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PRE-STANDARD

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

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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.

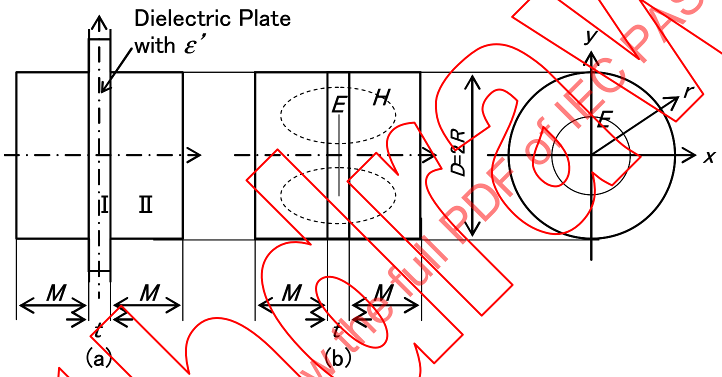

Figure 1a – Resonator used in measurement

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

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

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

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

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

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

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

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

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

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

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

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

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

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

where correction terms due to the fringing field $\Delta\varepsilon'/\varepsilon'_a$, $\Delta A/A$ 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 δ, $\Delta\varepsilon'$ 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 $\Delta\tan\delta_\delta$ are uncertainties of tan δ due to standard deviations of them, respectively.

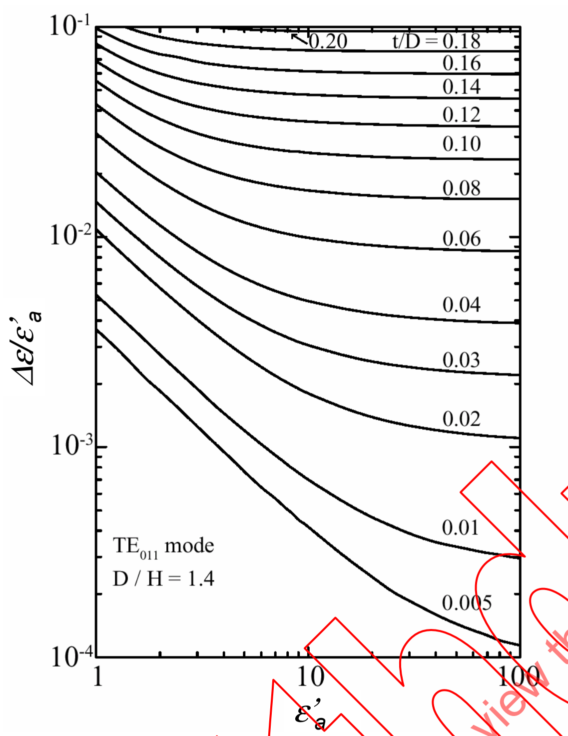

Figure 2 – Correction term $\Delta\varepsilon'/\varepsilon'_a$

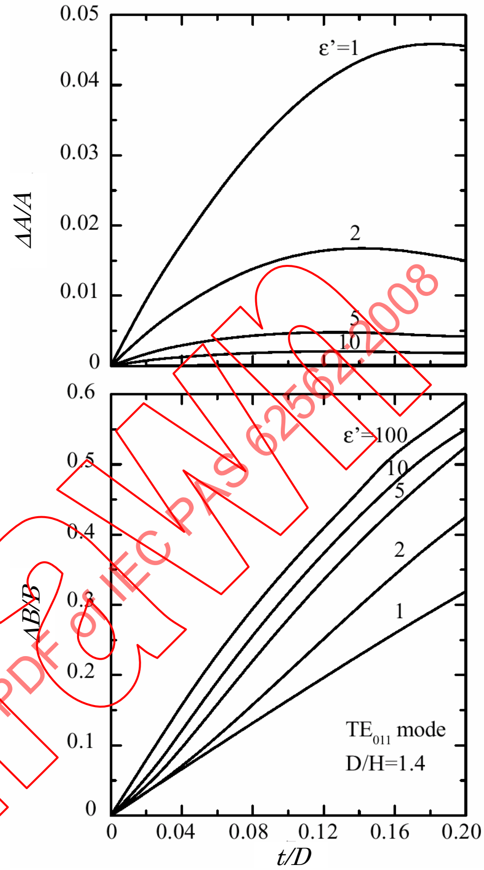

Figure 3 – Correction terms $\Delta A/A$ and $\Delta B/B$

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

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

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

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

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

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 millimeter 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 analyser can be used for the measurement shown in Figure 4a However, the vector network analyser shown in Figure 4b has an advantage in precision of the measurement data.

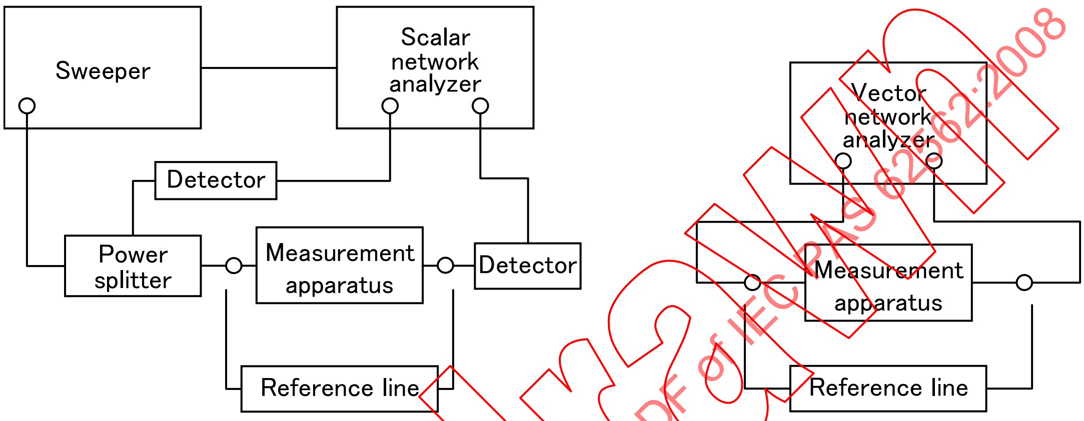

Figure 4a – Scalar network analyser system

Figure 4b – Vector network analyser 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 copper block. The cavity resonator has $D = 35$ mm, $H = 25$ mm and a flange diameter $D_f > 1{,}5$ 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 analyser by means of the swept-frequency method. The value of Q_u is given by

$$Q_u = \frac{Q_L}{1 - 10^{-IA_0(dB)/20}}, \quad Q_L = \frac{f_0}{f_{BW}} \qquad (30)$$

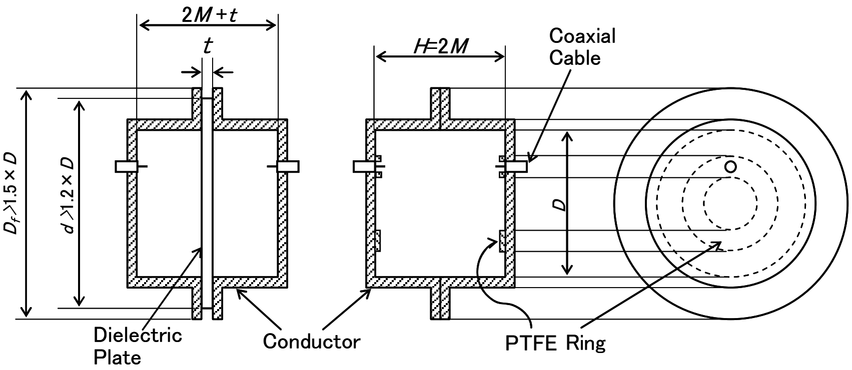

Figure 5a – Resonator clamping dielectric specimen

Figure 5b – Empty cavity resonator

Figure 5 – Cavity resonator used for measurement

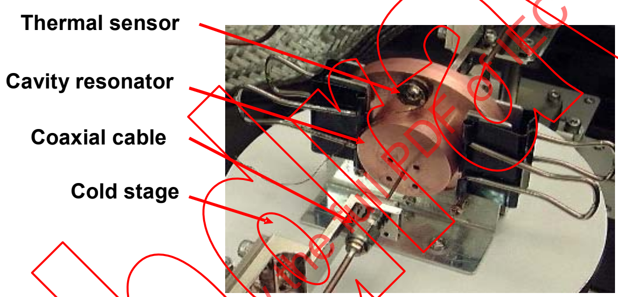

Figure 6 – Photograph of cavity resonator for measurement around 10 GHz

5 Measurement procedure

5.1 Preparation of measurement apparatus

Set up the measurement equipment and apparatus as shown in Figure 4. The cavity resonator and dielectric specimens shall be kept in a clean and dry state, as high humidity degrades unloaded Q. It is preferable that the relative humidity is less than 60 %.

5.2 Measurement of reference level

The reference level, level of full transmission power, is measured first. Connect the reference line to the measurement equipment and measure the full transmission power level over the entire measurement frequency range.

5.3 Measurement of cavity parameters: D, H, σ_r, α_c, $TC\rho$

Rough values of f_1 of the TE_{011} resonance mode and f_2 of the TE_{012} resonance modes can be estimated from the mode chart shown in Figure 7. Resonance peaks of cavity resonator with D = 35 mm and H = 25 mm are shown in Figure 8.

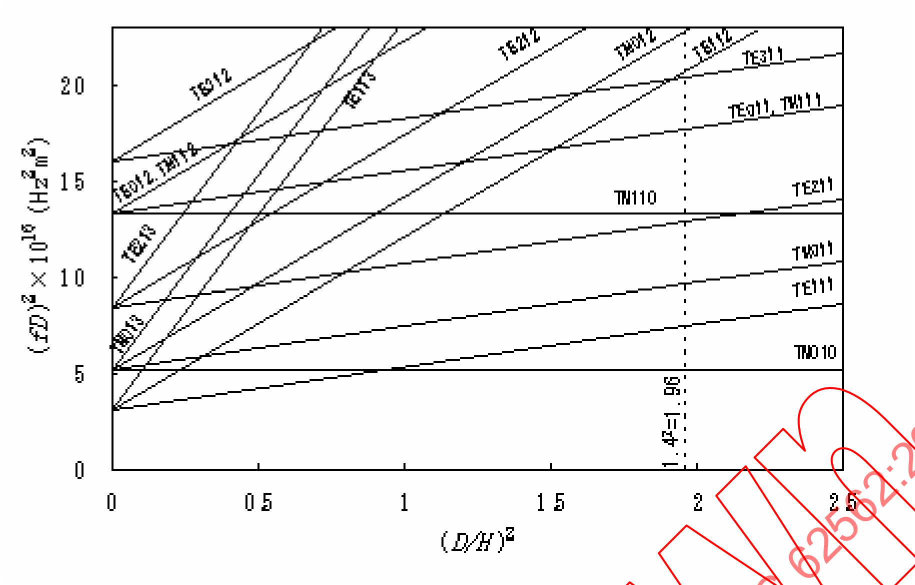

Figure 7 – Mode chart of cavity resonator

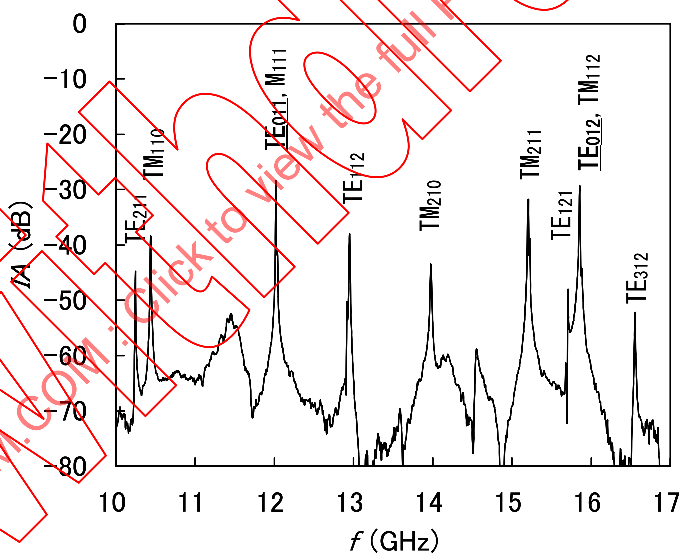

Figure 8 – Resonance peaks of cavity resonator

Attach PTFE rings to the end plates of the cavity to separate the degenerate $TM_{11\ell}$ (ℓ = 1, 2) modes from the $TE_{01\ell}$ modes, as shown in Figure 5. 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, as shown in Figure 9.

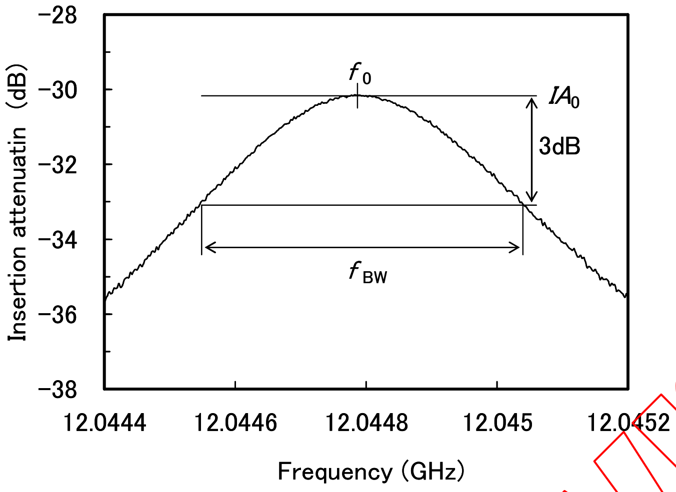

Figure 9 – Resonance frequency f_0, insertion attenuation IA_0 and half-power band width f_{BW}

Measure f_1 and Q_{uc} of the TE_{011} resonance mode and measure f_2 of the TE_{012} resonance modes. Calculate Q_{u1} by equation (30). Calculate the dimensions D, H, and σ_r of cavity resonator from equations (25), (26) and (28). Since the value of σ_r degrades due to oxidation of the metal surface, it shall be measured periodically. Next, measure the temperature dependence of f_1 and Q_u using the cavity placed in a temperature-stabilized oven. Calculate α_c and $TC\rho$ from equations (27) and (29).

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

Place the test specimen between two cylinders and clamp them by clips, as shown in Figure 6. Estimate a rough value of f_0 of the TE_{011} resonance mode from Figure 10. Then, measure f_0 and Q_u values. Calculate ε' and tan δ values using equations (4) to (17).

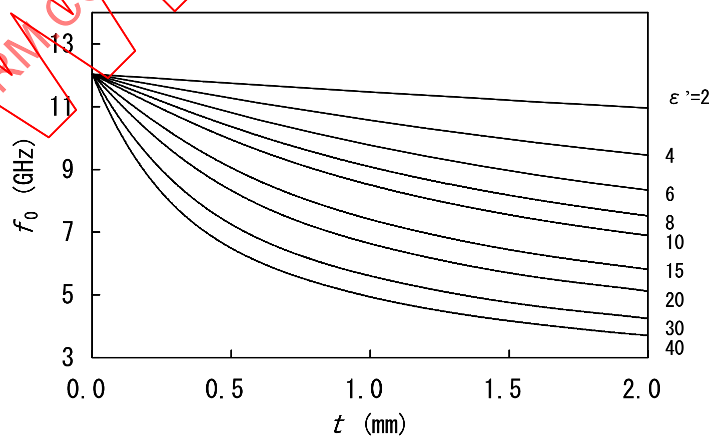

Figure 10 – Resonance frequency f_0 of TE_{011} mode of cavity resonator with dielectric plate (D = 35 mm, H = 25 mm)

5.5 Temperature dependence of ε' and tan δ

Place a cavity resonator clamping the dielectric plate in a temperature-stabilized oven, and measure f_0 and Q_u as a function of temperature T. Calculate ε' and tan δ values as a function T, taking account of α, α_c, and $TC\rho$. Then, calculate $TC\varepsilon$ by equation (3) or by the least squares method for many measurement points against T.

Annex A
(informative)

Example of measured result and accuracy

A.1 Cavity parameters

Table A.1 shows measured results of cavity parameters. As shown in this table, D and H can be determined accurately to μm order using f_1 and f_2. The value of σ_r depends on the surface roughness and the oxidation of the internal wall of cavity, and it is desired that it be higher than 80 % to keep high accuracy in the tan δ measurement.

Table A.1 – Measured results of cavity parameters

f_1(GHz) for TE_{011}	f_2(GHz) for TE_{012}	Q_u for TE_{011}	D mm	H mm	α_c ppm/K	σ_r %	$TC\rho$ 1/K
12,0456 ±0,0002	15,936 ±0,001	24256 ±145	35,053 ±0,001	24,884 ±0,002	15,5 ±0,3	84,4 ±1,0	0,0034 ±0,0003

Measured results of temperature dependence of f_1 and Q_{uc} for a empty cavity resonator are shown in Figure A.1. The value of α_c in Table 2 was determined from the temperature dependence of f_1 using equation (27). Furthermore, $TC\rho$ was determined from the temperature dependence of Q_{uc} using equation (29). In these calculations, $\Delta f_1/\Delta T$ and $\Delta\rho_r/\Delta T$ were determined by the least squares method. The values of α_c are nearly equal with nominal value of 16,5 ppm/K of copper. The values of $TC\rho$ are around the nominal value $TC\rho$ = 0,0039 (1/K) of copper at DC.

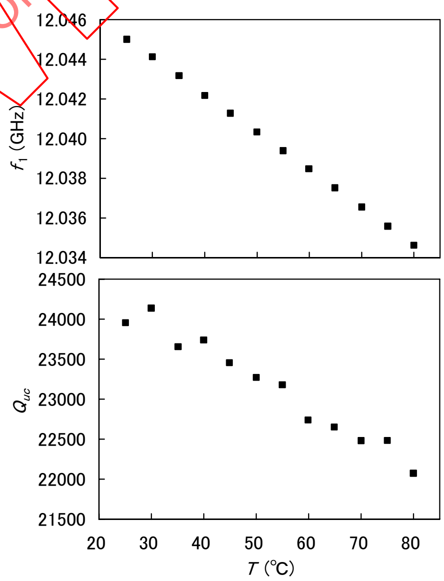

Figure A.1 – Measured temperature dependence of f_1 and Q_{uc}

A.2 Relative permittivity *ε′* and loss tangent tan δ

Figure A.2 shows measured resonance peaks of cavity resonator clamping sapphire plate with Table A.2 giving measured values of *ε′* and tan *δ* for the sapphire plate with t = 0,958 ± 0,002 mm at room temperature. The values of *ε′* are the perpendicular component of relative permittivity against c-axis. Measurement errors Δ*ε′* and Δtan *δ* were calculated by equations (18) and (19). A main cause of Δ*ε′* is the uncertainty of the sample thickness.

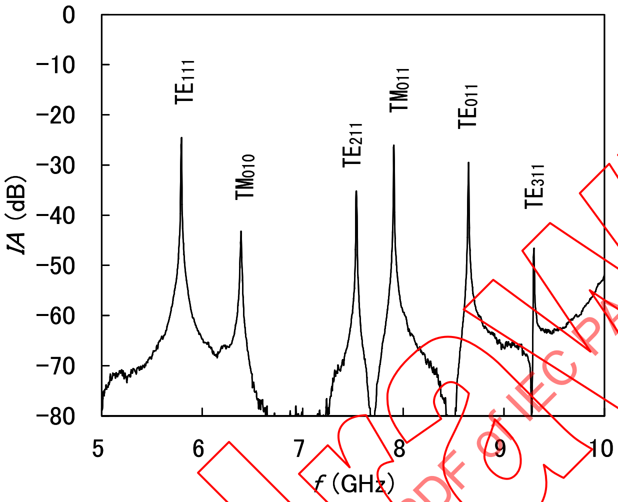

Figure A.2 – Resonance peaks of cavity resonator clamping sapphire plate

Table A.2 – Measured results of of *ε′* and tan*δ* for sapphire plate

f_0 GHz	Q_u	*E′*	tan *δ* 10^{-5}	σ_r %
8,7546	24043	9,404	0,91	84,4
±0,0001	±165	±0,017	±0,06	±1,0

Figure A.3 shows measured results of the temperature dependence of f_0, Q_u, *ε′*, and tan δ for the sapphire plate. The value of *ε′* decreases linearly and tan δ increases approximately linearly, with increasing T. The value of *TCε* was determined to be 92 ppm/K using the least squares method from *ε′* values against T.