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INTERNATIONAL STANDARD

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colour inside

Measurement of the complex permittivity for low-loss dielectric substrates balanced-type circular disk resonator method

Méthode au résonateur à disque circulaire de type symétrique pour mesurer la permittivité complexe des substrats diélectriques à faible perte

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MEASUREMENT OF THE COMPLEX PERMITTIVITY FOR LOW-LOSS DIELECTRIC SUBSTRATES BALANCED-TYPE CIRCULAR DISK RESONATOR METHOD

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

FDIS	Report on voting
46F/523/FDIS	46F/531/RVD

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

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MEASUREMENT OF THE COMPLEX PERMITTIVITY FOR LOW-LOSS DIELECTRIC SUBSTRATES BALANCED-TYPE CIRCULAR DISK RESONATOR METHOD

1 Scope

This document relates to a measurement method for complex permittivity of a dielectric substrates at microwave and millimeter-wave frequencies. This method has been developed to evaluate the dielectric properties of low-loss materials used in microwave and millimeter-wave circuits and devices. It uses higher-order modes of a balanced-type circular disk resonator and provides broadband measurements of dielectric substrates by using one resonator, where the effect of excitation holes is taken into account accurately on the basis of the mode-matching analysis.

In comparison with the conventional method described in IEC 62810 and IEC 61338-1-3, this method has the following characteristics:

- the values of the relative permittivity ε_r' and loss tangent tanδ normal to dielectric plate samples can be measured accurately and non-destructively;
- this method presents broadband measurements by using higher-order modes by one resonator;
- this method is applicable for the measurements on the following condition:
  - – frequency: 10 GHz ≤ f ≤ 110 GHz;
  - – relative permittivity: 1 ≤ ε_r' ≤ 10;
  - – loss tangent: 10^{-4} ≤ tanδ ≤ 10^{-2}.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 61338-1-3:1999, *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 62810:2015, *Cylindrical cavity method to measure the complex permittivity of low-loss dielectric rods*

3 Terms and definitions

No terms and definitions are listed in this document.

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

- IEC Electropedia: available at http://www.electropedia.org/
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4 Measurement parameters

The measurement parameters are defined as follows:

$$\varepsilon_r = \varepsilon_r' - j\varepsilon_r'' \tag{1}$$

$$\tan\delta = \varepsilon_r''/\varepsilon_r' \tag{2}$$

where ε_r' and ε_r'' are the real and imaginary parts of the complex relative permittivity ε_r.

5 Theory and calculation equations

A resonator structure used in this method is shown in Figure 1. A thin circular conductor disk with radius R is sandwiched between a pair of dielectric plate samples to be measured having the same thickness t and dielectric properties ε_r' and $\tan\delta$. Dielectric samples are sandwiched by two parallel conductor plates. The thickness of the conductor disk is negligibly thin in the analysis.

The resonator is excited and detected by coaxial lines through excitation holes having radius a and length M. Because only the TM_{0m0} modes have the electric field in the center of the resonator, only those modes are selectively excited in the resonator, where the electric field components in the resonator are normal to the plate samples for those modes.

ε_r' and $\tan\delta$ normal to the dielectric plates are determined from the measured values of the resonant frequencies f_0 and the unloaded Q-factor Q_u for the TM_{0m0} mode by solving the following resonant condition derived from the mode-matching analysis, where the exciting holes are accurately taken into account:

$$\det H(\varepsilon_r', f_0, t, R, a, M) = 0 \tag{3}$$

$$\tan\delta = (1/Q_u - 1/Q_c)(1 + W_1/W_2) \tag{4}$$

where

H	is $N \times N$ matrix derived from the boundary conditions;
N	is the number of terms of the series expansions for the mode-matching analysis;
Q_c	is the Q-factor due to the conductor loss;
W_1 and W_2	are the electric energies stored in the dielectric region and the excitation hole region, respectively.

W_1 and W_2 are calculated from the mode-matching analysis, and Q_c can be approximately by

$$Q_c = t/\delta_S = t(\pi f_0 \mu_0 \sigma)^{0,5} \tag{5}$$

where

δ_S	is the skin depth of the conductor;
σ	is the conductivity;
μ_0	is the permeability of free space.

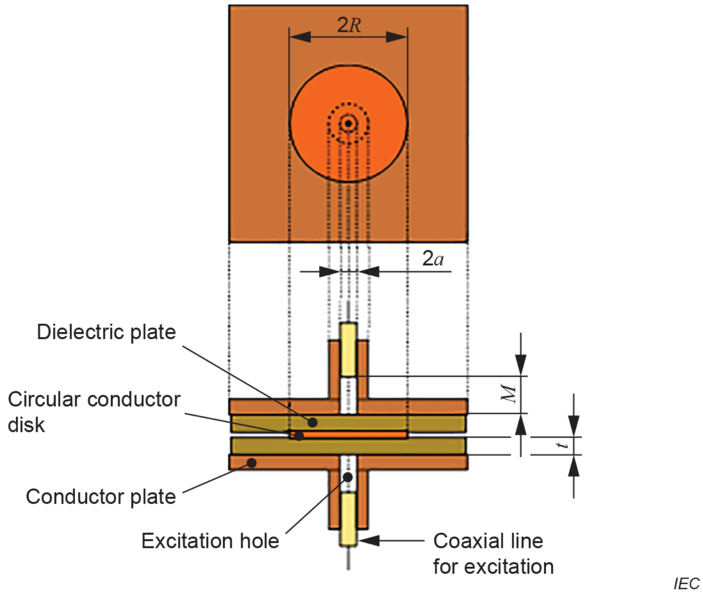


Figure 1 – Structure of a circular disk resonator

The maximum measurable frequency is limited by the following three cutoff frequencies:

a) cutoff frequency of coaxial lines used to excite the resonator f_c^{Coax};

b) cutoff frequency of excitation holes f_c^{Hole};

c) cutoff frequency for radial radiation through dielectric samples f_c^{Rad}.

f_c^{Hole} is calculated as a cutoff frequency for TM_{01} mode of a circular waveguide with radius a and is given by

$$f_c^{\mathrm{Hole}} = \chi_{01}/2\pi a \tag{6}$$

where

$\chi_{01} \approx 2{,}404\ 8$ is the first root of $J_0(\mathrm{x}) = 0$;

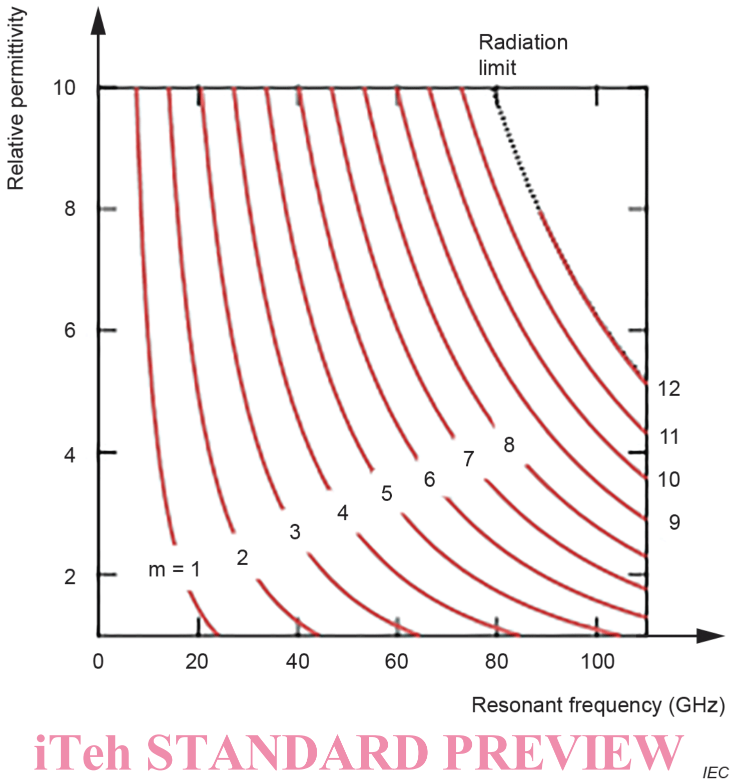
$J_0(\mathrm{x})$ is the Bessel function of order 0 of first kind;

c is the light velocity.

f_c^{Rad} is determined by the sample thickness t and relative permittivity ε_r' and is given by

$$f_c^{\mathrm{Rad}} = c/4t(\varepsilon_r')^{0,5} \tag{7}$$

Figure 2 shows the relations between f_0 and ε_r' for TM_{0m0} modes for R = 7,5 mm, a = 0,6 mm, M = 5 mm, and t = 0,3 mm. Multiple resonances are appeared from 5 GHz to 110 GHz for $1 \le \varepsilon_r' \le 10$ (5 to 11 modes). Radiation limit (f_c^{Rad}) is also shown in the same figure.



Key

m is mode number of resonances in measurement

R	7,5 mm	M	5 mm
a	0,6 mm	t	0,3 mm

Figure 2 – Relations between resonant frequency and relative permittivity

The conductivity σ is measured by the two dielectric resonator method [5][1].

Measurement uncertainties of ε_r' and tanδ are evaluated by considering the uncertainty propagations of the resonant frequency, Q-factor, dimensions of resonator and samples, and conductivity of the resonator, and by estimating the effect of the error of the mode-matching analysis [6].

6 Measurement system

Figure 3 shows a schematic diagram of a vector network analyzer measurement system for a transmission-type resonator. A scalar network analyzer can also be used for measuring equipment, because resonant frequencies and Q-factors can be derived from the frequency dependence of the amplitude of the transmission, S_{21}. However, a vector network analyzer has an advantage in precision of the measurement. Furthermore, resonant frequencies and Q-factors are more accurate and less susceptible when they are derived from complex values of measured S_{21} data by using the circle fitting on the complex plane of S_{21} [7].

[1] Figures in square brackets refer to the bibliography.

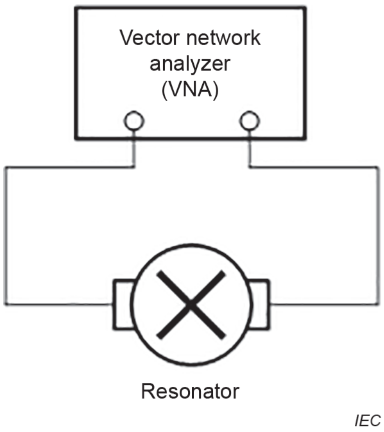


Figure 3 – Schematic diagram of a vector network analyzer measurement system

The structure of the resonator used in the complex permittivity measurements is shown in Figure 1. A pair of dielectric plate samples to be measured, thin circular conductor disk, and two parallel conductor plates constitutes a balanced-type circular disk resonator. The resonator is excited by coaxial lines through excitation holes and under-coupled equally to the input and output ports.

The resonant frequency f_0 and the loaded Q-factor Q_l are derived from the frequency dependence of S_{21} that is measured by using a vector network analyzer [7]. The unloaded Q-factor Q_u is given by

$$Q_u = Q_l / (1-10^{LA_0(\mathrm{dB})/20}) \quad (8)$$

Where LA_0(dB) is the insertion attenuation at f_0.

The coupling factor of electromagnetic wave signals shall be the same at input and output ports.

7 Measurement procedure

7.1 Preparation of measurement apparatus

Set up the measurement equipment and apparatus as shown in Figure 3. The cavity resonator and dielectric samples shall be kept in a clean and dry state, as high humidity degrades unloaded Q-factors.

7.2 Adjustment of measurement conditions

Set up the measurement conditions of a vector network analyzer. The interval between discrete frequency points shall preferably be less than one tenth of the half width of the resonant waveform. Intermediate frequency band width (IFBW), like as digital band pass filter condition in vector network analyzer, is determined such that the noise floor is at least 20 dB lower than the peak values.

7.3 Calibration of a vector network analyzer

A vector network analyzer shall be calibrated by using calibration kits.

7.4 Measurement of complex permittivity of test sample

Constitute a balanced-type circular disk resonator by the pair of test samples. Figure 4 shows the frequency dependence of $|S_{21}|$. Resonant frequencies of TM_{010} to TM_{050} modes are indicated by the downward arrows. Measure the resonant frequency and unloaded Q-factor of each mode and calculate the complex permittivity at each resonant frequency of test samples by using Equations (3) and (4).

The alignment between the conductor disk and excitation holes is critical to measurement results, but it is possible to find a misalignment by detecting resonances of unwanted modes between adjacent TM_{0m0} modes. In the frequency response of $|S_{21}|$, resonant peaks for unwanted modes shall be at least 15 dB lower than those for adjacent TM_{0m0} modes.

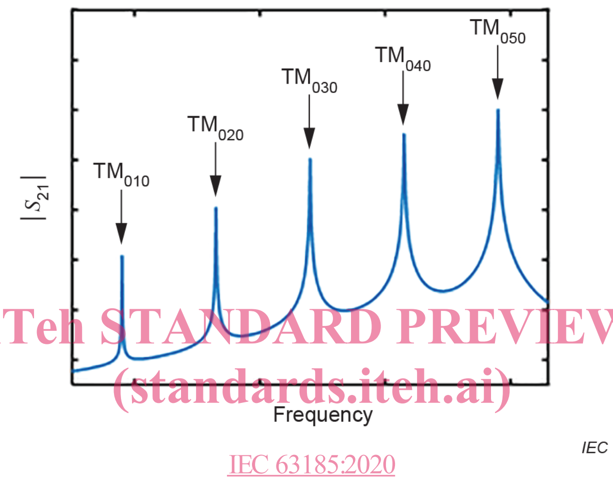


Figure 4 – Frequency response of $|S_{21}|$ of balanced-type circular disk resonator

7.5 Periodic checkup of metal in resonator

Since the conductivity of the conductor plates and circular disk degrades due to oxidation of the metals and scratches on the surfaces, the quality of the metals of the resonator shall be checked periodically. It can be checked by measuring the conductivity by using the two dielectric resonator method [5]. Instead, it can be checked by measuring the same low-loss sample periodically. By checking the reproducibility of the measurement results of loss tangent of the specified verification sample, it is possible to find the surface characteristic change in the metals of the resonator.