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inside

Cavity resonator method to measure the complex permittivity of low-loss dielectric plates

Méthode de la cavité résonante pour mesurer la permittivité complexe des plaques diélectriques à faibles pertes

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INTERNATIONAL ELECTROTECHNICAL COMMISION

CAVITY RESONATOR METHOD TO MEASURE THE COMPLEX PERMITTIVITY OF LOW-LOSS DIELECTRIC PLATES

FOREWORD

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International Standard IEC 62562 has been prepared by subcommittee 46F: R.F. and microwave passive components, of IEC technical committee 46: Cables, wires, waveguides, R.F. connectors, R.F. and microwave passive components and accessories.

This first edition cancels and replaces the PAS published in 2008.

This bilingual version, published in 2010-02, corresponds to the English version.

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

CDV	Report on voting
46F/118/CDV	46F/143/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.

The French version of this standard has not been voted upon.

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

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

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CAVITY RESONATOR METHOD TO MEASURE THE COMPLEX PERMITTIVITY OF LOW-LOSS DIELECTRIC PLATES

1 Scope

The object of this International Standard is to describe a measurement method of dielectric properties in the planar direction of dielectric plate at microwave frequency. This method is called a cavity resonator method. It has been created in order to develop new materials and to design microwave active and passive devices for which standardization of measurement methods of material properties is more and more important.

This method has the following characteristics:

- the relative permittivity ε' and loss tangent $\tan\delta$ values of a dielectric plate sample can be measured accurately and non-destructively;
- temperature dependence of complex permittivity can be measured;
- the measurement accuracy is within 0,3 % for ε' and within 5×10^{-6} for $\tan\delta$;
- fringing effect is corrected using correction charts calculated on the basis of rigorous analysis.

This method is applicable for the measurements on the following condition:

– frequency : $2\ \text{GHz} < f < 40\ \text{GHz}$;

– relative permittivity: $2 < \varepsilon' < 100$;

– loss tangent : $10^{-6} < \tan\delta < 10^{-2}$.

2 Measurement parameters

The measurement parameters are defined as follows:

$$\varepsilon_{\mathrm{r}} = \varepsilon' - j\varepsilon'' = D/(\varepsilon_0 E) \tag{1}$$

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

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

where

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

3 Theory and calculation equations

3.1 Relative permittivity and loss tangent

A resonator structure used in the nondestructive measurement of the complex permittivity is shown in Figure 1a.

A cavity having diameter D and length $H = 2M$ is cut into two halves in the middle of its length.

A dielectric plate sample having ε', $\tan\delta$ and thickness t is placed between these two halves.

The TE_{011} mode, having only the electric field component tangential to the plane of the sample, is used for the measurement, since air gaps at the plate-cavity interfaces do not affect the electromagnetic field. Taking account of the fringing field in the plate region outside diameter of the cavity on the basis of the rigorous mode matching analysis, we determine ε' and $\tan\delta$ from the measured values of the resonant frequency f_0 and the unloaded Q-factor Q_u. This numerical calculation, however, is rather tedious.

Therefore,

a) approximated values ε'_a and $\tan\delta_\mathrm{a}$ from the f_0 and Q_u values by using simple formula for a resonator structure shown in Figure 1b, where a fringing effect for Figure 1a is neglected, will be determined;

b) then, accurate values ε' and $\tan\delta$ from ε'_a and $\tan\delta_\mathrm{a}$ using charts calculated from the rigorous analysis will be obtained.

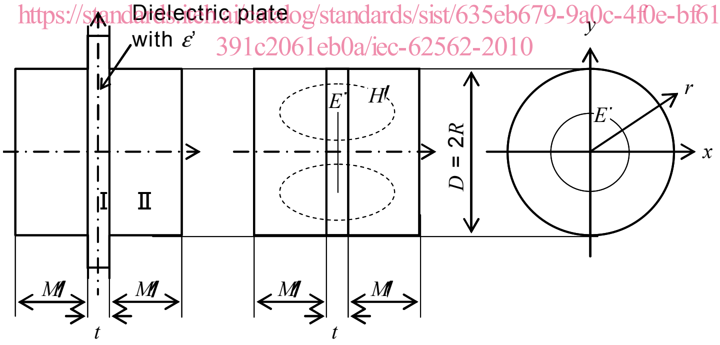

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Figure 1a – Resonator used in measurement	**Figure 1b – Resonator to calculate ε'_a and tan δ_a**

Figure 1 – Resonator structures of two types

The value of ε'_a is given by

$$\varepsilon'_\mathrm{a} = \left(\frac{c}{\pi t f_0}\right)^2 \left\{X^2 - Y^2\left(\frac{t}{2M}\right)^2\right\} + 1 \tag{4}$$

where c is the velocity of light in a vacuum ($c = 2{,}997\,9 \times 10^8 \,\mathrm{m/s}$) and the first root X is calculated from a given value Y, using the following simultaneous equations:

$$X \tan X = \frac{t}{2M} Y \cot Y \tag{5}$$

$$Y = M\sqrt{k_0{}^2 - k_r{}^2} = jY' \tag{6}$$

with $k_0 = 2\pi f_0/c$, $k_r = j'_{01}/R$, and $j'_{01} = 3{,}83173$ for the TE_{011} mode. When $k_0 - k_r < 0$, Y is replaced by jY'.

The value of $\tan\delta_a$ is given by

$$\tan\delta_a = \frac{A}{Q_u} - R_s B \tag{7}$$

where R_s is the surface resistance of the conductor of cavity, given by

$$R_s = \sqrt{\frac{\pi f_0 \mu}{\sigma}} \text{ (1/S)}, \quad \sigma = \sigma_0 \sigma_r \text{ (S/m)} \tag{8}$$

Here, μ and σ are the permeability and conductivity of the conductor. Furthermore, σ_r is the relative conductivity and $\sigma_0 = 5{,}8 \times 10^7$ S/m is the conductivity of standard copper. Constants A and B are given by

$$A = 1 + \frac{W_2^e}{W_1^e} \tag{9}$$

$$B = \frac{P_{cy1} + P_{cy2} + P_{end}}{\omega R_s W_1^e} \tag{10}$$

In the above, $W_1{}^e$ and $W_2{}^e$ are electric field energies stored in the dielectric plate of region 1 and air of region 2 shown in Figure 1a. Furthermore, P_{cy1}, P_{cy2} and P_{end} are the conductor loss at the cylindrical wall in the region 1, 2 and at the end wall. These parameters are given by

$$W_1^e = \frac{\pi}{8}\varepsilon_0 \varepsilon'_a \mu_0^2 \omega^2 j'^2_{01} J_0^2(j'_{01}) t \left(1 + \frac{\sin 2X}{2X}\right) \tag{11}$$

$$W_2^e = \frac{\pi}{4}\varepsilon_0 \mu_0^2 \omega^2 j'^2_{01} J_0^2(j'_{01}) M \left(1 - \frac{\sin 2Y}{2Y}\right) \frac{\cos^2 X}{\sin^2 Y} \tag{12}$$

$$P_{cy1} = \frac{\pi}{4} R_s J_0^2(j'_{01}) t R k_r{}^4 \left(1 + \frac{\sin 2X}{2X}\right) \tag{13}$$

$$P_{cy2} = \frac{\pi}{2} R_s J_0^2(j'_{01}) M R k_r{}^4 \left(1 - \frac{\sin 2Y}{2Y}\right) \frac{\cos^2 X}{\sin^2 Y} \tag{14}$$

$$P_{end} = \frac{\pi}{2} R_s j'^2_{01} J_0^2(j'_{01}) \left(\frac{Y}{M}\right)^2 \frac{\cos^2 X}{\sin^2 Y} \tag{15}$$

Then, accurate values of ε' and $\tan\delta$ are given by

$$\varepsilon' = \varepsilon'_a \left(1 - \frac{\Delta\varepsilon'}{\varepsilon'_a}\right) \tag{16}$$

$$\tan\delta = \frac{A}{Q_\mathrm{u}}\left(1+\frac{\Delta A}{A}\right) - R_\mathrm{s}B\left(1+\frac{\Delta B}{B}\right) \tag{17}$$

where correction terms due to the fringing field $\Delta\varepsilon'/\varepsilon'_\mathrm{a}$, $\Delta A/A$ and $\Delta B/B$ are calculated numerically on the basis of rigorous mode matching analysis using the Ritz-Galerkin method, as shown in Figures 2 and 3. It is found from the analysis for a circular dielectric plate with diameter d that f_0 converges to a constant value for $d/D > 1{,}2$. The correction terms shown in Figures 2 and 3 were calculated for $d/D > 1{,}5$. Therefore, the correction terms are applicable to dielectric plates with any shape if $d/D > 1{,}2$.

Measurement uncertainties of ε' and $\tan\delta$, $\Delta\varepsilon'$ and $\Delta\tan\delta$ are estimated as the mean square errors and given respectively by

$$(\Delta\varepsilon')^2 = (\Delta\varepsilon'_f)^2 + (\Delta\varepsilon'_t)^2 + (\Delta\varepsilon'_D)^2 + (\Delta\varepsilon'_H)^2 \tag{18}$$

$$(\Delta\tan\delta)^2 = (\Delta\tan\delta_Q)^2 + (\Delta\tan\delta_\sigma)^2 \tag{19}$$

where $\Delta\varepsilon'_f$, $\Delta\varepsilon'_t$, $\Delta\varepsilon'_D$ and $\Delta\varepsilon'_H$ are the uncertainties of ε' due to standard deviations of f_0, t, D, and H, respectively. Also, $\Delta\tan\delta$ is mainly attributed to measurement errors of Q_u and σ_r, and $\Delta\tan\delta_Q$ and $\Delta\tan\delta_\sigma$ are uncertainties of $\tan\delta$ due to standard deviations of them, respectively.

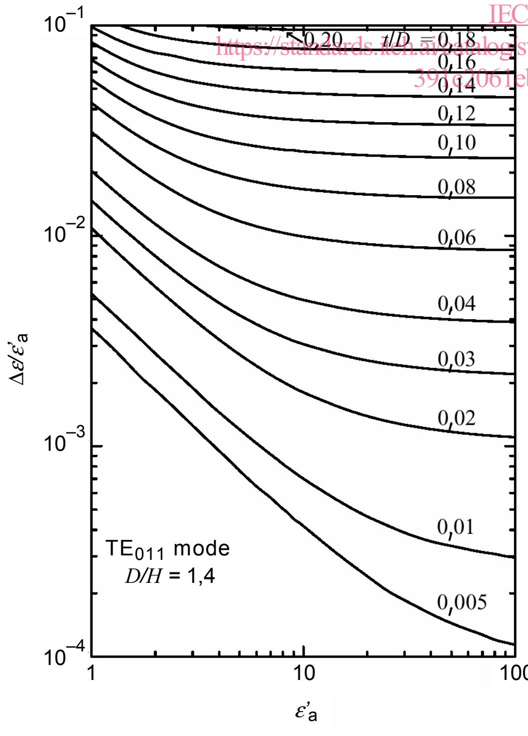

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Figure 2 – Correction term $\Delta\varepsilon'/\varepsilon'_\mathrm{a}$

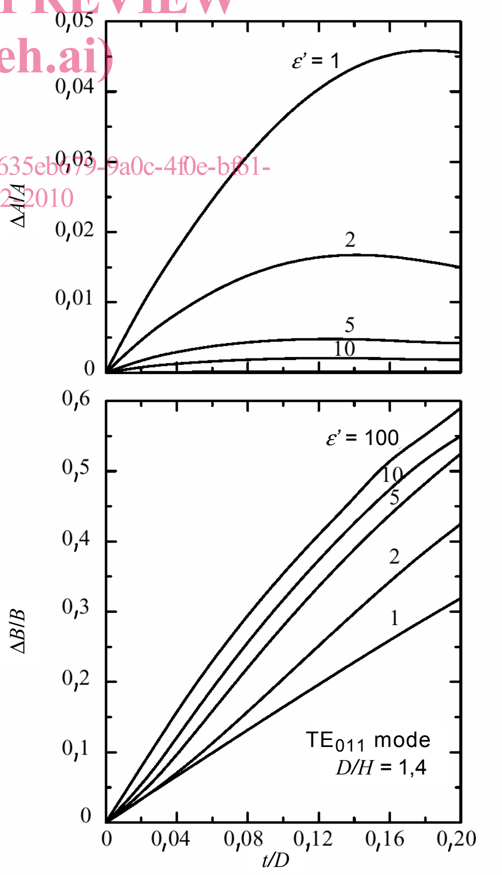

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Figure 3 – Correction terms $\Delta A/A$ and $\Delta B/B$

3.2 Temperature dependence of ε' and $\tan\delta$

Temperature dependence of ε' and $\tan\delta$ also can be measured using this method. Temperature coefficient of relative permittivity $TC\varepsilon$ is calculated by equation (3).

When the temperature dependences of ε' is linear, particularly, $\varepsilon'(T)$ is given by

$$\varepsilon'(T)=\varepsilon'(T_0)[1+TC\varepsilon(T-T_0)] \tag{20}$$

where T and T_0 are the temperatures in measurement and the reference temperature, respectively. In this case, $TC\varepsilon$ can be determined by the least squares method for many measurement points against T.

The thermal linear expansion coefficient of the dielectric plate α and that of the conductor cavity α_c should be considered in the $TC\varepsilon$ measurement. Furthermore, the temperature coefficient of resistivity $TC\rho$ should be considered in the temperature dependence measurement of $\tan\delta$. Using these parameters, temperature dependent values of $t(T)$, $D(T)$, $H(T)$, and $\rho(T)$ are given by

$$t(T)=t(T_0)[1+\alpha(T-T_0)] \tag{21}$$

$$D(T)=D(T_0)[1+\alpha_c(T-T_0)] \tag{22}$$

$$H(T)=H(T_0)[1+\alpha_c(T-T_0)] \tag{23}$$

$$\rho(T)=\frac{1}{\sigma(T)}=\rho(T_0)[1+TC\rho(T-T_0)] \tag{24}$$

3.3 Cavity parameters

Cavity parameters such as D, $H=2M$, α_c, σ_r and $TC\rho$ are determined from the measurements for the TE_{011} and TE_{012} resonance modes of an empty cavity without a sample, in advance of complex permittivity measurements. At first, D and H are determined from two measured resonant frequencies, f_1 for the TE_{011} mode and f_2 for the TE_{012} mode, by using

$$D=\frac{cj'_{01}}{\pi}\sqrt{\frac{3}{4f_1^2-f_2^2}} \tag{25}$$

$$H=\frac{c}{2}\sqrt{\frac{3}{f_2^2-f_1^2}} \tag{26}$$

which can be derived easily from the resonance condition of the cavity.

Secondly, α_c is determined from the measurement of temperature dependence of f_1, by using

$$\alpha_c = -\frac{1}{f_1}\frac{\Delta f_1}{\Delta T} \tag{27}$$

Thirdly, σ_r is determined from the measured values D, H, f_1, Q_{uc}, which is the unloaded Q-factor for the TE$_{011}$ mode, by the following equation:

$$\sigma_r = \frac{4\pi f_1 Q_{uc}^2 \left\{ j'^2_{01} + 2\pi^2 \left(\frac{D}{2H}\right)^3 \right\}^2}{\sigma_0 \mu_0 c^2 \left\{ j'^2_{01} + \left(\frac{\pi D}{2H}\right)^2 \right\}^3} \tag{28}$$

Finally, $TC\rho$ is determined from the measurement of temperature dependence of $\rho_r = \sigma_0/\sigma$ by using

$$TC\rho = \frac{1}{\rho_r}\frac{\Delta \rho_r}{\Delta T} \tag{29}$$

4 Measurement equipment and apparatus

4.1 Measurement equipment

Figure 4 shows a schematic diagram of two equipment systems 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. Therefore, a scalar network analyzer can be used for the measurement shown in Figure 4a. However, a vector network analyzer, as shown in Figure 4b, has an advantage in precision of the measurement data.

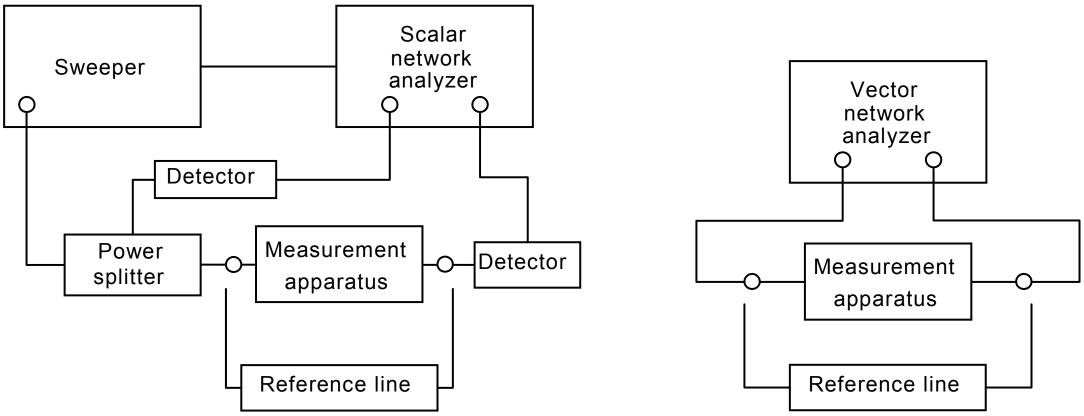

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Figure 4a – Scalar network analyzer system

Figure 4b – Vector network analyzer system

Figure 4 – Schematic diagram of measurement equipments

4.2 Measurement apparatus for complex permittivity

The structure of the cavity resonator used in the complex permittivity measurement is shown in Figure 5. A cylindrical cavity containing two cup-shaped parts is machined from a copper block. The cavity resonator has $D = 35$ mm, $H = 25$ mm and a flange diameter $D_{\mathrm{f}} > 1{,}5$ mm for the measurement around 10 GHz. A specimen with diameter $d > 1{,}2 \times D$ is placed between the two parts and clamped with clips to fix this structure. This cavity resonator is excited by the two semi-rigid coaxial cables, each of which has a small loop at the top. The transmission-type resonator is constituted and under-coupled equally to the input and output loops with setting $S_{11} = S_{22}$. The photograph is shown in Figure 6.

The resonance frequency f_0, half-power band width f_{BW}, and the insertion attenuation IA_0 (dB) at f_0 are measured using a network analyzer by means of the swept-frequency method. The value of Q_{u} is given by

$$Q_{\mathrm{u}} = \frac{Q_{\mathrm{L}}}{1 - 10^{-IA_0(\mathrm{dB})/20}}, \quad Q_{\mathrm{L}} = \frac{f_0}{f_{\mathrm{BW}}} \tag{30}$$

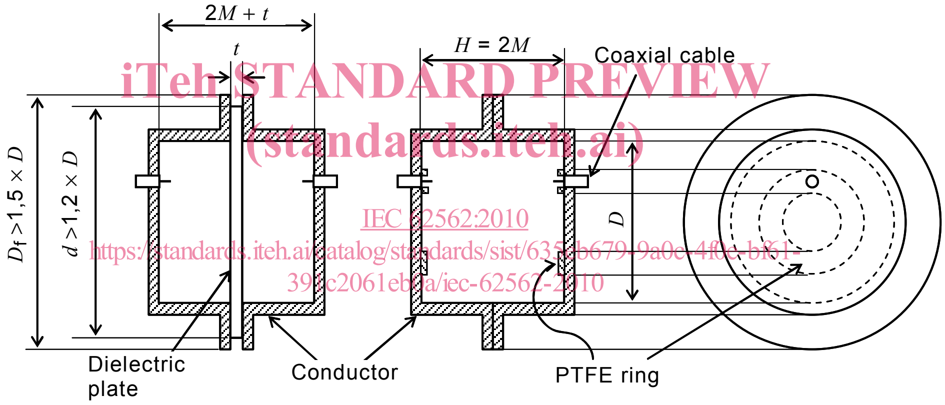

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Figure 5a – Resonator clamping dielectric specimen

Figure 5b – Empty cavity resonator

Figure 5 – Cavity resonator used for measurement

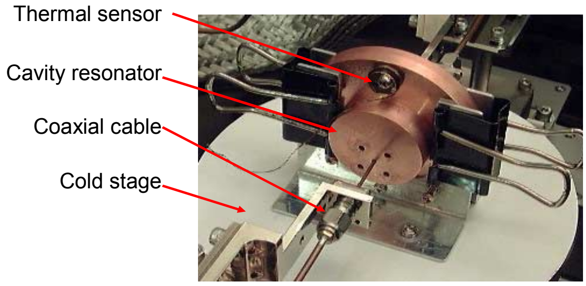

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Figure 6 – Photograph of cavity resonator for measurement around 10 GHz