Millimeter wave measurements of temperature dependence of complex permittivity of dielectric plates by a cavity resonance method

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Abstract----**A novel circular cavity resonance method based on a rigorous analysis by the mode matching technique is proposed to measure the temperature dependences of complex permittivity of low loss dielectric plates accurately in the millimeter wave range 30-100 GHz. The measured results for GaAs substrates verify the usefulness.**

I. INTRODUCTION

Open resonator methods are known as precise measurement methods of low loss dielectric materials in the millimeter wave range 30-300 GHz[1]-[3]. However these methods are not suitable to measure the temperature dependences, because the measurement apparatus is mechanically unstable for temperature change. On the other hand, cavity resonance methods using the TE_{01p} mode in a circular conductor cylinder [4] or in a circular conductor cavity [5] are also known to be able to measure low-loss materials precisely. These structures are available to measure the temperature dependences. Recently the temperature dependences for dielectric plates were measured at 48 GHz, by using WRJ-500 rectangular waveguides to excite and detect this cavity [6]. However it is found that adjustment of coupling strength in this structure is not easy. Presently we can commercially utilize millimeter wave vector network analyzers constituted by a coaxial cable system. The excitation of a cavity by a coaxial cable makes cavity measurements easy in the millimeter wave range 30-100 GHz.

In this paper a circular cavity resonance method based on coaxial cable excitation is proposed to measure the temperature T dependences of complex permittivity of low loss dielectric plates accurately at 50 GHz.

II. MEASUREMENT PRINCIPLE

Figure 1 shows geometry of analysis used for a rigorous analysis performed by the mode matching technique with Ritz-Galerkin method. A dielectric plate sample of the relative permittivity ε_r, thickness t, and diameter d, which is sandwitched with dielectric supports of the relative permittivity ε_g and thickness g, is placed in a conductor cavity of diameter D and height H having cavity fringe of diameter d.

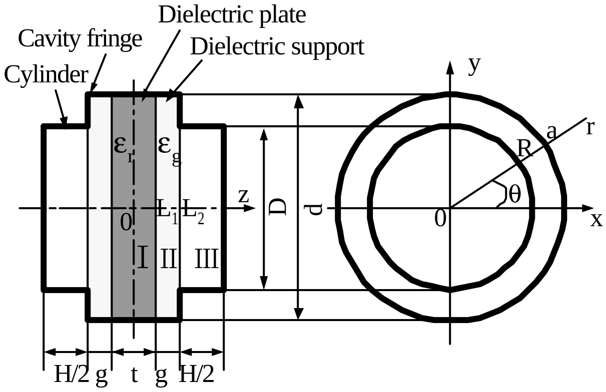

Fig.1 Geometry of analysis.

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Values of ε_r and loss tangent $\tan\delta$ of the sample can be determined precisely from the measured values of the resonance frequency f_0 and unloaded Q, Q_u of the TE_{0mp} modes, by using a program for a Windows 95 personal computer developed on the basis of this analysis, that is,

$$\det F\ (f_0;\ \varepsilon_r,\ \varepsilon_g,\ t,\ g,\ D,\ H,\ d) = 0 \qquad (1)$$

for the ε_r measurements and

$$\tan\delta = A/Q_u - BR_s \qquad (2)$$

for the $\tan\delta$ measurements, where $R_s=(\omega\mu/2\sigma)^{1/2}$ is the surface resistance, $\sigma=\sigma_r\sigma_0$ is the conductivity, σ_r is the effective conductivity and σ_0= 58x10^6 S/m is the conductivity of the standard copper. Also A and B are constants calculated from the frequency changes due to each perturbations of ε_a, D, H, and g for ε_g=1, by using eq. (1), that is,

$$A = \frac{f_0}{-\left(\dfrac{\Delta f_0}{\Delta \varepsilon_r}\right)} \qquad (3)$$

$$B = \frac{1}{120\pi k_0}\frac{1}{\varepsilon_r}\frac{\Delta\varepsilon_r}{\Delta f_0}\left(\frac{\Delta f_0}{\Delta H}+\frac{\Delta f_0}{\Delta R}+\frac{\Delta f_0}{\Delta g}\right) \qquad (4)$$

The derivation of these formulas is omitted because of the limited space.

III. CAVITY STRUCTURE

A structure of a circular cavity used in this measurement is shown in Fig. 2. The cavity with the diameter D, machined from copper, is cut into two parts in the middle of the height H, as shown in Fig. 2(a). The resonant frequency of the degenerate TM_{11p} mode can be separated from the TE_{01p} mode by grooves at both ends of the cylinder. The cavity is excited and detected

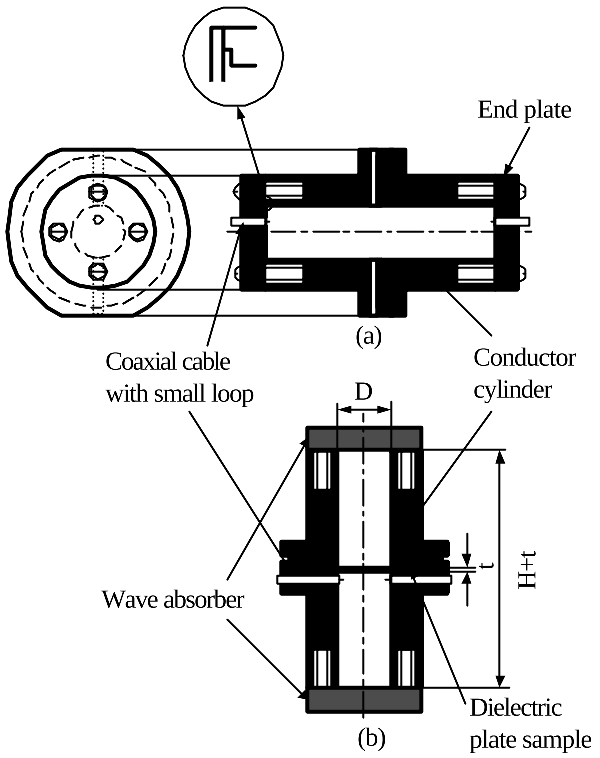


Fig.2 Cross-sectional view of a cavity for the measurement.
(a) Empty cavity.
(b) Cavity clamping a dielectric plate sample.

at end plates by UT-47 semi-rigid coaxial cables (outer diameter 1.2mm) with small loop at the top. Prior to measuring ε_r and $\tan\delta$ of a dielectric plate, we need to measure the values of D, H and σ_r. The values of D and H were calculated from two resonant frequencies measured for the TE_{013} and TE_{014} modes and σ_r was determined from the measured unloaded Q, Q_u for the TE_{013} mode[5]. The measured results are shown in Table 1.

Table 1 Measured results for empty cavity.

Mode	f_0 (GHz)	Q_u for TE_{013}	D (mm)	H (mm)	σ_r (%)
TE_{013} TE_{014}	54.300 ±0.002 55.770 ±0.001	10180 ±60	6.985 ±0.001	31.150 ±0.010	61.0 ±0.7

A dielectric plate sample with the thickness t and the larger size than D is clamped by two clips, as shown in Fig. 2 (b). In this case, wave absorbers are attached in place of the end plates. The TE_{0mp} modes are used in the accurate measurements and are excited by the coaxial loops near the plate. Such a cavity structure of D=3 mm has capabilities of realizing material measurements at 100 GHz.

IV. IDENTIFICATION OF RESONANCE MODES BY A MODE CHART

For a simple cavity resonator where the fringe effect is neglected in Fig. 2(b), as is well known, the characteristic equations are given by

$$u \tan (u - p\,\pi/2) = v \qquad (5)$$

for the TE_{nmp} mode with $J'_n(j'_{nm})=0$ and

$$u \tan (u - p\,\pi/2) = \varepsilon_a v \qquad (6)$$

for the TM_{nmp} mode with $J_n(j_{nm})=0$, where

$$u = \left(\frac{\pi t f_0}{c}\right)\left[\varepsilon_a - \left(\frac{c\, j^{(\prime)}_{nm}}{\pi D f_0}\right)^2\right]^{1/2} \qquad (7)$$

$$v = \left(\frac{\pi t f_0}{c}\right)\left[\left(\frac{c\, j^{(\prime)}_{nm}}{\pi D f_0}\right)^2 - 1\right]^{1/2} \qquad (8)$$

A program making mode charts was developed to calculate resonance frequencies for a complete set of the resonance modes as a function of ε_a (the approximate relative permittivity for neglecting the fringe effect) for given values of D and t, using (5) and (6). Figure 3 shows the mode chart calculated for D=6.985 mm and a GaAs plate of t=0.607 mm, where the broken curves indicate ones for the TE_{011} and TE_{021} modes used for ε_r measurements. This mode

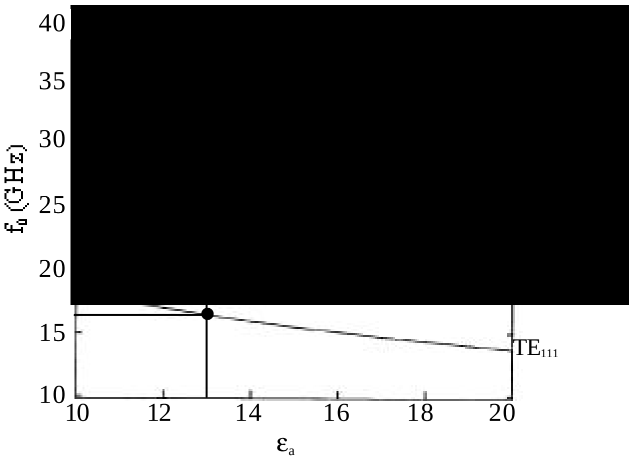


Fig. 3 Mode chart for D=6.985mm and t=0.607mm.

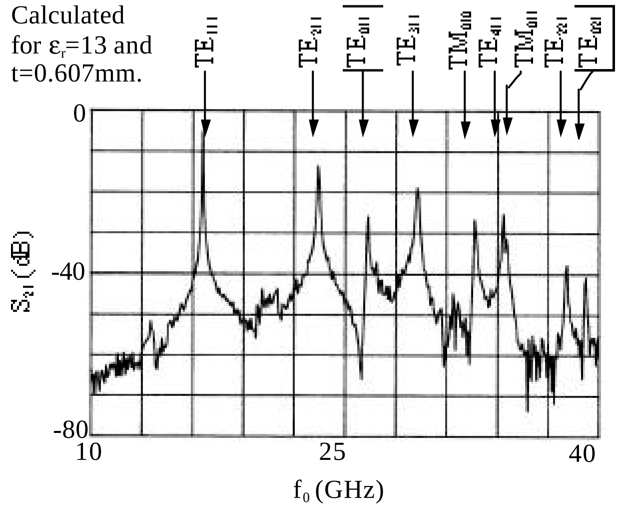
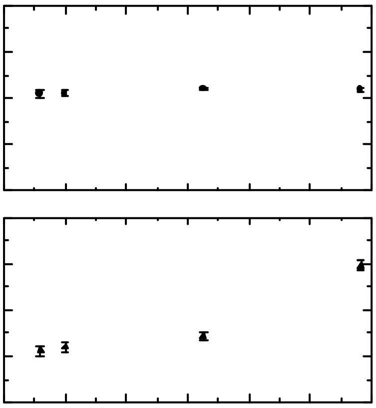


Fig. 4 Frequency response measured for cavity clamping a GaAs plate and resonant frequencies calculated using mode chart.

chart is useful for the measurement of dielectric plates with unknown ε_r values, as described below. Figure 4 shows the frequency response measured for the structure shown in Fig 2 (b). Mode identification of these measured resonance peaks can be performed directly from the resonance frequencies calculated from the mode chart, indicated on the top of of Fig. 4. In this case the measured lowest frequency 17 GHz corresponds to the dominant TE_{111} mode for the



approximate value $\varepsilon_a = 13$. The expected f_0 values are 26.5 GHz for the TE_{011} mode and 39 GHz for the TE_{021} mode, as shown in Fig. 4. The measured results are shown in Fig. 5, in which the values for 13 and 15 GHz indicate the measured results for the other two cavities with different dimensions. These measured values agree well with ones presented in [7].

V. MEASUREMENT OF TEMPERATURE DEPENDENCE

Prior to measure the temperature T dependences of ε_r and tanδ, the T dependences of D, H and σ_r are measured for the empty cavity set in a T-controlled oven. Then the dependences of ε_r and tanδ are measured for a plate sample. The T dependences for a PTFE plate of t=1.007 mm and a polyethylene plate of t = 0.835 mm have been measured at 48 GHz [6]. A similar measurement for a GaAs plate will be performed soon.

VI. CONCLUSION

It is verified that the resonance method developed realizes accurate and easy measurement of the temperature dependences of ε_r and tanδ for any low loss dielectric plate samples in the millimeter wave range 30-100 GHz.

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