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PUBLICLY AVAILABLE SPECIFICATION

PRE-STANDARD

**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/PAS 61338-1-5:2010(E)

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CONTENTS

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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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IEC/PAS 61338-1-5 has been processed by IEC technical committee 49: Piezoelectric and dielectric devices for frequency control and selection.

The text of this PAS is based on the following document:	This PAS was approved for publication by the P-members of the committee concerned as indicated in the following document
Draft PAS	**Report on voting**
49/873/PAS	49/902/RVD

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A list of all parts of IEC 61338 series under the general title *Waveguide type dielectric resonators* can be found on the IEC website.

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

INTRODUCTION

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“Measurement method of conductivity at interface of conductor layer”

“Measurement method of conductivity of conductor layer”

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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 needed 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.

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 PAS, and is called surface conductivity (Figure 1). This PAS 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.

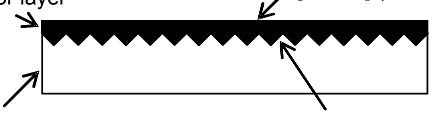


Figure 1 – Surface resistance R_s, surface conductivity σ_s, interface resistance R_i, and interface conductivity σ_i.

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 δ in 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 interface conditions increase the conductor loss. Therefore, the evaluation of R_i and σ_i is important to design microwave circuit and to improve the conductor fabrication process.

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 $\sigma_{ri} = \sigma_i / \sigma_0$ are calculated from the measured R_i value, where $\sigma_0 = 5{,}8 \times 10^7$ S/m is the conductivity of standard copper;

– the measurement uncertainty of σ_{ri} ($\Delta\sigma_{ri}$) is less than 5%.

2 Normative references

The following referenced documents are indispensable for the application of this PAS. 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 61338-1-4: *Waveguide type dielectric resonators - Part 1-4: General information and test conditions – Measurement method of complex relative permittivity for dielectric resonator materials at millimetre-wave frequency*

3 Measurement and related parameters

The relationship between R_s and σ_s is given by

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

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

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

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 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 in this PAS because of the reference dielectric rods used in this PAS.

4 Calculation equations for R_i and σ_i

Figure 2 shows the structure of a $\mathrm{TE}_{01\delta}$ 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.

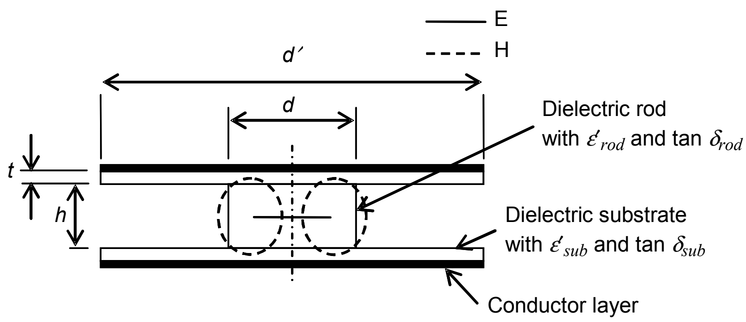


Figure 2 – The $\mathrm{TE}_{01\delta}$ mode dielectric rod resonator to measure σ_i.

In this structure, the conductive loss of the $\mathrm{TE}_{01\delta}$ 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 $\mathrm{TE}_{01\delta}$ 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 PAS 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 $(Zr,Sn)TiO_4$ ceramic rod is provided from Japan fine ceramics center. The parameters f_0, g, P_{rod} and P_{sub} for the reference rods were calculated by a 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. The values of ε'_{rod} and $\tan\delta_{rod}$ are measured by the dielectric rod resonator method described in IEC 61338-1-3. The values of ε'_{sub} and $\tan\delta_{sub}$ can be measured by the cavity resonator method described in IEC 61338-1-4.

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	$<10\times10^{-4}$	14,00 ± 0,05	6,46 ± 0,05

NOTE 1 The axis of sapphire rod should be parallel to the c-axis within 0,3 degree.

NOTE 2 The reference dielectric rod of $(Zr,Sn)TiO_4$ is provided by JFCC (Japan fine ceramics center) as ER-ZST.

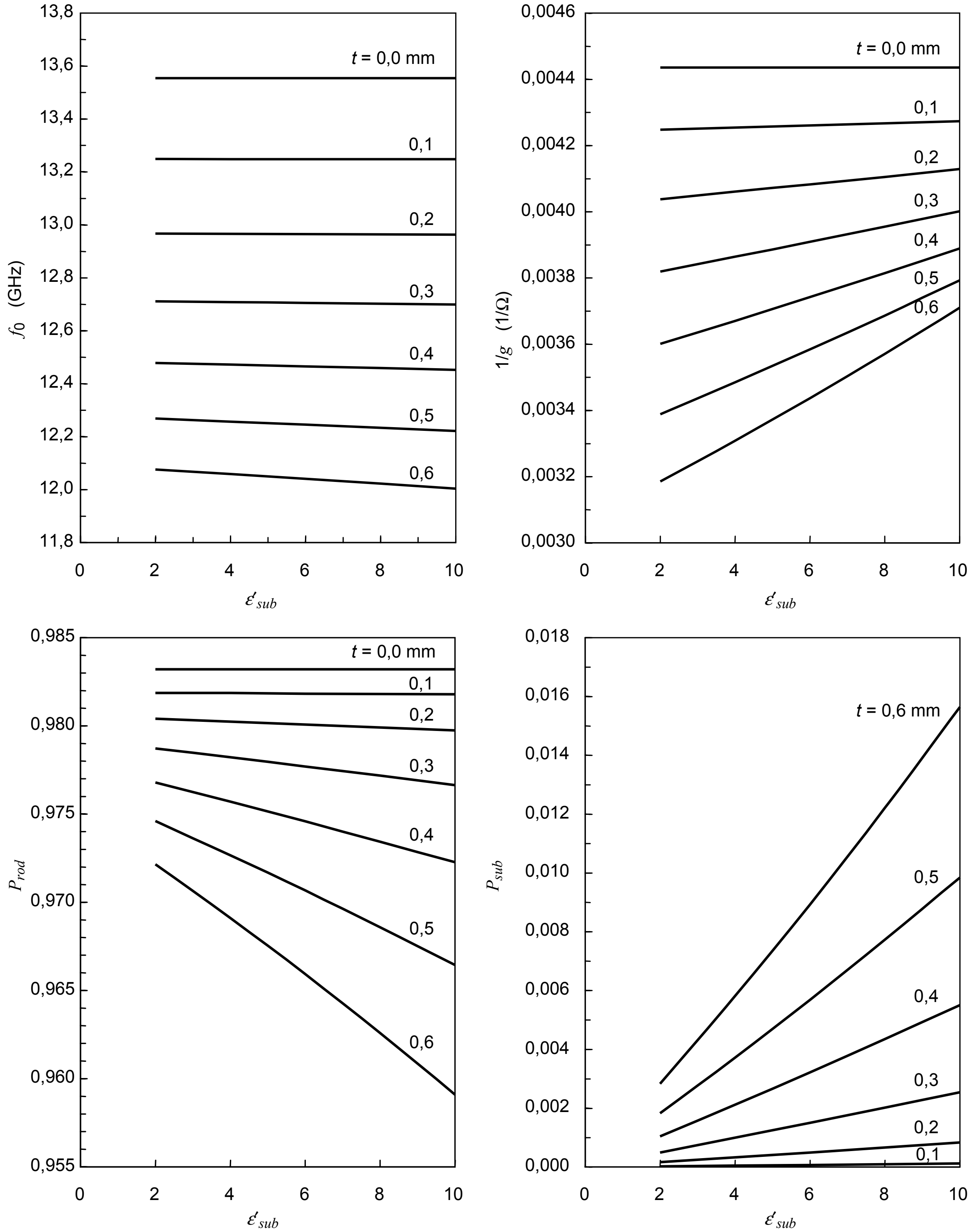


Figure 3 – Parameters chart of f_0, g, P_{rod} and P_{sub} for reference sapphire rod
Calculation conditions: ε'_{rod} = 9,4 , *d* = 10,00 mm and *h* = 5,00 mm

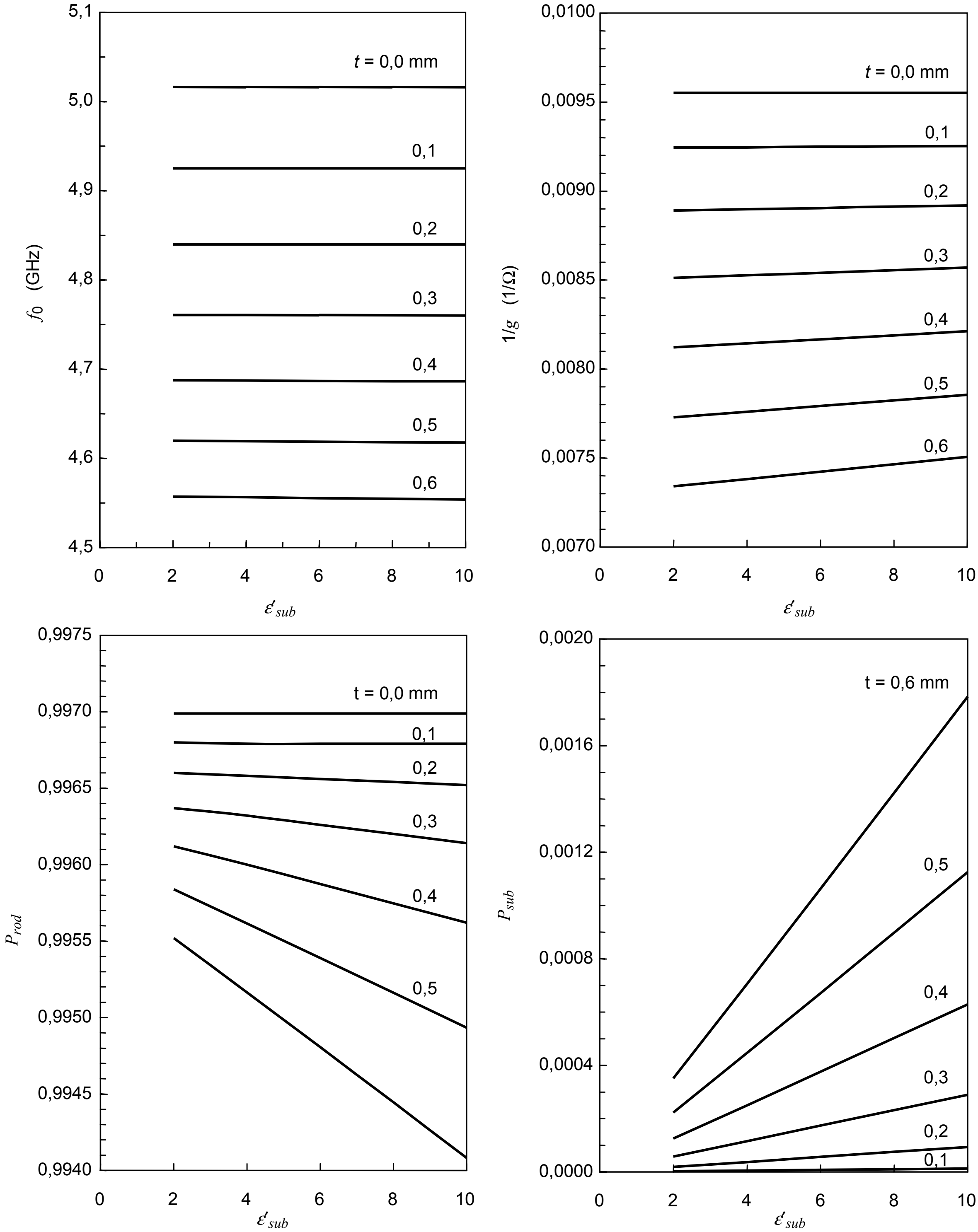


Figure 4 – Parameters chart of f_0, g, P_{rod} and P_{sub} for reference (Zr,Sn)TiO_4 rod
Calculation conditions: ε'_{rod} = 39, *d* = 14,00 mm and *h* = 6,46 mm

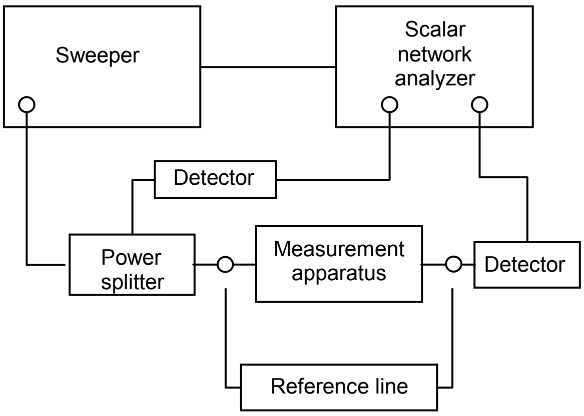
5 Preparation of specimen

Two test specimens of dielectric substrates with a conductor at one side are prepared for the σ_{ri} 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_{ri}. A substrate/conductor/substrate layer structure, where a conductor is formed between two dielectric substrates, is effective to avoid the bending of specimen.

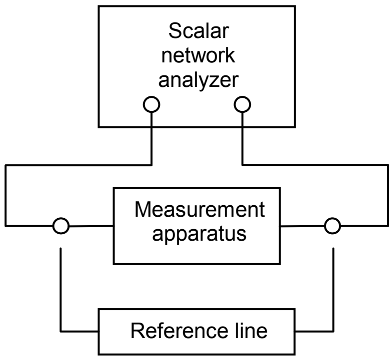
6 Measurement equipment and apparatus

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_{ri}, 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.



5(a) Scalar network analyzer system



5(b) Vector network analyzer system

Figure 5 – Schematic diagram of measurement equipments

6.2 Measurement apparatus

Figure 6 shows a measurement apparatus for σ_{ri}. 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.

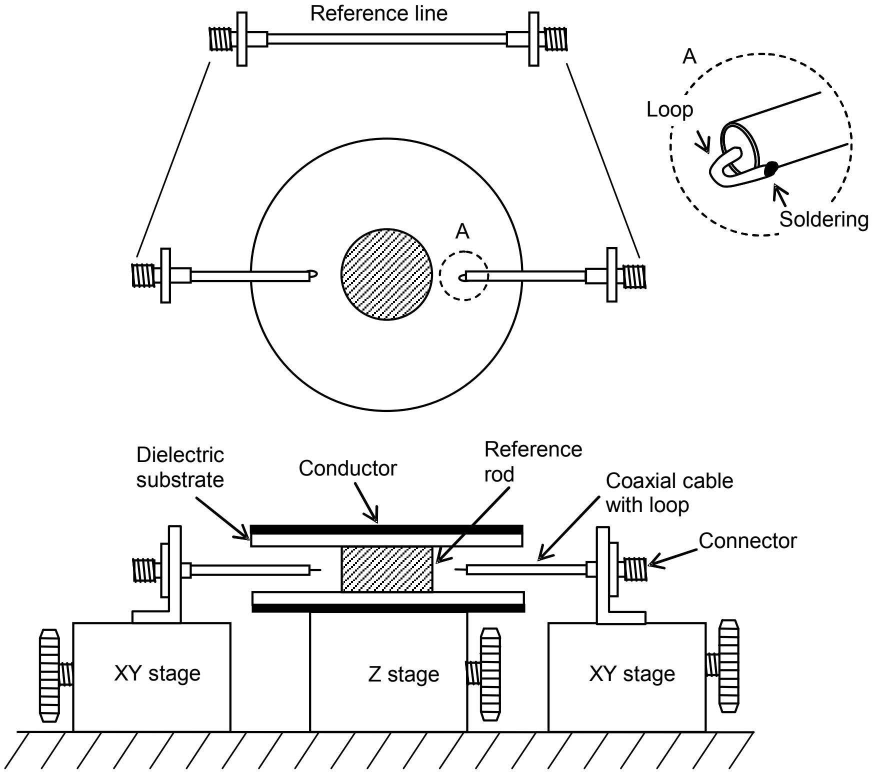


Figure 6 – Schematic diagram of measurement apparatus for σ_{ri}

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 $\mathrm{TE}_{01\delta}$ mode resonance peak of the resonator on the display of the network analyzer, by reading the approximate f_0 value of the $\mathrm{TE}_{01\delta}$ 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 $\mathrm{TE}_{01\delta}$ 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

$$Q_L = \frac{f_0}{f_{BW}} \tag{6}$$

$$Q_u = \frac{Q_L}{1 - A_t}, \qquad A_t = 10^{-\left|IA_0\,(\mathrm{dB})\right|/20} \tag{7}$$

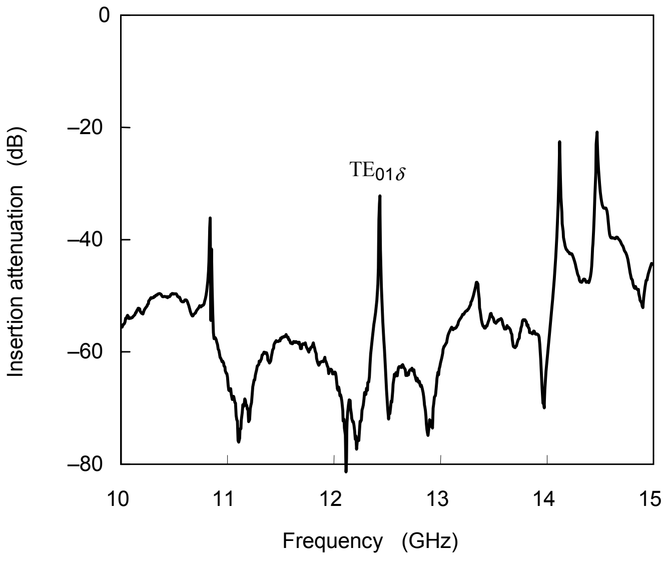


Figure 7 – Frequency response for reference sapphire rod with two dielectric substrates as shown in Figure 2

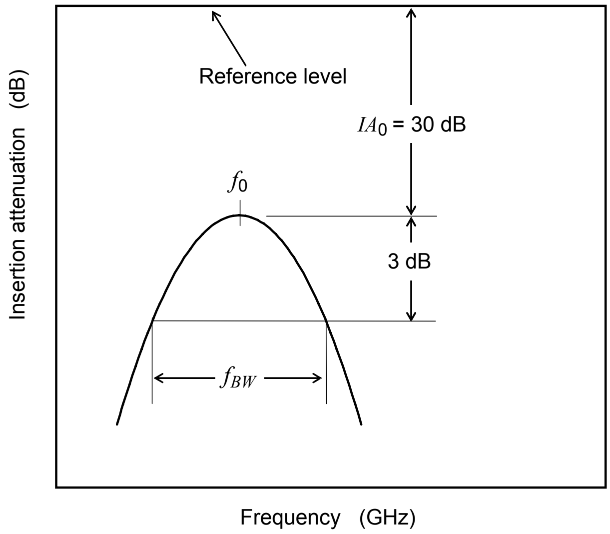


Figure 8 – Resonance frequency f_0, insertion attenuation IA_0 and half-power band width f_{BW}

7.4 Determination of σ_i and measurement uncertainty

Repeat this measurement several times. Then, calculate R_i from the mean value of Q_u using Equation (5). The values g, P_{rod} and P_{sub} 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

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

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 61338-1-4). 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 (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 a LTCC test substrate measured by the method (IEC 61338-1-4)

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 with ε'_{sub} = 4,76, *d'* = 45 mm and *t* = 0,415 mm

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

Annex A
(informative)

Derivation of Equation (4) for R_i

The unloaded quality factor Q_u of the $\mathrm{TE}_{01\delta}$ dielectric rod resonator (Figure 2) is defined by

$$\begin{aligned}\frac{1}{Q_u} &= \frac{energy\ loss\ per\ second}{\omega \cdot stored\ energy} \\ &= \frac{P_{ci} + \omega W_{rod} \tan\delta_{rod} + \omega W_{sub} \tan\delta_{sub}}{\omega W}, \quad W = W_{rod} + W_{sub} + W_{air}\,,\end{aligned} \tag{A.1}$$

where

ω	is $2\pi f_0$;
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;
W	is the total electric energy stored in the resonant space;
$\omega W_{rod} \tan\delta_{rod}$	is the dielectric energy loss in the dielectric rod;
$\omega W_{sub} \tan\delta_{sub}$	is the dielectric energy loss in the dielectric substrate.

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

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

$$P_{rod} = \frac{W_{rod}}{W} = \frac{\frac{1}{2}\varepsilon_0 \varepsilon'_{rod} \iiint_{Vrod} |E|^2 dv}{W} \tag{A.3}$$

$$P_{sub} = \frac{W_{sub}}{W} = \frac{\frac{1}{2}\varepsilon_0 \varepsilon'_{sub} \iiint_{Vsub} |E|^2 dv}{W} \tag{A.4}$$

$$W = \frac{1}{2}\varepsilon_0 \left(\varepsilon'_{rod} \iiint_{Vrod} |E|^2 dv + \varepsilon'_{sub} \iiint_{Vsub} |E|^2 dv + \iiint_{Vair} |E|^2 dv \right) \tag{A.5}$$

where

$\iint |H_t|^2 ds$ 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}, 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 ε'_{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 ε'_{rod} = 9,4. The actual sapphire rod usually has the ε'_{rod} in the range from 9,35 to 9,45. Table B.2 shows the calculated parameters for the sapphire rods with ε'_{rod} = 9,4 and 9,3. It shows that this difference of 0,1 on ε'_{rod} results in the calculation difference of 0,004 on σ_i. This value is negligibly small, compared with the measurement uncertainties of σ_i given in Table 4.

Table B.1 – Parameters obtained by FEM and rigorous analysis (IEC 61338-1-3) for the TE_{011} mode resonator with ε'_{rod} = 9,4, *d* = 10,0 mm, and *h* = 5,0 mm

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

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 with ε'_{rod} = 9,4 and 9,3, with the test condition of ε'_{sub} = 6,0, $\tan\delta_{sub}$ = 0,001, *t* = 0,5 mm, and Q_u = 6 000

Parameter	ε'_{rod} = 9,4	ε'_{rod} = 9,3	Difference
f_0 (GHz)	12,2452	12,3089	-0,0637
$1/g$ ($1/\Omega$)	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

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