{i}, only the information on the amplitude of transmitted power is needed, that is, the information on the phase of the transmitted power is not required. Therefore, a scalar network analyzer can be used for the measurement shown in Figure 5(a). However, a vector network analyzer shown in Figure 5(b) has better measurement accuracy than a scalar network analyzer due to its wide dynamic range.

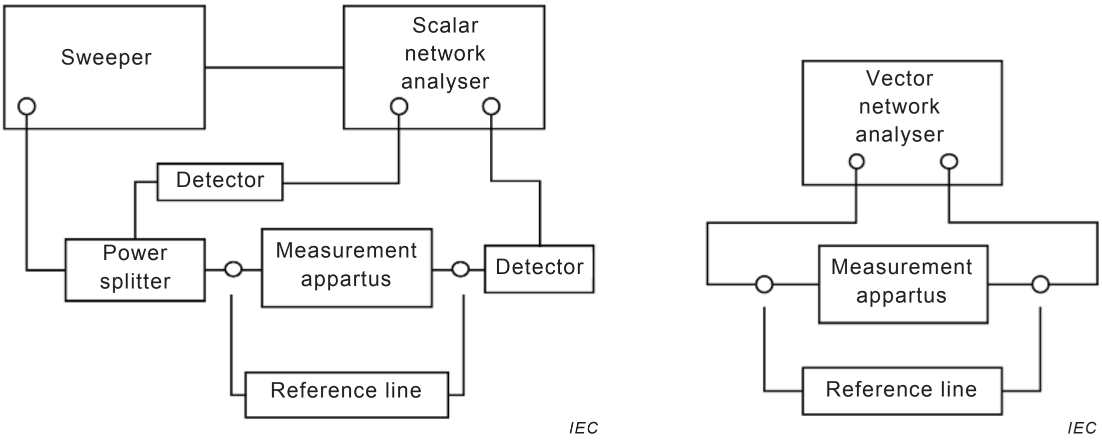


Figure 5a) Scalar network analyzer system **Figure 5b) Vector network analyzer system**

Figure 5 – Schematic diagram of measurement equipments

6.2 Measurement apparatus

Figure 6 shows a measurement apparatus for σ_{i}. The reference dielectric rod is placed between the dielectric sides of two substrates with a conductor at one side. Two substrates are set to be parallel to each other.

Each of the two semi-rigid coaxial cables have a small loop at the top. The semi-rigid cable with the outer diameter of 1,2 mm is recommended. The two loops have the same diameter and the length shall be less than the quarter wavelength of measurement frequency. In practice, the loop with a diameter from 1 mm to 2 mm is preferable for the measurement around 10 GHz. The plane of the loop is set parallel to the dielectric substrates to suppress the excitation of the unwanted TM mode. The cables can move right and left to adjust the insertion attenuation IA_0 at f_0 to be around 30 dB (as shown in Figure 8). The IA_0 value is recommended to be between 20 dB and 30 dB, in order to decrease the field disturbance due to the coupling loop and to decrease the noise influence on the resonance curve of the network analyzer.

A reference line made of a semi-rigid cable, shown in Figure 6, is used to measure the full transmission power level, i.e., the reference level as shown in Figure 8. This cable has a length equal to the sum of the two cables with a loop.

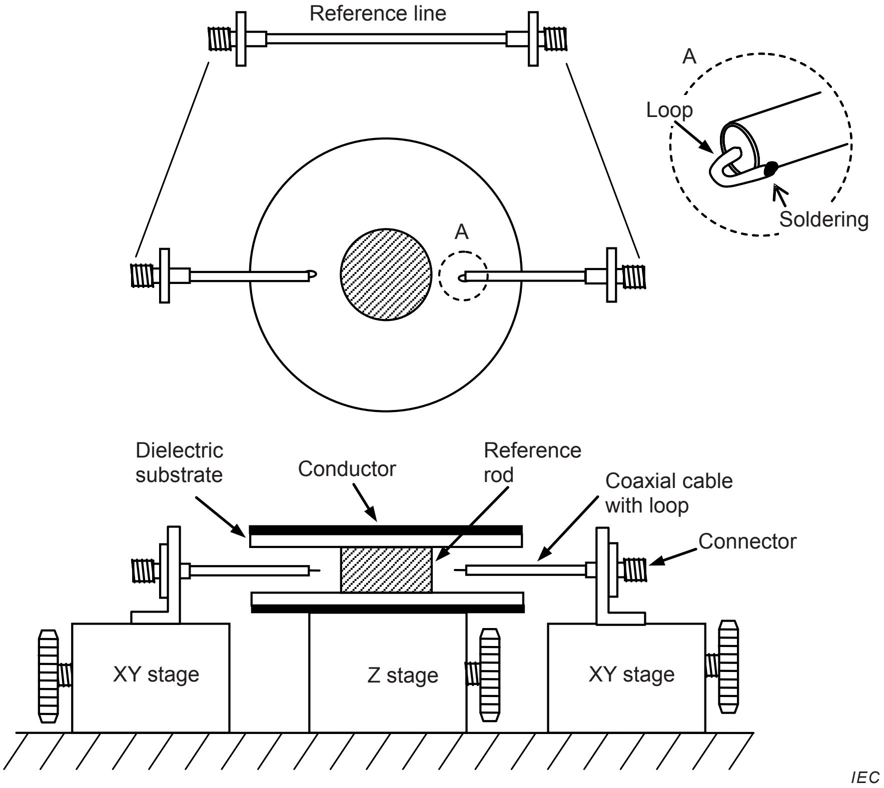


Figure 6 – Schematic diagram of measurement apparatus for σ_i.

7 Measurement procedure

7.1 Set-up of measurement equipment and apparatus

Set up the measurement equipment and apparatus as shown in Figures 5 and 6. Relative humidity shall be less than 60 %, because high humidity degrades Q_u.

7.2 Measurement of reference level

Measure the reference transmission level, shown in Figure 8, over the entire measurement frequency range.

7.3 Measurement procedure of Q_u

Place the reference dielectric rod between the dielectric sides of two substrates. Adjust the distance between the reference rod and each of the loops of the semi-rigid cables to be equal.

Find the $TE_{01\delta}$ mode resonance peak of the resonator on the display of the network analyzer, by reading the approximate f_0 value of the $TE_{01\delta}$ mode resonance from Figures 3 or 4 for each reference rod. This peak can be identified as the one which shifts downward in frequency when the upper substrate is slowly separated from the top of the reference dielectric rod. Figure 7 shows an example of frequency response for a resonator.

Narrow the frequency span, so that only the resonance peak of $\text{TE}_{01\delta}$ mode can be shown on the display as shown in Figure 8. By changing the distance between the reference dielectric rod and the loops of the semi-rigid cables, adjust IA_0 to be around 30 dB from the reference level.

Measure f_0, the half-power band-width f_{BW} and IA_0. The loaded quality factor Q_{L} and the unloaded quality factor Q_{u} of this resonance mode are given by

$$Q_{\text{L}} = \frac{f_0}{f_{\text{BW}}} \tag{6}$$

$$Q_{\text{u}} = \frac{Q_{\text{L}}}{1 - A_{\text{t}}}, \qquad A_{\text{t}} = 10^{-\left|IA_0(\text{dB})\right|/20} \tag{7}$$

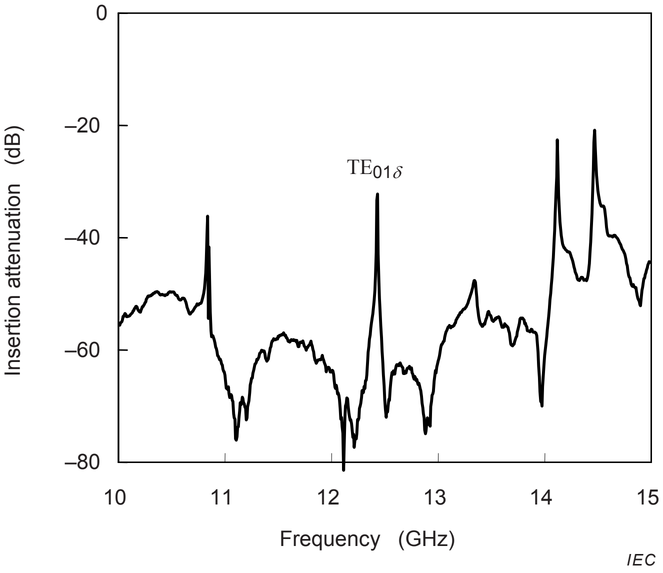


Figure 7 – Frequency response for reference sapphire rod with two dielectric substrates as shown in Figure 2.

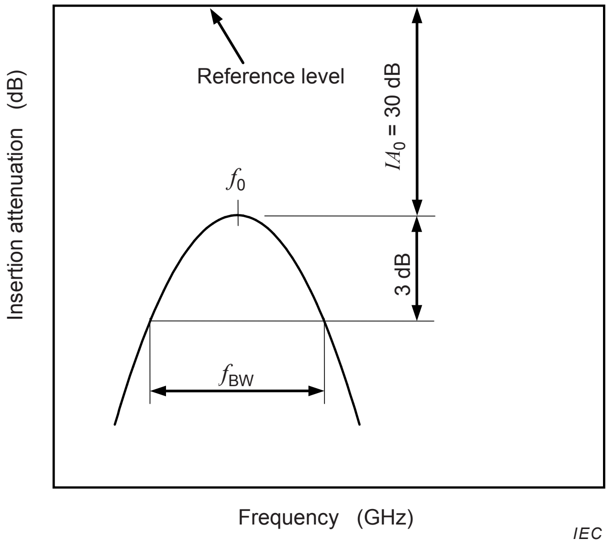


Figure 8 – Resonance frequency f_0, insertion attenuation IA_0 and half-power band width f_{BW}

7.4 Determination of σ_i and measurement uncertainty

Repeat the measurement of Q_u several times. Then, calculate R_i from the mean value of Q_u using Equation (5). The values g, P_{rod} and P_{sud} are given from Figures 3 and 4 using the ε'_{sub} and thickness t of the test substrate. The values σ_i and σ_{ri} are given from R_i using Equation (2).

Measurement uncertainty of σ_i, $\Delta\sigma_i$, estimated as the mean square errors is given by

$$(\Delta\sigma_i)^2 = (\Delta\sigma_{i,Qu})^2 + (\Delta\sigma_{i,\tan\delta rod})^2 + (\Delta\sigma_{i,\tan\delta sub})^2 \qquad (8)$$

where

$\Delta\sigma_{i,Qu}$ is the uncertainty of σ_i due to standard deviations of Q_u;
$\Delta\sigma_{i,\tan\delta rod}$ is the uncertainty of σ_i due to standard deviations of $\tan\delta_{rod}$;
$\Delta\sigma_{i,\tan\delta sub}$ is the uncertainty of σ_i due to standard deviations of $\tan\delta_{sub}$.

8 Example of measurement result

Table 2 shows the values of ε'_{rod} and $\tan\delta_{rod}$ for the reference rods measured by the dielectric rod resonator method (IEC 61338-1-3). Table 3 shows the values of ε'_{sub} and $\tan\delta_{sub}$ of a LTCC test substrate measured by the cavity resonator method (IEC 62562). A copper layer was co-fired in this substrate and the σ_i and σ_{ri} were measured. The results are shown in Table 4.

Table 2 – ε'_{rod} and $\tan\delta_{rod}$ of reference rods measured by the method of IEC 61338-1-3

Reference Rod	D mm	h mm	f_0 GHz	Q_u	ε'_{rod}	$\tan\delta_{rod}$ (10^{-4})
Sapphire	10,000 ±0,001	5,004 ±0,001	13,524 ±0,002	6 413 ±52	9,435 ±0,004	0,13 ±0,01
$(Zr,Sn)TiO_4$	14,000 ±0,001	6,465 ±0,001	4,9966 ±0,0004	3 612 ±21	39,27 ±0,01	0,90 ±0,02

Table 3 – ε'_{sub} and $\tan\delta_{sub}$ of an LTCC test substrate measured by the method of IEC 62562

d' mm	t mm	f_0 GHz	Q_u	ε'_{sub}	$\tan\delta_{sub}$ (10^{-4})
50	0,965 ±0,08	10,287 ±0,003	3 313 ±22	4,76 ±0,04	7,18 ±0,05

Table 4 – Measurement results of σ_i and σ_{ri} of a copper layer in LTCC substrate

Reference rod	f_0 GHz	Q_u	σ_i 10^7 S/m	σ_{ri} %
Sapphire	12,426 ±0,002	6 725 ±5	3,68 ±0,05	63,5 ±0,9
(Zr,Sn)TiO_4	4,6626 ±0,0003	3 738 ±20	3,83 ±0,10	66,0 ±1,8

NOTE The calculation conditions are ε'_{sub} = 4,76, d' = 45 mm and t = 0,415 mm.

Annex A
(informative)

Derivation of Equation (4) for R_i

The unloaded quality factor Q_u is defined by

$$\frac{1}{Q_u} = \frac{P_d}{\omega_0 W} \tag{A.1}$$

where

P_d	is the power dissipated in the resonator per second;
ω_0	is $2\pi \times f_0$;
W	is the energy stored in the resonator.

In the $TE_{01\delta}$ dielectric rod resonator (Figure 2), P_d and W are given by

$$P_d = P_{ci} + \omega_0 W_{rod} \tan\delta_{rod} + \omega_0 W_{sub} \tan\delta_{sub} \tag{A.2}$$

$$W = W_{rod} + W_{sub} + W_{air} \tag{A.3}$$

where

P_{ci}	is the conductive energy loss at the interface between the conductor and the dielectric substrate;
W_{rod}	is the electric energy stored in the dielectric rod;
W_{sub}	is the electric energy stored in the dielectric substrate;
W_{air}	is the electric energy stored in the air region;
$\omega_0 W_{rod} \tan\delta_{rod}$	is the dielectric energy loss in the dielectric rod;
$\omega_0 W_{sub} \tan\delta_{sub}$	is the dielectric energy loss in the dielectric substrate.

Equation (3) is obtained from Equation (A.1), (A.2) and (A.3), using the parameters, g, P_{rod} and P_{sub} defined as follows:

$$\frac{1}{g} = \frac{P_{ci}}{\omega W R_{si}} = \frac{\frac{1}{2}\iint \left|H_t\right|^2 ds}{\omega W} \tag{A.4}$$

$$P_{rod} = \frac{W_{rod}}{W} = \frac{\frac{1}{2}\varepsilon_0 \varepsilon'_{rod} \iiint_{Vrod} \left|E\right|^2 dv}{W} \tag{A.5}$$

$$P_{sub} = \frac{W_{sub}}{W} = \frac{\frac{1}{2}\varepsilon_0 \varepsilon'_{sub} \iiint_{Vsub} \left|E\right|^2 dv}{W} \tag{A.6}$$

$$W = \frac{1}{2}\varepsilon_0\left(\varepsilon'_{\mathrm{rod}}\iiint_{Vrod}\left|E\right|^2 dv + \varepsilon'_{\mathrm{sub}}\iiint_{Vsub}\left|E\right|^2 dv + \iiint_{Vair}\left|E\right|^2 dv\right) \tag{A.7}$$

where

$\iint \left|H_{\mathrm{t}}\right|^2 ds$ is the surface integration of the tangential magnetic field at the interface between the conductor and the dielectric substrate.

Annex B
(informative)

Calculation uncertainty of parameters in Figure 3

The parameters f_0, g, P_{rod} and P_{sub} in Figures 3 and 4 were calculated by using a FEM analyzed in cylindrical coordinate. The resonator structure for t = 0,0 mm in Figure 2 corresponds to the TE_{011} mode dielectric resonator short-circuited at the both ends, described in IEC 61338-1-3. So, the comparison of the calculated parameters for t = 0,0 mm by the FEM and by the rigorous analysis in IEC 61338-1-3 gives the calculation uncertainty of the FEM. Table B.1 shows calculated results for the TE_{011} mode sapphire resonator with the values of $\varepsilon'_{\mathrm{rod}}$ = 9,4, d = 10,0 mm and h = 5,0 mm. The difference between the two methods is negligibly small for the calculation of R_{i} and σ_{i}.

The parameters in Figure 3 were calculated for the reference sapphire rod with $\varepsilon'_{\mathrm{rod}}$ = 9,4. The actual sapphire rod usually has the $\varepsilon'_{\mathrm{rod}}$ in the range from 9,35 to 9,45. Table B.2 shows the calculated parameters for the sapphire rods with $\varepsilon'_{\mathrm{rod}}$ = 9,4 and 9,3. It shows that this difference of 0,1 on $\varepsilon'_{\mathrm{rod}}$ results in the calculation difference of 0,06 % on σ_{ri} . This value is negligibly small, compared with the measurement uncertainties of σ_{ri} given in Table 4.

Table B 1 – Parameters obtained by FEM and rigorous analysis of IEC 61338-1-3 for the TE_{011} mode resonator

Parameter	FEM	IEC 61338-1-3	Difference
f_0 (GHz)	13,5566	13,5545	0,0021
1/g (1/Ω)	0,004432	0,004436	-0,000004
P_{rod}	0,98319	0,98321	-0,00002

NOTE The calculation conditions are $\varepsilon'_{\mathrm{rod}}$ = 9,4, d = 10,0 mm, and h = 5,0 mm.

Table B.2 – Calculated parameters f_0, g, P_{rod}, P_{sub}, R_{i}, σ_{i} and σ_{ri} for the $\mathrm{TE}_{01\delta}$ mode resonator

Parameter	$\varepsilon'_{\mathrm{rod}}$ = 9,4	$\varepsilon'_{\mathrm{rod}}$ = 9,3	Difference
f_0 (GHz)	12,2452	12,3089	-0,0637
1/ g (1/Ω)	0,003584	0,003570	0,000014
P_{rod}	0,9707	0,9703	0,0004
P_{sub}	0,00569	0,00575	-0,00006
R_{i} (mΩ)	41,60	41,73	-0,13
σ_{i} (10^7 S/m)	2,794	2,790	0,004
σ_{ri} (%)	48,17	48,11	0,06

NOTE The calculation conditions are $\varepsilon'_{\mathrm{sub}}$ = 6,0, tanδ_{sub} = 0,001, t = 0,5 mm, and Qu = 6 000.

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