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PRE-STANDARD

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

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

1 Scope

This PAS describes the measurement method of dielectric properties in the planer direction of dielectric plate at microwave frequency in order to develop new materials and to design microwave active and passive devices. This method is called a cavity resonator method.

This method has the following characteristics:

- the relative permittivity ε' and loss tangent tan δ 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 δ;
- fringing effect is corrected using correction charts calculated on the basis of rigorous analysis.

This method is applicable for measurements in the following conditions:

- frequency : 2 GHz < f < 40 GHz;
- relative permittivity : 2 < ε' < 100;
- loss tangent : 10^{-6} < tan δ < 10^{-2}.

2 Measurement parameters

The measurement parameters are defined as follows.

$$\varepsilon_r = \varepsilon' - j\varepsilon'' = D/(\varepsilon_0 E) \quad (1)$$

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

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

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 ε_{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 non-destructive 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 δ 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 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 δ 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, we first determine approximate values ε'_a and tan δ_a from the f_0 and Q_u values by using simple formula for a resonator structure shown in Figure 1b, where the fringing effect for Figure 1a is neglected. Then, we obtain accurate values ε' and tan δ from ε'_a and tan δ_a using charts calculated from the rigorous analysis.

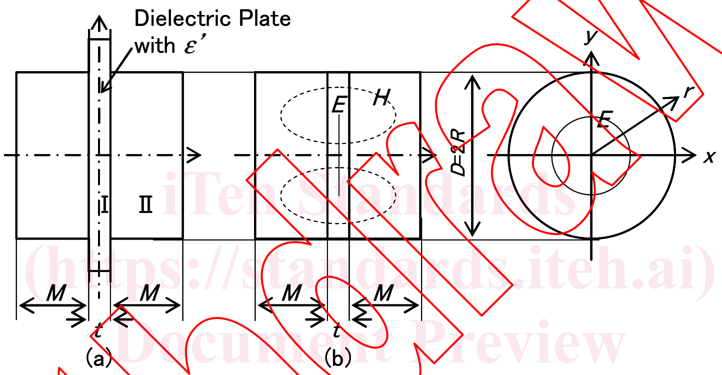

Figure 1a – Resonator used in measurement

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

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

where c is the velocity of light in a vacuum (c = 2,9979 × 0^8 m/s) and the first root X is calculated from a given value Y, using the following simultaneous equations:

$$X \tan X = \frac{t}{2M} Y \cot Y \qquad (5)$$

$$Y = M\sqrt{k_0^{\,2} - k_r^{\,2}} = jY' \qquad (6)$$

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 δ_a is given by

$$\tan \delta_a = \frac{A}{Q_u} - R_s B \qquad (7)$$

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

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

Here, μ and σ are the permeability and conductivity of the conductor. Furthermore, σ_r is the relative conductivity and σ_0 = 5,8 × 10^7 S/m is the conductivity of standard copper. Constants A and B are given by

$$\mathrm{A} = 1 + \frac{W_2^e}{W_1^e} \qquad (9)$$

$$\mathrm{B} = \frac{P_{cy1} + P_{cy2} + P_{\mathrm{end}}}{\omega R_s W_1^e} \qquad (10)$$

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 regions 1 and 2 and at the end wall. These parameters are given by

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

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

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

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

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

Then, accurate values of ε' and tan δ are given by

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

$$\tan\delta = \frac{A}{Q_u}\left(1 + \frac{\Delta A}{A}\right) - R_s B \left(1 + \frac{\Delta B}{B}\right) \qquad (17)$$

where correction terms due to the fringing field $\Delta\varepsilon'/\varepsilon'_a$, ΔA/A and ΔB/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 δ, Δε′ and Δtan δ, are estimated as the mean square errors and given respectively by

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

$$(\Delta\tan\delta)^2 = (\Delta\tan\delta_Q)^2 + (\Delta\tan\delta_\sigma)^2 \qquad (19)$$

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, Δtan δ is mainly attributed to measurement errors of Q_u and σ_r, and $\Delta\tan\delta_Q$ and $\Delta\tan\delta_\delta$ are uncertainties of tan δ due to standard deviations of them, respectively.

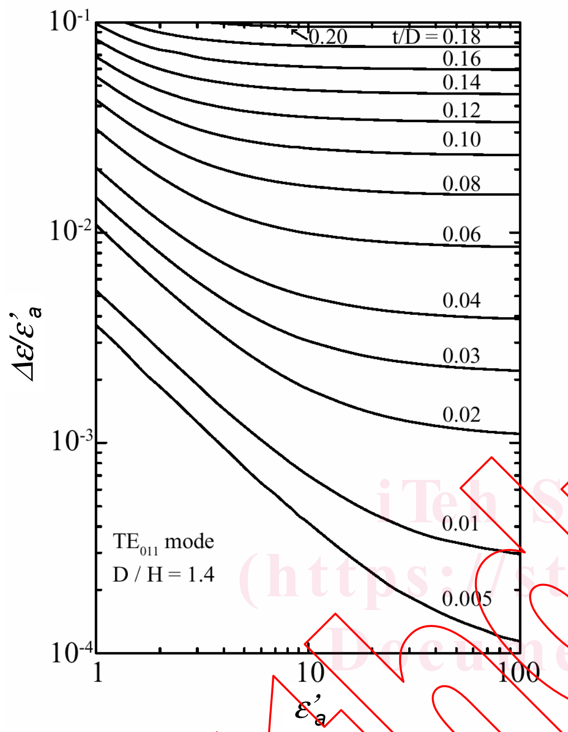

Figure 2 – Correction term $\Delta\varepsilon'/\varepsilon'_a$

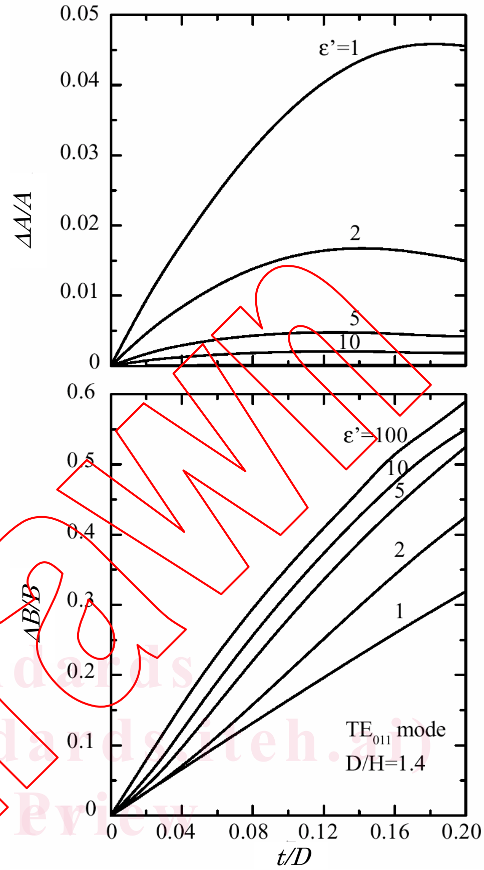

Figure 3 – Correction terms $\Delta A/A$ and $\Delta B/B$

3.2 Temperature Dependence of ε' and tan δ

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

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

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

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 δ. Using these parameters, temperature dependent values of $t(T)$, $D(T)$, $H(T)$, and $\rho(T)$, are given by

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

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

$$H(T) = H(T_0)\ [1 + \alpha_c (T - T_0)] \qquad (23)$$

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

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

$$D = \frac{c j'_{01}}{\pi} \sqrt{\frac{3}{4 f_1^2 - f_2^2}} \qquad (25)$$

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

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

$$\alpha_c = -\frac{1}{f_1} \frac{\Delta f_1}{\Delta T} \qquad (27)$$

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.

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

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

$$TC\rho = \frac{1}{\rho_r} \frac{\Delta \rho_r}{\Delta T} \qquad (29)$$