INTERNATIONAL STANDARD

IEC 61338-1-4

First edition
2005-11

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

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

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

FOREWORD

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International Standard IEC 61338-1-4 has been prepared by IEC Technical committee 49: Piezoelectric and dielectric devices for frequency control and selection.

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

FDIS	Report on voting
49/748/FDIS	49/751/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.

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 millimetre-wave frequency

Part 2: Guidelines for oscillator and filter applications

Part 4: Sectional specification

Part 4-1: Blank detail specification

The committee has decided that the contents of this publication 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 publication will be

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- withdrawn,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

A bilingual version of this publication may be issued at a later date.

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

1 Scope and object

This part of IEC 61338 describes the measurement method of dielectric properties for dielectric resonator materials at millimetre-wave frequency.

This standard consists of two measurement methods: a) the dielectric rod resonator method excited by NRD-guide (Non-Radiative Dielectric waveguide) and b) the cut-off waveguide method excited by coaxial cables with small loops.

a) The dielectric rod resonator method excited by NRD-guide is similar to the dielectric rod resonator method given in IEC 61338-1-3. This method has the following characteristics:
   - a complete and exact mathematical solution of complex permittivity is given by computer software;
   - the measurement error is less than 0,3 % for ε' and less than 0,05 $\times 10^{-4}$ for tan δ;
   - the applicable measuring ranges of complex permittivity for this method are as follows:

     frequency: 30 GHz < f < 100 GHz;

     relative permittivity: 2 < ε' < 30;

     loss factor: 10^{-6} < tan δ < 10^{-2}.

b) The cut-off waveguide method excited by coaxial cables with small loops uses a dielectric plate sample placed in a circular cylinder of the TE_{011} mode. This method has the following characteristics:
   - fringe effect is corrected using the correction charts on the basis of rigorous analysis;
   - the measurement error is less than 0,5 % for ε' and less than 0,05$\times 10^{-4}$ for tan δ;
   - the *TCF* is measured with high accuracy;
   - the applicable measuring ranges of dielectric properties for this method are as follows:

     frequency: 30 GHz < f < 100 GHz;

     relative permittivity: 2 < ε' < 30;

     loss factor: 10^{-6} < tan δ < 10^{-2}.

2 Normative references

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

IEC 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*

3 Measurement parameter

The measuring parameters are defined as follows:

$$\dot{\varepsilon}_r = \varepsilon' - j\varepsilon'' = D/(\varepsilon_0 E) \quad (1)$$

$$\tan\ \delta = \varepsilon''/\varepsilon' \quad (2)$$

$$TC\varepsilon = \frac{1}{\varepsilon_{\mathrm{ref}}} \frac{\varepsilon_{\mathrm{T}} - \varepsilon_{\mathrm{ref}}}{T - T_{\mathrm{ref}}} \times 10^6 \qquad (1\times10^{-6}/\mathrm{K}) \quad (3)$$

$$TCF = \frac{1}{f_{\mathrm{ref}}} \frac{f_T - f_{\mathrm{ref}}}{T - T_{\mathrm{ref}}} \times 10^6 \qquad (1\times10^{-6}/\mathrm{K}) \quad (4)$$

where

D	is the electric flux density;
E	is the electric field strength;
ε_0	is the permittivity in a vacuum;
$\dot{\varepsilon}_r$	is the complex relative permittivity;
ε' and ε''	are the real and imaginary components of the complex relative permittivity $\dot{\varepsilon}_r$;
$TC\varepsilon$	is the temperature coefficient of relative permittivity, and TCF being the temperature coefficient of resonance frequency;
ε_{T} and $\varepsilon_{\mathrm{ref}}$	are the real parts of the complex relative permittivity at temperature T and reference temperature T_{ref} (T_{ref} = 20 °C to 25 °C), respectively;
f_{T} and f_{ref}	are the resonance frequency at temperature T and T_{ref}, respectively.

The TCF is related to $TC\varepsilon$ by the following equation:

$$TCF = -\frac{1}{2} TC\varepsilon - \alpha \quad (5)$$

where α is the coefficient of thermal expansion of the dielectric specimen.

It should be noted that this equation is satisfied when the 100 % of electro-magnetic energy in the measuring resonance mode is concentrated inside the dielectric specimen. In the actual case, TCF deviates by several 10^{-6}/K from the calculated value, because some portion of electro-magnetic energy is stored outside the dielectric specimen.

4 Dielectric rod resonator method excited by NRD-guide

4.1 Measurement equipment and apparatus

The measurement equipment and apparatus are as follows:

a) Measurement equipment

Figure 1 shows a schematic diagram of the equipment required for millimetre wave measurement. For the measurement of dielectric properties, 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. A scalar network analyzer can be used for the measurement, but a vector network analyzer has an advantage in precision of the measurement data.

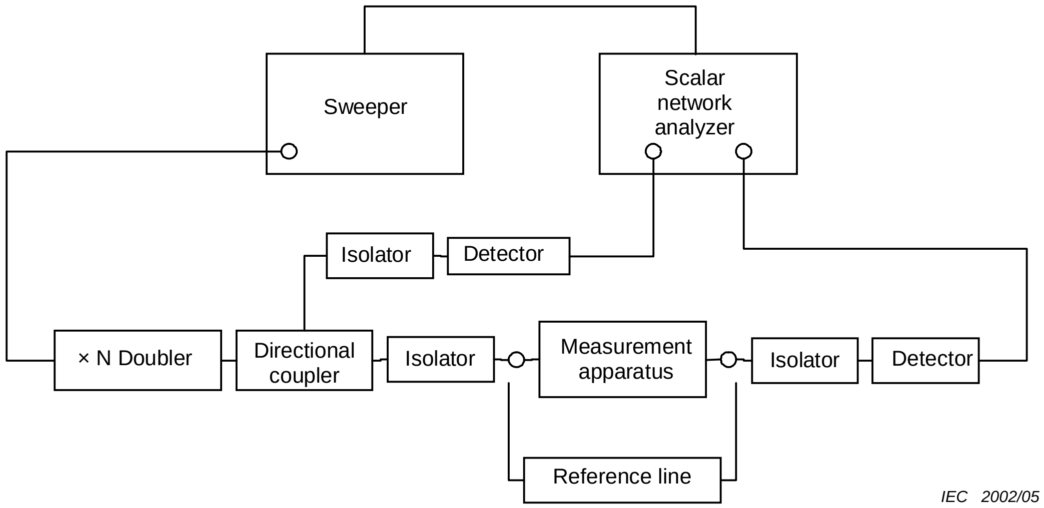

Figure 1a – Scalar network analyzer

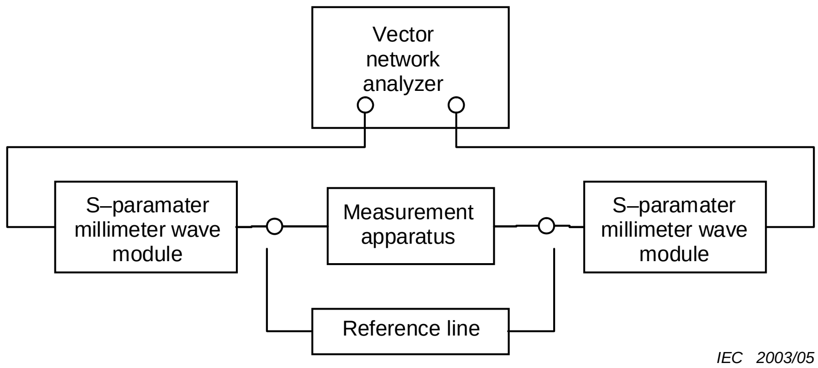

Figure 1b – Vector network analyzer

Figure 1 – Schematic diagram of measurement equipment

b) Measurement apparatus

Figure 2a shows a configuration of measuring apparatus of dielectric rod resonator method excited by NRD-guide. Figure 2b shows a cross-sectional view of the apparatus for measuring ε' and tan δ of a dielectric specimen with height h and d. The dielectric specimen is placed at the centre of the apparatus between two parallel conducting plates, and coupled to input and output NRD-guides. There remains a small air gap Δh between the dielectric specimen and the upper conducting plate. For Δh < 50 μm, the air gap can be neglected for the calculation of ε' (see Annex A).

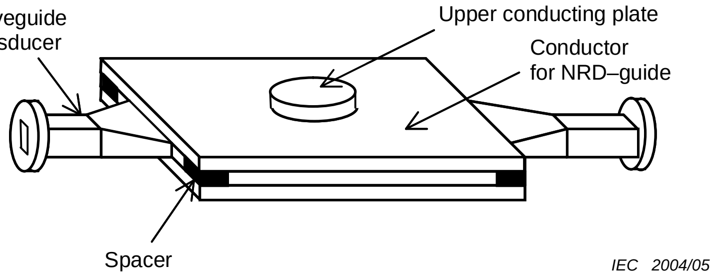

Figure 2a – Configuration of apparatus

Dimensions in millimetres

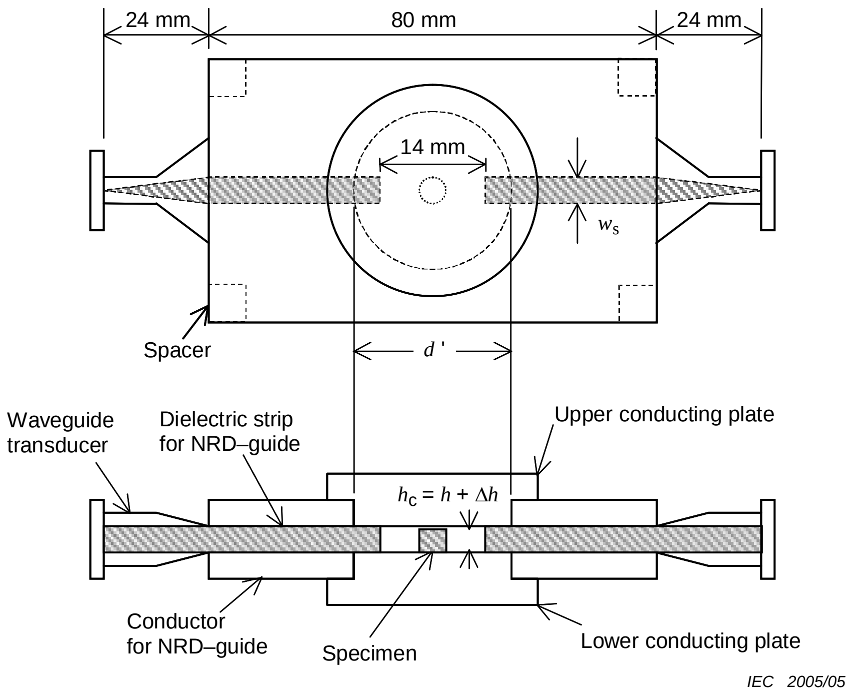

Figure 2b – Apparatus for ε' and tan δ measurement

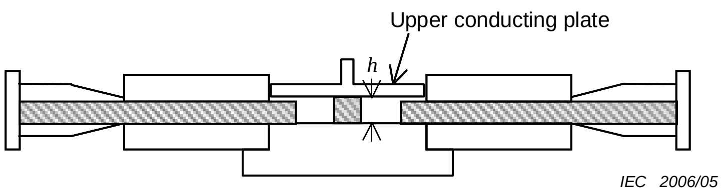

Figure 2c – Apparatus for *TCF* and *TC*ε measurement

Figure 2 – Measurement apparatus of dielectric rod resonator method excited by NRD-guide

Figure 2c shows an apparatus for measuring the temperature coefficient of resonance frequency TCF or that of relative permittivity $TC\varepsilon$. For this measurement, the upper conducting plate should be contacted to the dielectric specimen. The height h_S of dielectric strip for NRD-guide is designed to be smaller than height h of the dielectric specimen. The upper conducting plate is set gently to touch the top face of the specimen, so that an excessive pressure does not damage the surface of conducting plate.

As shown in Table 1, a diameter of the conducting plates in Figure 2b is determined by the diameter of dielectric specimen. In this measurement method, the ε' and tan δ are calculated under the condition that the conducting plates have an infinitely large diameter. As actual conducting plates have a finite diameter, a part of electro-magnetic energy leaks outward the conducting plates. Although this leaky energy shifts the resonance frequency and decreases the unloaded Q, its contribution is negligibly small under the condition of $d'/d > 5$.

Table 2 shows the example of dimensions for dielectric strips of NRD-guide in Figure 2b. Dielectric strips of the NRD-guide are made of PTFE or cross-linked styrene copolymer.

Figure 3 shows a waveguide transducer that connects the measuring apparatus to the measurement equipment with WR-15 or WR-10 waveguides. Table 3 shows the dimensions of the waveguide transducers. As shown in Figure 2b, the end of the dielectric strip of the NRD-guide is sharpened in the transducer.

Table 1 – Diameter of conducting plate

Diameter d'	$d' = 5d \sim 10d$ d : diameter of dielectric specimen
Material of conducting plate	Copper or silver is recommended

Table 2 – Dimension of dielectric strip of NRD-guide

Material	**Measurement frequency range** GHz	**Height h_s** mm	**Width w_s** mm
PTFE (ε' = 2,0)	55 to 65	2,25	2,50
	75 to 80	1,80	1,90
Cross-linked styrene Copolymer (ε' = 2,5)	55 to 65	2,25	2,00
	75 to 80	1,80	1,60

Table 3 – Dimensions of waveguide transducer

Waveguide	**Frequency range** GHz	h_{wg} mm	w_{wg} mm	h_s mm
WR-15	55 to 65	3,80	1,90	2,25
WR-10	75 to 80	2,54	1,27	1,80

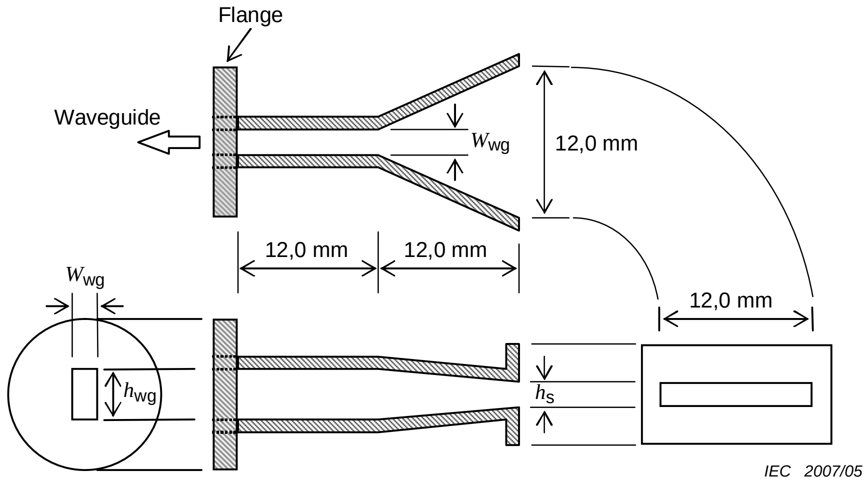

Figure 3 – Waveguide transducer from NRD-guide to waveguide

4.2 Theory and calculation equations

4.2.1 Measurement of relative permittivity and loss factor

Figure 4 shows a configuration of the TE_{0m1} mode resonator. The cylindrical dielectric specimen is short-circuited at both ends by the two parallel conducting plates. The values ε' and tan δ of the dielectric resonator are calculated from the resonance frequency f_0 and unloaded quality factor Q_u measured for the TE_{0m1} resonance mode. It is recommended to use the TE_{011}, TE_{021} and TE_{031} resonance modes for the materials with ε' = 2 to 4, 4 to 20 and 20 to 30, respectively.

The resonance wavelength λ_0 in free space and the guiding wavelength λ_g in the dielectric transmission line are given by the following equations:

$$\lambda_0 = \frac{c}{f_0}, \quad \lambda_g = 2h \tag{6}$$

where c is the velocity of light in a vacuum (c = 2,997 9 × 10^8 m/s).

As described in 4.1b), the air gap Δh can be neglected for the calculation of ε' and tan δ in the case of Δh < 50 μm. So, the height h is used in equation (6).

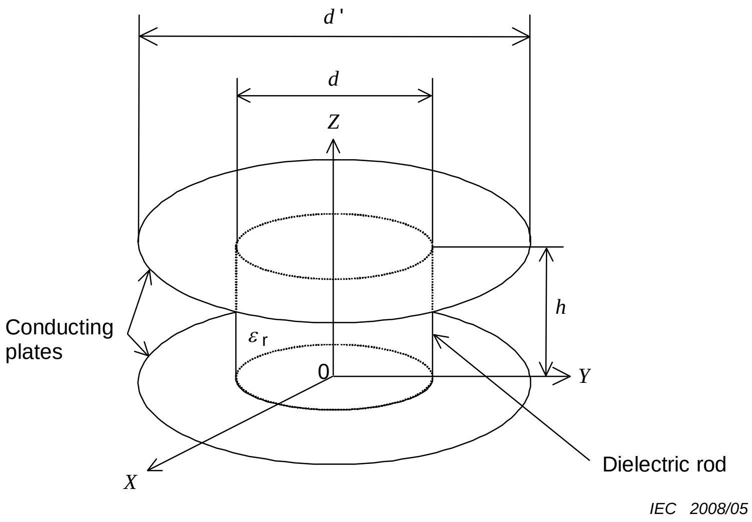

Figure 4 – Configuration of a cylindrical dielectric rod resonator short-circuited at both ends by two parallel conducting plates

The value v^2 is calculated from λ_0 and λ_g:

$$v^2 = \left(\frac{\pi d}{\lambda_0}\right)^2 \left[\left(\frac{\lambda_0}{\lambda_g}\right)^2 - 1\right] \tag{7}$$

Using the value v^2, the value u^2 is calculated:

$$u\frac{J_0(u)}{J_1(u)} = -v\frac{K_0(v)}{K_1(v)} \tag{8}$$

where $J_n(u)$ is the Bessel function of the first kind and $K_n(v)$ is the modified Bessel function of the second kind. For any value of v, the m-th solution u exists between u_{0m} and u_{1m}, where $J_0(u_{0m}) = 0$ and $J_1(u_{1m}) = 0$. The first, second and third solution of m = 1, 2 and 3 are shown in Figure 5.

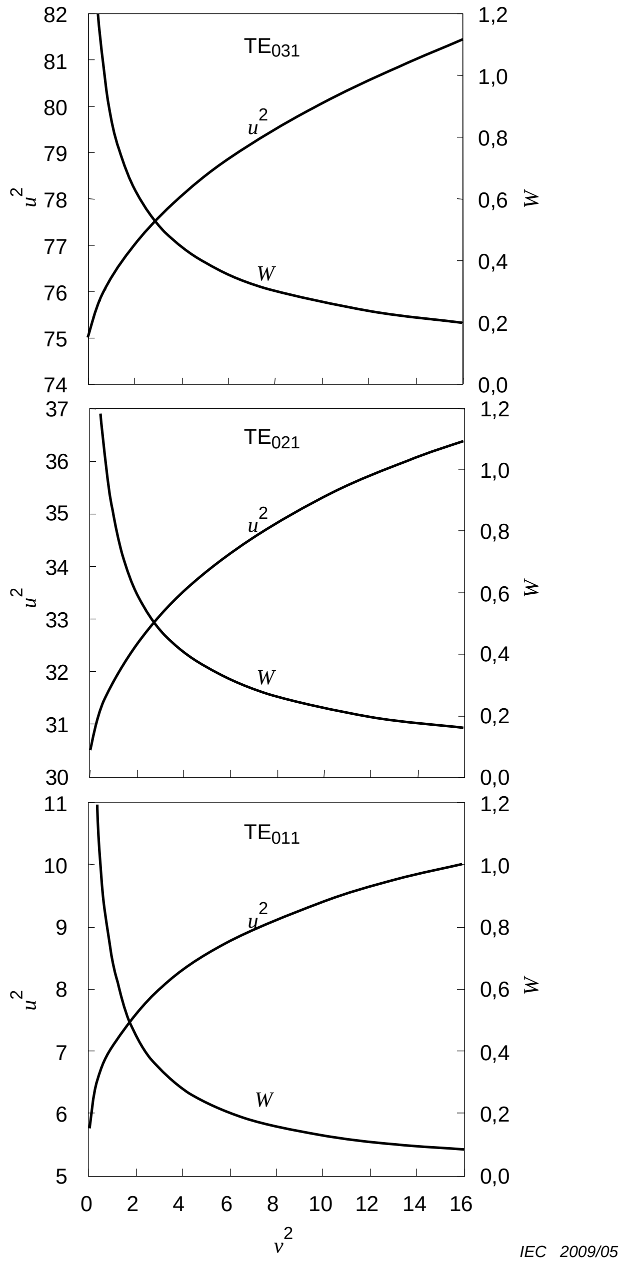

Figure 5 –Calculations of u^2 and W as a function of v^2 for TE_{011}, TE_{021} and TE_{031} resonance modes

The relative permittivity ε' is calculated by the following equation using the values v^2 and u^2:

$$\varepsilon' = \left(\frac{\lambda_0}{\pi d}\right)^2 \left(u^2 + v^2\right) + 1 \qquad (9)$$

By using the measured unloaded Q, Q_u, the loss factor tan δ is calculated:

$$\tan\delta = \frac{A}{Q_u} - BR_S = \frac{A}{Q_u} - \frac{B'}{\sqrt{\sigma_r}} \qquad (10)$$

where

$$R_S(\Omega) = \sqrt{\frac{\pi f_0 \mu}{\sigma}} = \sqrt{\frac{\pi f_0 \mu}{\sigma_0 \sigma_r}} \qquad (11)$$

$$A = 1 + \frac{W}{\varepsilon'} \qquad (12)$$

$$B = \left(\frac{\lambda_0}{\lambda_g}\right)^3 \frac{1+W}{30\pi^2 \varepsilon'}, \qquad B' = B\sqrt{\frac{\pi f_0 \mu}{\sigma_0}} \qquad (13)$$

$$W = \frac{J_1^2(u)}{K_1^2(v)} \cdot \frac{K_0(v)K_2(v) - K_1^2(v)}{J_1^2(u) - J_0(u)J_2(u)} \qquad (14)$$

Here, R_S is the surface resistance of the conducting plates and σ is the conductivity of the conducting plates. The relative conductivity σ_r is defined as $\sigma = \sigma_0 \sigma_r$, where σ_0 is the conductivity of the international standard annealed copper ($\sigma_0 = 5{,}8 \times 10^7$ S/m at 20 °C). μ is the permeability of conducting plates which has the value of $\mu = \mu_0 = 4\pi \times 10^{-7}$ H/m for non-magnetic conductors such as Cu or Ag.

The tan δ is calculated by using R_S and B , or, σ_r and B' . As σ_r is independent of frequency and being a good indicator for the degradation level of conductivity caused by the surface roughness or oxidation on conducting plates, σ_r is conveniently used.

The function W/ε' equals the ratio of electric-field energy stored outside to inside of the dielectric specimen. The W equals zero when 100 % electric-field energy is concentrated inside the specimen. The calculated results of W against v for the TE_{011}, TE_{021} and TE_{031} resonance modes are shown in Figure 5.

4.2.2 Relative conductivity of conducting plates

The value of σ_r or R_S of the conducting plates is determined in advance of the calculation for the tan δ of dielectric specimens. The measurement accuracy of σ_r has vital importance on the accuracy of tan δ, because A/Q_u and $B'/\sqrt{\sigma_r}$ in equation (10) have the same order of magnitude for tan δ of 10^{-4}.

Figure 6 shows a configuration of the apparatus to measure the σ_r of conducting plates. Two single crystal sapphires with the TE_{021} and $TE_{02\delta}$ resonance modes are used for measuring the σ_r . The sapphires used as reference resonators have low tan δ at millimetre-wave frequency and have the same ε' and tan δ. The axis of each rod is parallel to C-axis. The dimensions of the TE_{021} and $TE_{02\delta}$ resonance modes are designed so that they have the same resonance frequency. Table 4 shows the dimensions of sapphires for the resonance frequency of 60 GHz and 77 GHz.

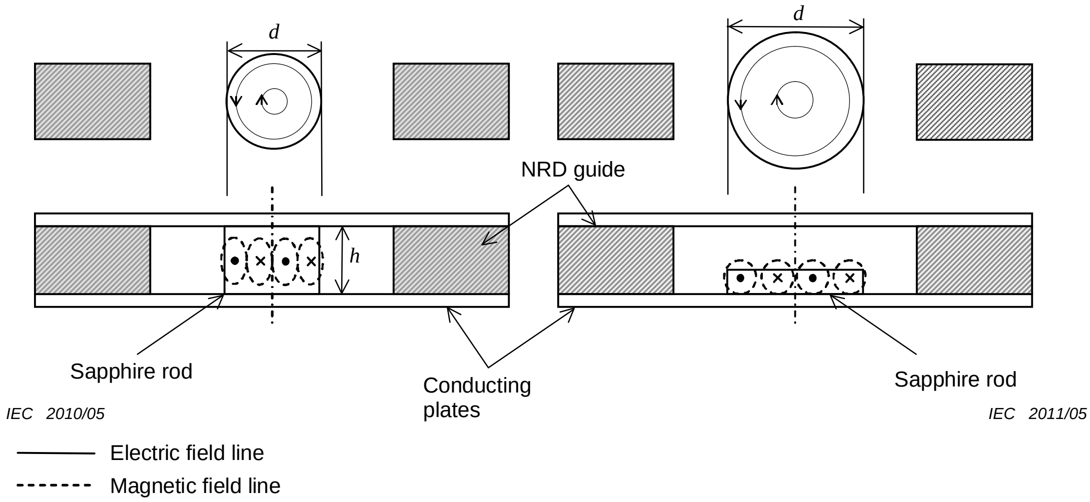

Figure 6a – TE $_{021}$ mode resonator   Figure 6b – TE $_{02\delta}$ mode resonator

Figure 6 –Configuration of reference dielectric resonator for measurement of σ_r of conducting plates

Table 4 – Dimensions of reference sapphire resonators and their partial electric energy filling factor P_e and geometric factor G

	TE_{021}				$TE_{02\delta}$			
f_0 GHz	d mm	h mm	P_{e1}	G_1 Ω	d mm	h mm	$P_{e\delta}$	G_δ Ω
60	3,14	2,25	0,915	1 182	4,49	0,80	0,906	409
77	2,42	1,80	0,901	1 208	3,60	0,60	0,894	382

NOTE 1 Specifications for sapphire rod are as follows:

ε' =9,4, flatness: <0,005 mm, roughness of both ends: R_a< 0,01 μm, roughness of side of rod: R_a < 1 μm, perpendicular : <0,1°, axis: parallel to c-axis < 0,3°.

NOTE 2 Values $P_{e\delta}$ and G_δ are effective for the standard sapphire rod having the tolerance of ε' to be 9,4 ± 0,1 and the dimensional tolerance of d and h to be ±0,1 mm, respectively.

As shown in Figure 6, the TE $_{02\delta}$ mode resonator has a larger d/h ratio. The electromagnetic field of this mode is more concentrated near the surface of the lower conductor compared with the TE_{0m1} mode resonator. The different contribution of conductor loss on unloaded Q_u for each resonator enables the calculation of σ_r. High accuracy on σ_r is obtained by enlarging the difference of the Q_u values between the TE $_{021}$ and TE $_{02\delta}$ mode resonators.

The resonance frequency and unloaded Q for the TE $_{021}$ and TE $_{02\delta}$ mode resonators are noted by using the subscripts 1 and δ: f_{01} and Q_{u1} for the TE_{021} resonator, $f_{0\delta}$ and $Q_{u\delta}$ for the TE $_{02\delta}$ resonator. The reference TE $_{021}$ and TE $_{02\delta}$ resonators have the same resonance frequency f_{01} = $f_{0\delta}$, and different unloaded Q, ($Q_{u1} > Q_{u\delta}$). The value σ_r at the resonance frequency f_{01} = $f_{0\delta}$ is given by the following equation:

$$\sigma_r = \sigma / \sigma_0 = \frac{\pi \mu f_0}{\sigma_0}\left[\frac{Q_{u1}Q_{u\delta}}{G_1 G_\delta}\cdot\frac{G_1 P_{e1} - G_\delta P_{e\delta}}{Q_{u1}P_{e1} - Q_{u\delta}P_{e\delta}}\right]^2 \quad (15)$$

where P_{e1} and $P_{e\delta}$ are the partial electric energy filling factors of the reference TE_{021} and $TE_{02\delta}$ resonators, respectively. G_1 and G_δ being the geometric factors for each reference resonators. Calculated values of P_e and G for the reference sapphire resonators with ε' = 9,4 are given in Table 4. These values are applicable when the actual dimensions agree with the designed dimensions within the deviation of 0,01 mm. The derivation of equation (15) and the formulas for P and G are given in Annex B.

NOTE 3 Loss factor of reference resonators is calculated by the following equation if needed.

$$\tan\delta_1 = \tan\delta_\delta = \frac{1}{Q_{u1}Q_{u\delta}} \cdot \frac{G_1 Q_{u\delta} - G_\delta Q_{u1}}{G_1 P_{e1} - G_\delta P_{e\delta}} \quad (16)$$

4.2.3 Temperature coefficient of resonance frequency and relative permittivity

The temperature coefficient of resonance frequency TCF is given by measuring the resonance frequency at temperature T and reference temperature T_{ref} using equation (4). In the same way, temperature coefficient of relative permittivity $TC\varepsilon$ is given by calculating relative permittivity at temperature T and reference temperature T_{ref} using equation (3).

A dielectric material generally has nonlinear dependence of relative permittivity on temperature. A procedure to deal with this non-linear temperature dependence of resonance frequency or relative permittivity is described in IEC 61338-1-3.

4.2.4 Temperature dependence of loss factor

The temperature dependence of tan δ is given by measuring the tan δ at various temperatures. For the calculation of tan δ at each temperature, the temperature dependence of σ_r is needed. The temperature dependence of conductivity for the annealed copper in conformity with the international standard is given as follows.

$$\sigma_0(T) = \frac{5{,}8 \times 10^7}{1 + 3{,}93 \times 10^{-3}(T - 20)} \ \text{(S/m)} \quad (17)$$

When the σ_r at reference temperature T_{ref} is measured, one can use following equation for as the first order approximation of σ_r at temperature T.

$$\sigma_r(T) = \frac{\sigma_r}{1 + 3{,}93 \times 10^{-3}(T - T_{ref})} \ (\%) \quad (18)$$

4.3 Measurement procedure

The preparation of dielectric specimens and measurement procedure are as follows:

a) Preparation of reference sapphire resonator

Prepare the reference sapphire resonators with the dimensions shown in Table 4. In order to minimize the measurement error on σ_r of the conducting plates, their c-axes shall be parallel to z-direction, and both ends of the rod shall be polished parallel to each other and perpendicular to c-axis.

b) Preparation of test specimens

The TE_{011} mode dielectric resonators have very small dimensions for the measurement at millimetre-wave frequency. It is preferable to use the TE_{021} or TE_{031} resonance modes especially for measuring the high-ε' materials. Table 5 shows recommended diameters for the materials with ε' from 2 to 40. The height h is fixed to 2,25 mm and 1,80 mm for the measurement at 60 GHz and 77 GHz, respectively. Figures 7 and 8 show the diameter d of the TE_{011}, TE_{021} and TE_{031} mode resonators with resonance frequencies 60 GHz and 77 GHz, respectively.

Table 5 – Diameter *d* of test specimens for 60 and 77 GHz measurement. Height *h* is fixed to 2,25 mm and 1,80 mm for 60 GHz and 77 GHz measurement, respectively

ε'	d (mm) f_0 = 60 GHz			d (mm) f_0 = 77 GHz		
	TE_{011}	TE_{021}	TE_{031}	TE_{011}	TE_{021}	TE_{031}
2,0	5,05	-		3,68		
2,5	3,80	-		2,83		
3,0	3,16	-		2,38		
3,5	2,75	-		2,08		
4,0	2,47	5,49		1,88	4,20	
5,0	-	4,67			3,59	
6,0	-	4,14			3,19	
8,0	-	3,45			2,67	
10,0	-	3,02			2,34	
12,0		2,72			2,11	
14,0		2,50			1,93	
16,0		2,32			1,80	
18,0		2,17			1,69	
20,0		2,05	3,21		1,59	2,49
25,0			2,85			2,21
30,0			2,58			2,01
35,0			2,38			1,85
40,0			2,22			1,73

c) Preparation of measurement apparatus

Set up the measurement equipment and apparatus as shown in Figures 1 and 2. All measurement equipments, apparatus and dielectric specimens shall be kept in a clean, dry state as high humidity degrades unloaded Q. The relative humidity is preferable to be less than 60 %.

d) Measurement of reference level

Measure the through level of transmission power, reference level. Connect the input and output NRD-guides with a dielectric strip, the length of which is 14 mm, and the height h_s and width W_s shown in Table 2. Measure the through transmission power level over the measurement frequency range.

e) Measurement of conductivity of the conducting plates

Connect the measurement apparatus as shown in Figure 6. Insert the TE_{021} sapphire resonator at the center of the conducting plates and adjust the distance between resonator and NRD-guide strip.

Figure 9 shows an example of the TE_{021} mode resonance peak. The identification of this peak is relatively easy, since the TM or hybrid resonance modes are suppressed in the resonator excited by the NRD-guide. This peak is identified as it shifts downward in frequency when the upper plate separates slowly from top face of the resonator.

Adjust the insertion attenuation IA_0(dB) of the resonance peak to be from 15 dB and 30 dB from the reference level by changing the distance between sapphire resonators and NRD-guide strip. Measure the f_{01} and the half-power band-width Δf of the TE_{021} mode resonator. Calculate the unloaded Q, Q_{u1}, using the following equation.

$$Q_u = \frac{f_0 / \Delta f}{1 - 10^{-IA_0/20}} \qquad (19)$$

In a similar way, insert the $TE_{02\delta}$ mode sapphire resonator in the apparatus and measure the $f_{0\delta}$ and $Q_{u\delta}$.

In order to improve the measurement accuracy of σ_r, repeat this measurement several times for the TE_{021} and $TE_{02\delta}$ mode resonators. Using the mean values of f_{01}, Q_{u1}, $f_{0\delta}$ and $Q_{u\delta}$, calculate σ_r using equation (15). As the σ_r of the conducting plates degrades day by day due to wear or oxidation of the metal surface, this measurement shall be repeated every time prior to the measurement of test specimens. It is preferable to polish the surface of the conducting plates when the σ_r degrades more than 10 %.

f) Measurement of complex permittivity of test specimen

In a similar way, measure the f_0 and Q_u of the TE_{0m1} resonance mode of the test specimens. Calculate their ε' and tan δ from equation (10).

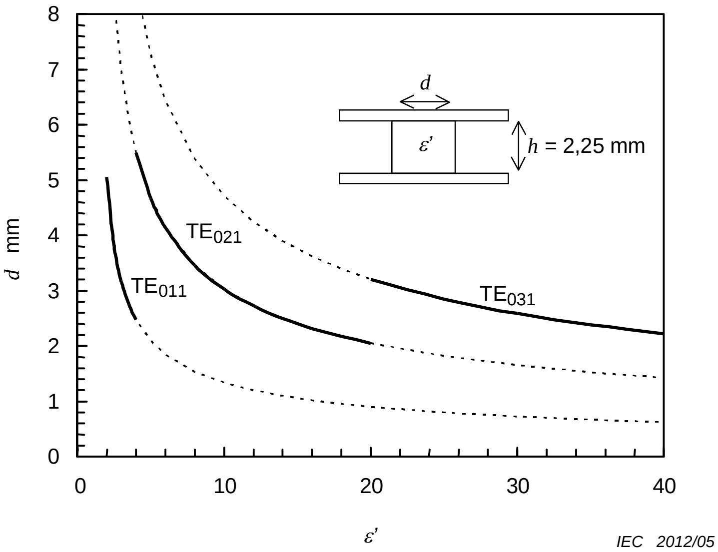

Figure 7 – Diameter *d* of TE_{011}, TE_{021} and TE_{031} mode resonators with resonance frequency of 60 GHz

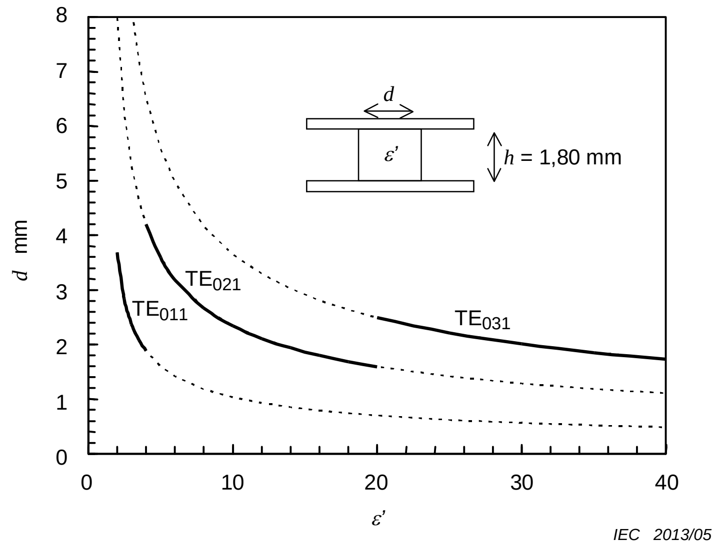

Figure 8 – Diameter *d* of TE_{011}, TE_{021} and TE_{031} mode resonators with resonance frequency of 77 GHz

4.4 Example of measurement result

a) Measurement result of σ_r of conducting plates

Table 6 shows a measurement result of σ_r of conducting plates at 60 GHz. The reference sapphire resonators with dimensions of 3,13 mm × 2,25 mm and 4,49 mm × 0,87 mm were used for the measurement. The height h_C = 2,279 mm of the apparatus was used for the calculation of σ_r. The measurement errors are shown in each column using the term "±".

b) Measurement results of ε' and tan δ

Table 7 shows the measurement results of ε' and tan δ at 57 GHz. Sapphire and PTFE were used as the test specimens. The values σ_r = 80,5 % and h_C = 2,323 were used for the calculation.

c) Measurement results of TCF and $TC\varepsilon$

Figure 10 shows a measurement result of temperature dependence for resonance frequency and relative permittivity of sapphire crystal at 60 GHz.

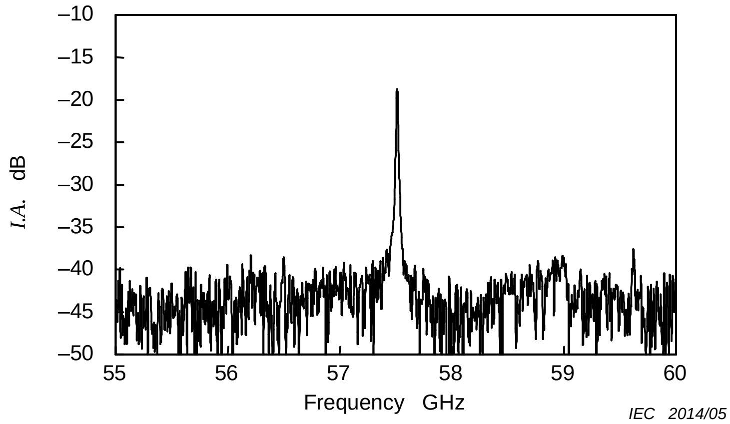

Figure 9 – Example of TE_{021} mode resonant peak

Table 6 – Measurement results of σ_r of conducting plates

Reference resonators (Mode)	d mm	h mm	P_e	G	f_0 GHz	IA_0 dB	Q_u	σ_r %	tan δ 10^{-5}
Sapphire (TE_{021})	3,130 ±0,005	2,250 ±0,001	0,910	1 197	59,876 ±0,008	19,0 ±1,0	8 782 ±119	87 ±4	6,2 ±0,3
Sapphire ($TE_{02\delta}$)	4,490 ±0,004	0,807 ±0,001	0,907	413	59,692 ±0,047	19,0 ±0,3	4510 ±50		

Temperature : 20 °C, Humidity : 50 %

Table 7 – Measurement results of ε' and tan δ of sapphire and PTFE specimen

Specimen	Mode	d mm	h mm	f_0 GHz	IA_0 dB	Q_u	ε'	tan δ 10^{-5}
Sapphire -1	TE_{021}	3,276 ±0,001	2,269 ±0,001	57,540 ±0,003	21,6 ±0,1	8 868 ±14	9,417 ±0,005	5,80 ±0,05
Sapphire -2	TE_{021}	3,277 ±0,001	2,261 ±0,001	57,528 ±0,010	21,7 ±0,1	8 972 ±40	9,416 ±0,007	5,65 ±0,06
PTFE -1	TE_{011}	5,456 ±0,005	2,267 ±0,002	56,610 ±0,010	20,5 ±0,1	2 820 ±12	2,065 ±0,002	18,8 ±0,2
PTFE -2	TE_{011}	5,443 ±0,004	2,266 ±0,002	56,640 ±0,013	20,1 ±0,1	2 816 ±14	2,066 ±0,002	18,9 ±0,3

Temperature : 25 °C, Humidity : 50 %

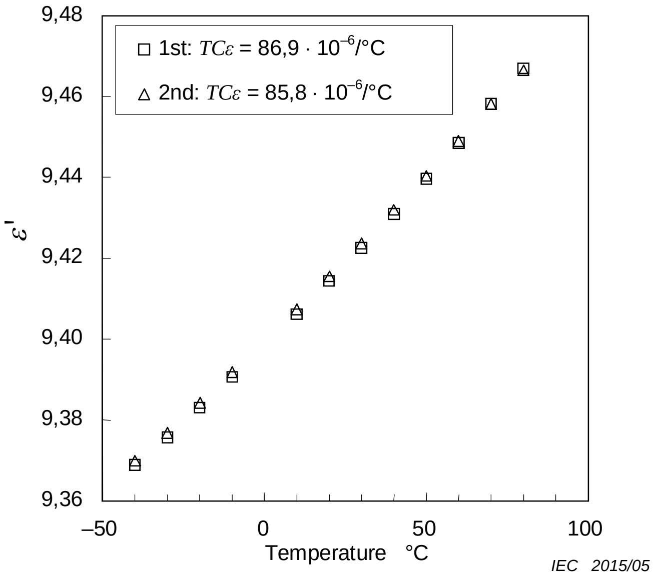

Figure 10a – Resonance frequency

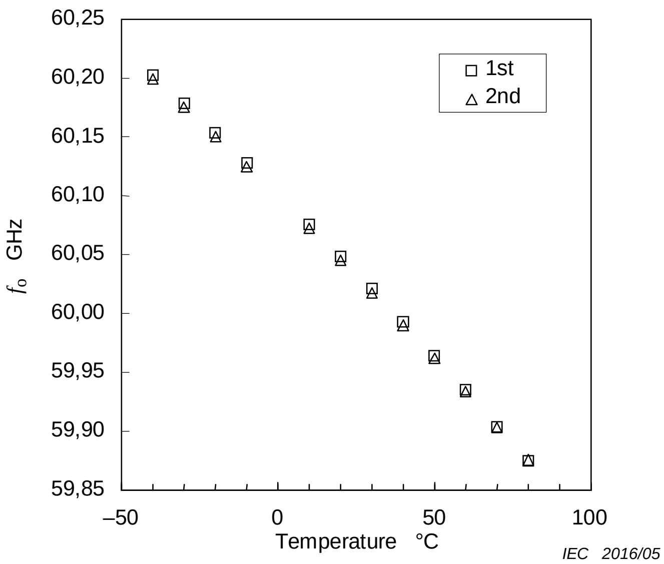

Figure 10b – Relative permittivity

Figure 10 – Measurement result of temperature dependence of f_0 and ε' of sapphire

5 Cut-off waveguide method excited by coaxial cables with small loops

5.1 Measurement equipment and apparatus

The measurement equipment and apparatus are as follows:

a) Measurement equipment

The same measurement equipment used for the dielectric rod resonator method is used for the cut-off waveguide method (Figure 1). For the measurement of dielectric properties, 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.

b) Measurement apparatus

Figure 11a shows an apparatus for measuring the complex permittivity of dielectric specimen. The components of the apparatus are the conducting cylinder that is cut into two parts at the middle of the height, two electro-magnetic wave absorbers on the top and bottom of the cylinder, and two semi-rigid cables with small loops. A dielectric plate specimen with diameter d_s and thickness t is placed at the middle of the cylinder and clamped by clips.

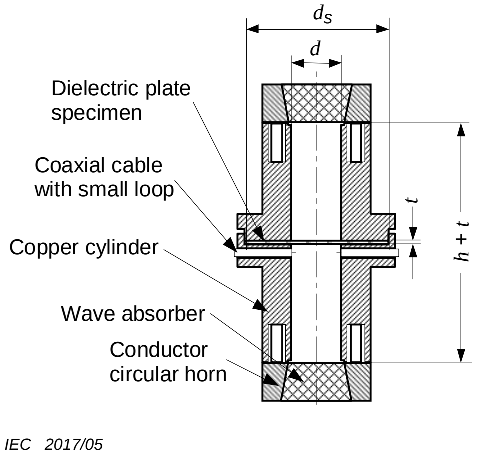

Figure 11a – Conducting cylindrical resonator clamping a dielectric specimen

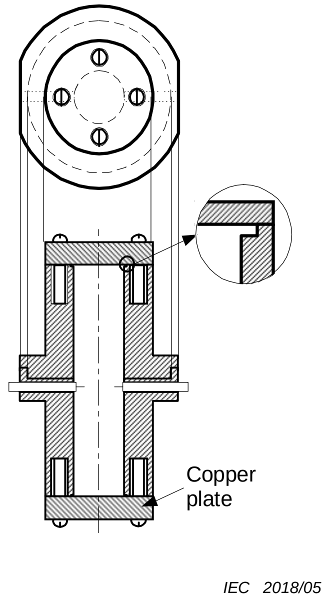

Figure 11b – Empty cavity

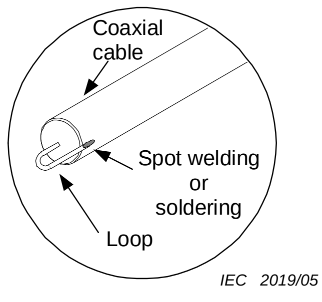

Figure 11c – Exciting coaxial cable with small loop

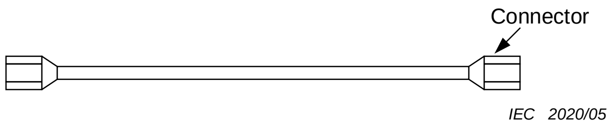

Figure 11d – Reference line for calibration with total length of two coaxial exciting cables

Figure 11 – Measurement apparatus for cut-off waveguide method

For the conducting cylinder, high conductivity metals such as copper or copper-plated metals, which plating thickness should be greater than 3 µm, are generally used. The inner surface of the cylinder is preferable to be polished to a mirror-like sheen with a surface roughness less than 0,1 µm.

The dimensions d, h and surface resistance of the conducting cylinder are measured by using an empty cavity shown in Figure 11b. Here, the dielectric specimen and electro-magnetic wave absorbers are removed from the conducting cylinder, and two copper plates are attached at the top and bottom of the cylinder.

Figure 11c shows a small loop at the end of each semi-rigid cable. The plane of the loop is set parallel to that of the dielectric substrate. The recommended type of semi-rigid cable is UT-47 or UT-34 with outer diameters of 1,2 mm or 0,9 mm, respectively.

The distance between two cables is adjusted for the insertion attenuation (IA_0) to be around 30 dB. Lower IA_0 (<20 dB) increases the field disturbance in the measurement mode, and higher IA_0 (> 40 dB) increases the thermal noise of the network analyzer excessively

Figure 11d shows a reference semi-rigid cable used for the calibration of full transmission power level, i.e. the reference level. The length of this cable is equal to the sum of two semi-rigid cables.

Table 8 shows recommended dimensions of inner diameter d and height h of the conducting cylinder for the measurement at 50 GHz or 80 GHz frequencies. These dimensions are determined so that the resonance frequencies of the TE_{011} and TE_{013} mode have not those of the other resonance modes near by.

The dielectric specimen is prepared to have the diameter d_s greater than 1,2d ($d_s \geq 1{,}2d$) and the thickness t.

Table 8 – Recommended dimensions for conducting cylinder

Frequency	d mm	h mm
50 GHz	7,0	31,0
	7,0	23,0
80 GHz	4,5	19,9
	4,5	15,3

5.2 Theory and calculation equations

5.2.1 Dimension of dielectric specimen and relative conductivity of conducting cylinder: *d*, *h*, σ_r

In advance with the measurements of ε' and tan δ for dielectric specimen, the dimensions d, h and relative conductivity σ_r of the conducting cylinder are measured. Measurement of dimensions by micrometer often causes the errors depending on measuring points. The effective dimensions for d and h are obtained precisely by measuring the resonance frequencies of the TE_{011} and TE_{013} modes using the empty cavity (Figure 11b).

Figure 12 shows an example of frequency responses for the empty cavity with dimensions d = 7 mm and h = 31 mm. The resonance frequencies f_{01} and f_{03} of the TE_{011} and TE_{013} resonance modes are measured, respectively. The dimensions d and h of this empty cavity are given as follows:

$$d = \frac{c j_{01}^{'}}{\pi} \sqrt{\frac{8}{9 f_{01}^{2} - f_{03}^{2}}} \tag{20}$$

$$h = \frac{c}{2} \sqrt{\frac{8}{f_{03}^{2} - f_{01}^{2}}} \tag{21}$$

where c is the velocity of light and $j_{01}^{'}$ is the first root of its derivative of the Bessel function of the first kind, $j_{0}^{'}(j_{01}) = 0$ (c = 2,9979 x 10^8 m/s and $j_{01}^{'}$ = 3,871 7).

The relative conductivity of the conducting cylinder is given by measuring the unloaded Q, Q_{u1}, of the TE_{011} resonance mode of the empty cavity. The surface resistance R_S is given by the following equation:

$$R_S = \frac{\pi \sqrt{30 \mu_0 f_0 d \left\{ j'^{2}_{01} + \left(\frac{\pi d}{2h} \right)^{2} \right\}^{\frac{5}{2}}}}{Q_{u1} \left\{ j'^{2}_{01} + 2\pi^{2} \left(\frac{d}{2h} \right)^{3} \right\}} \tag{22}$$

where μ_0 is the permittivity in a vacuum ($\mu_0 = 4\pi \times 10^{-7}$ H/m).

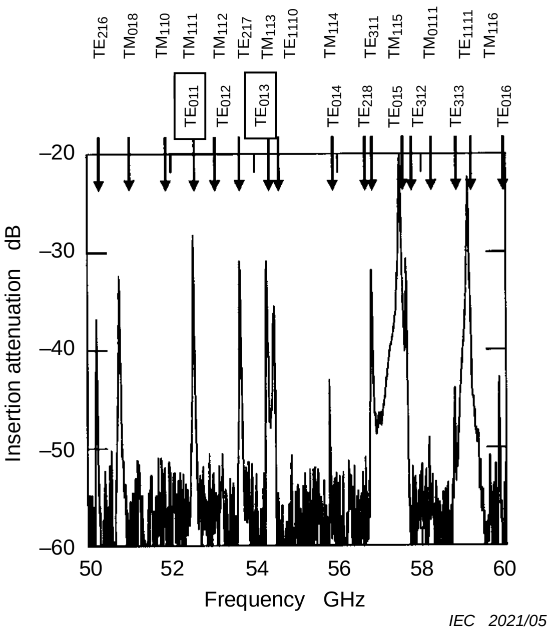

Figure 12 – Frequency response for the empty cavity with dimensions of d = 7 mm and h = 31 mm

The surface resistance R_S is the function of conductivity σ.

$$R_S = \sqrt{\pi f_0 \mu_0 / \sigma} \tag{23}$$

The relative conductivity σ_r of the conducting cylinder is defined as $\sigma = \sigma_0 \sigma_r$, where σ_0 is the conductivity of the universal standard copper ($\sigma_0 = 58 \times 10^6$ S/m). σ_r is given as follows:

$$\sigma_r = \frac{Q_u^2 \left\{ j'^2_{01} + 2\pi^2 \left(\frac{d}{2h} \right)^3 \right\}^2}{30\pi\sigma_0 d \left\{ j'^2_{01} + \left(\frac{\pi d}{2h} \right)^2 \right\}^{\frac{5}{2}}} \tag{24}$$

This value σ_r is conveniently used instead of R_S since this value is independent of frequency and indicates the degradation level of conductivity caused by the surface roughness or oxidation of copper cylinder.

5.2.2 Relative permittivity and loss factor of dielectric specimen: ε', tan δ

The axially symmetric TE_{011} mode resonance is used for the measurement of ε' and tan δ of dielectric specimen. The dielectric specimen with diameter d_S and thickness t is set as shown in Figure 11a. The resonance frequency f_0 and the unloaded quality factor Q_u of the TE_{011} resonance mode are measured.

The approximate relative permittivity ε_a is calculated first: The ε_a is the value neglecting the fringe effect at the cylinder-dielectric interface, where a radial cut-off waveguide is formed and the electro-magnetic wave decays rapidly along the radial direction.

From the measured values f_0, d and t, the value Y is calculated:

$$Y = \frac{t}{2}\sqrt{k_r^2 - k_0^2} \tag{25}$$

where

$$k_0 = \frac{2\pi f_0}{c} \tag{26}$$

$$k_r = \frac{2 j'_{01}}{d}. \tag{27}$$

The value X is calculated from Y as follows:

$$X \tan\left(X + \frac{\pi}{2} \right) = Y \quad \left(\frac{\pi}{2} < X < \pi \right) \tag{28}$$

The value ε_a is given from X and Y.

$$\varepsilon_a = \left(\frac{c}{\pi f_0 t}\right)^2 (X^2 + Y^2) + 1 \tag{29}$$

By taking account of the fringe effect, the corrected relative permittivity ε' is given as follows:

$$\varepsilon' = \varepsilon_a \left(1 - \frac{\Delta\varepsilon}{\varepsilon_a}\right) \tag{30}$$

where the correction term $\Delta\varepsilon / \varepsilon_a$ is given from ε_a and t/d in Figure 13, which was calculated by the mode matching method.

The loss factor $\tan\delta$ taking account of the fringe effect is calculated from the following equation:

$$\tan\delta = \frac{A}{Q_u}\left(1 + \frac{\Delta A}{A}\right) - R_S B\left(1 + \frac{\Delta B}{B}\right) \tag{31}$$

where R_S is the surface resistance of the conducting cylinder, and values A and B are calculated from the following equations:

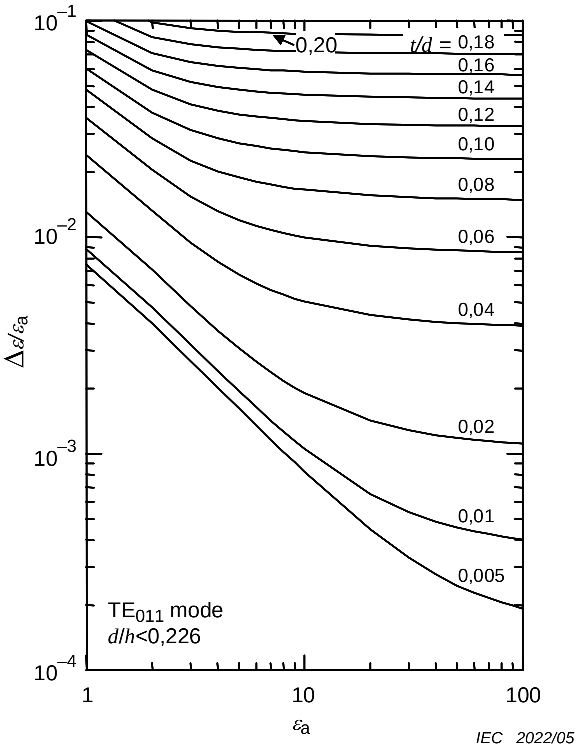

Figure 13 – Correction term $\Delta\varepsilon / \varepsilon_a$

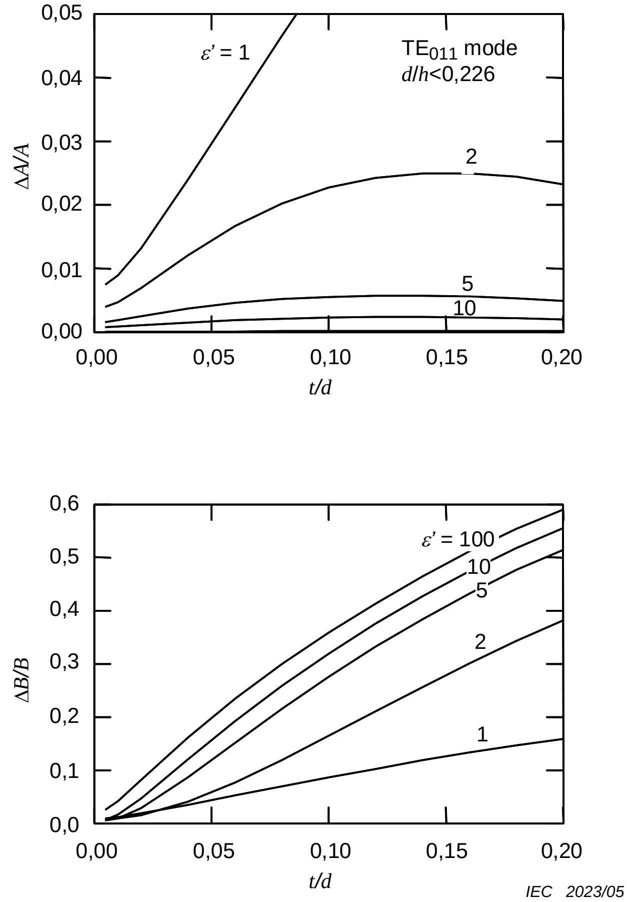

Figure 14 – Correction terms $\Delta A/A$ and $\Delta B/B$

$$W = \frac{\cos^2(X - \pi/2)}{Y + \sin^2(X - \pi/2)} \quad (32)$$

$$A = 1 + \frac{W}{\varepsilon'} \quad (33)$$

$$B = \left(\frac{cj'_{01}}{\pi f_0 d}\right)^3 \frac{1+W}{60\pi j'_{01}\varepsilon'} \quad (34)$$

The correction terms $\Delta A/A$ and $\Delta B/B$ in equation (31) are given from ε' and t/d in Figure 14, which was calculated by the mode matching method.

5.2.3 Temperature coefficient of relative permittivity: $TC\varepsilon$

Figure 15 shows an apparatus for the measurement of temperature coefficient of relative permittivity. The conducting cylinder with dielectric specimen is set in the case. Upper head of the conducting cylinder is fixed by a spring that allows smooth thermal expansion of the conducting cylinder.

The apparatus is set in the oven, and ε' of dielectric specimen is measured at each temperature. Temperature coefficient of ε' is calculated from equation (3). If necessary, the temperature dependence of tan δ is measured by calculating tan δ at each temperature.

5.3 Measurement procedure

Measurement procedure is as follows:

a) Preparation of measurement apparatus

Set up the measurement equipment and apparatus as shown in Figures 1 and 2. All measurement equipments, apparatus and dielectric specimens shall be kept in a clean, dry state as high humidity degrades unloaded Q. The relative humidity is preferable to be less than 60 %.

b) Measurement of reference level

The reference level, level of full transmission power, is measured first. Connect the reference line between the S parameter modules and measure the full transmission power level over the entire measurement frequency range.

c) Measurements of dimensions and relative conductivity of conducting cylinder: d, h, σ_r

Set the empty cavity and adjust the insertion attenuation IA_0 to be around 30 dB by changing the distance between two semi-rigid cables.

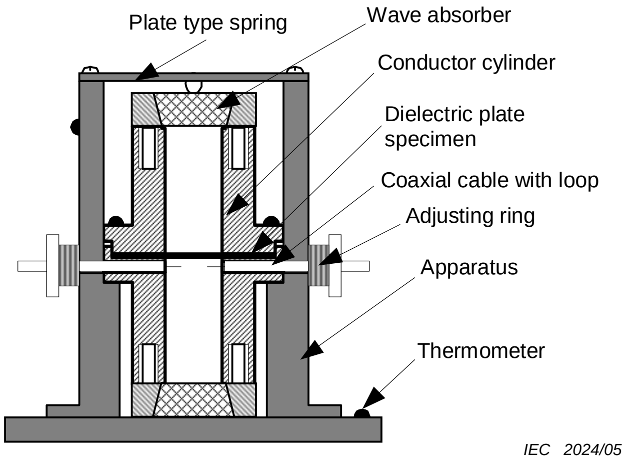

Figure 15 – Measurement apparatus for temperature coefficient of relative permittivity

Measure f_{01} and Q_{u1} of the TE_{011} resonance mode and measure f_{03} of the TE_{013} resonance modes. Rough values of f_{01} and f_{03} are estimated from the mode chart shown in Figure 16. Calculate unloaded Q by the following equation:

$$Q_u = \frac{f_0 / \Delta f}{1 - A_t} \quad (35)$$

$$A_t = 10^{-IA_0 / 20} \quad (36)$$

Calculate the dimensions d, h, and σ_r of conducting cylinder from equations (20) to (22).

As the conductivity of the conducting cylinder degrades day by day due to wear or oxidation of the metal surface, this measurement of d, h, and σ_r shall be repeated every time prior to the measurement of the test specimens. It is preferable to polish the surface of the conducting cylinder when the conductivity degrades about 5 %.

d) Measurement of complex permittivity of test specimen: ε', tan δ

Place the test specimen between two cylinders and clamp them by clips. Measure the resonance frequency and unloaded Q of the TE_{011} resonance mode. Calculate the ε' and tan δ from equations (30) and (31).

e) Measurement of temperature coefficient of relative permittivity: $TC\varepsilon$

Set the measurement apparatus with dielectric specimen in oven (Figure 15). By changing the temperature in the oven, measure the resonance frequency of TE_{011} resonance mode. Calculate the ε' at each temperature and calculate $TC\varepsilon$ from equation (3).

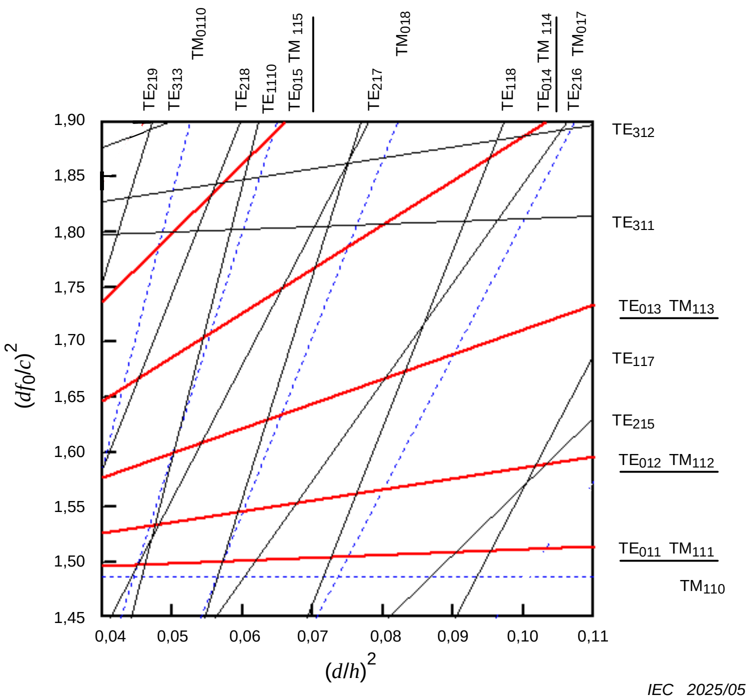

Figure 16 – Mode chart of TE_{011} and TE_{013} modes for an empty cavity

Annex A
(informative)

Errors on ε_r caused by air gap between dielectric specimen and upper conducting plate

Figure A.1 shows the error of ε' caused by the air gap between dielectric specimen and upper conducting plates. The error $\Delta\varepsilon$ was calculated for the TE_{021} mode dielectric specimens with resonance frequency of 77 GHz. Three dielectric specimens have the following ε' and diameter: ε' = 5 and d = 3,59 mm, ε' = 10 and d = 2,40 mm, and ε' = 20 and d = 1,59 mm. The height h_c is fixed to be 1,80 mm in the calculation.

As shown in the figure, the error $\Delta\varepsilon / \varepsilon'$ is less than 0,01 % in the case of Δh < 50 µm. As a result, the height h_c can be used for an effective height h of the dielectric specimen in the calculation of ε' and tan δ.

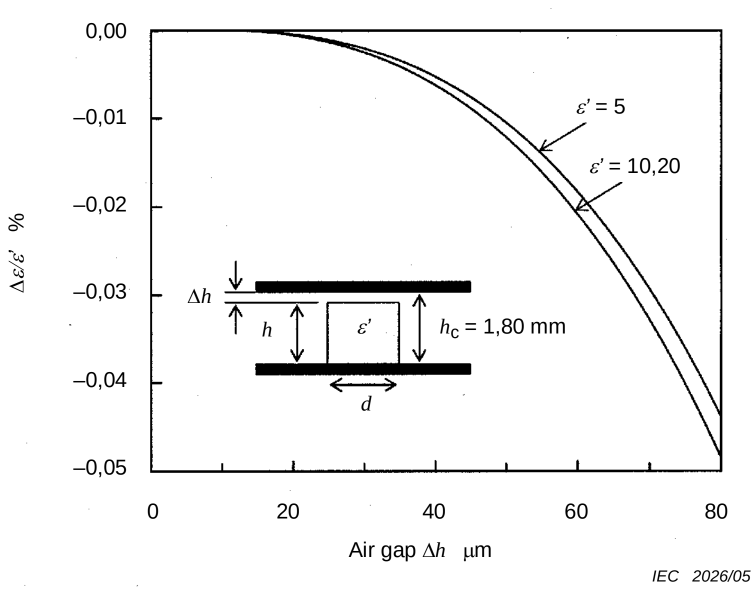

Figure A.1 – Error on ε' caused by air gap between dielectric specimen and upper conducting plates

Annex B
(informative)

Derivation of equation (15) for σ_r

By using equation (10), unloaded Q's of the TE_{021} and $TE_{02\delta}$ mode reference resonators are given by the following equations:

$$\frac{1}{Q_{u1}} = P_{e1} \tan\delta_1 + \frac{R_{S1}}{G_1} \tag{A.1}$$

$$\frac{1}{Q_{u\delta}} = P_{e\delta} \tan\delta_\delta + \frac{R_{S\delta}}{G_\delta} \tag{A.2}$$

where P_{e1} and $P_{e\delta}$ are the partial electric energy filling factors, and G_1 and G_δ are the geometric factors for each reference resonators. The values P and G are given by following equations:

$$P_e = \frac{\varepsilon' \iiint_{Vd} |E|^2 dv}{\varepsilon' \iiint_{Vd} |E|^2 dv + \iiint_{Vair} |E|^2 dv} \tag{A.3}$$

$$G_1 = 2\pi f_0 \frac{\mu_0 \iiint_{Vt} |H|^2 dv}{\iint_S |H_t|^2 ds} \tag{A.4}$$

where $\iiint_{Vd}|E|^2 dv$ and $\iiint_{Vair}|E|^2 dv$ are the integration of the electric field inside and outside of the dielectric rod;

$\iiint_{Vt}|H|^2 dv$ is the integration of the magnetic field in the resonance space, and

$\iint_S|H_t|^2 ds$ the tangential magnetic field at the surface of the conducting plates.

The factors P_{e1} and G_1 in equation (A.1) are given by as follows by comparing equations (A.1) and (10):

$$P_{e1} = \frac{1}{A} \tag{A.5}$$

$$G_1 = \frac{A}{B} \tag{A.6}$$

The factors $P_{e\delta}$ and G_δ in equation (A.2) are calculated by the numerical analyses such as the Finite Element Method or the Mode Matching Method. The values are given in Table 4 for the reference sapphire resonators used in this document.

Although the reference resonators are designed to have the same resonance frequency, actual resonance frequencies f_{01} and $f_{0\delta}$ for the TE_{021} and $TE_{02\delta}$ mode resonators are slightly different. In this case, $\tan\delta_1$ and $\tan\delta_\delta$ for the TE_{021} and $TE_{02\delta}$ mode resonators satisfy the following relations.

$$\frac{f_{01}}{\tan\delta_1} = \frac{f_{0\delta}}{\tan\delta_\delta} \tag{A.7}$$

The surface resistance R_S at the frequencies f_{01} and $f_{0\delta}$ are given from equation (11):

$$R_{S1} = \sqrt{\frac{\pi f_{01}\mu}{\sigma_0\sigma_r}} \text{ and } R_{S\delta} = \sqrt{\frac{\pi f_{0\delta}\mu}{\sigma_0\sigma_r}} \tag{A.8}$$

Using the equations (A.1), (A.2), (A.7) and (A.8), σ_r of the conducting plates is given as follows:

$$\sigma_r = \sigma / \sigma_0 = \frac{\pi\mu f_{01} f_{0\delta}}{\sigma_0}\left[\frac{Q_{u1}Q_{u\delta}}{G_1 G_\delta}\cdot\frac{G_1 P_{e1}\sqrt{f_{01}} - G_\delta P_{e\delta}\sqrt{f_{0\delta}}}{Q_{u1}P_{e1}f_{01} - Q_{u\delta}P_{e\delta}f_{0\delta}}\right]^2 \tag{A.9}$$

Equation (15) is derived from equation (A.9) under the condition of $f_{01} = f_{0\delta}$.

In the same way, equation (16) is given from equations (A.1) and (A.2) under the condition of $f_{01} = f_{0\delta}$, $\tan\delta_1 = \tan\delta_\delta$, and $R_{S1} = R_{S\delta}$.

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Q1 Please report on **ONE STANDARD** and **ONE STANDARD ONLY**. Enter the exact number of the standard: *(e.g. 60601-1-1)*

....

Q2 Please tell us in what capacity(ies) you bought the standard *(tick all that apply).* I am the/a:

- purchasing agent ❑
- librarian ❑
- researcher ❑
- design engineer ❑
- safety engineer ❑
- testing engineer ❑
- marketing specialist ❑
- other...

Q3 I work for/in/as a: *(tick all that apply)*

- manufacturing ❑
- consultant ❑
- government ❑
- test/certification facility ❑
- public utility ❑
- education ❑
- military ❑
- other...

Q4 This standard will be used for: *(tick all that apply)*

- general reference ❑
- product research ❑
- product design/development ❑
- specifications ❑
- tenders ❑
- quality assessment ❑
- certification ❑
- technical documentation ❑
- thesis ❑
- manufacturing ❑
- other...

Q5 This standard meets my needs: *(tick one)*

- not at all ❑
- nearly ❑
- fairly well ❑
- exactly ❑

Q6 If you ticked NOT AT ALL in Question 5 the reason is: *(tick all that apply)*

- standard is out of date ❑
- standard is incomplete ❑
- standard is too academic ❑
- standard is too superficial ❑
- title is misleading ❑
- I made the wrong choice ❑
- other ....

Q7 Please assess the standard in the following categories, using the numbers:
(1) unacceptable,
(2) below average,
(3) average,
(4) above average,
(5) exceptional,
(6) not applicable

- timeliness ....
- quality of writing....................................
- technical contents.................................
- logic of arrangement of contents ....
- tables, charts, graphs, figures...............
- other ....

Q8 I read/use the: *(tick one)*

- French text only ❑
- English text only ❑
- both English and French texts ❑

Q9 Please share any comment on any aspect of the IEC that you would like us to know:

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