Millimeter wave measurements of some low-loss dielectric plates by a novel cut-off circular waveguide method

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ABSTRACT ***An easy-to-treatment technique is proposed to measure low-loss dielectric plates by a cut-off circular waveguide method in millimeter wave region. The fringe effect can be corrected simply using correction charts calculated from the rigorous analysis based on Ritz-Galerkin method. Some low-loss dielectric plates were measured by this method to find out proper material for millimeter wave applications. It is found that modified polyolefin has an excellent electric characteristic of ε_r=2.31 and $\tan\delta$=1.3x10^{-4}, which is similar to PTFE.***

INTRODUCTION

For application to millimeter wave circuit, development of new material with low-loss electric characteristics and low price is requested. Some measurement methods have been presented to evaluate these dielectric materials in millimeter wave region [1][2]. Authors have developed a cut-off circular waveguide method [3] – [5] to measure the temperature dependence of complex permittivity of low-loss dielectric plates accurately and efficiently. However, the treatment of measurement formulas of this method is rather difficult and the numerical calculation time take long, because the formulas are derived on the basis of rigorous analysis by the mode matching technique with the Rits-Galerkin method.

In this paper, an easy-to-treatment technique is proposed to correct the fringe effect simply using correction charts calculated from the rigorous analysis described above. Moreover, the measured results of some low-loss dielectric plates are presented.

MEASUREMENT PRINCIPAL

A resonator structure used in this measurement is shown in Fig.1. A circular cylindrical resonator clamping a dielectric plate is shown in Fig.1 (a). A conductor cylinder with the diameter D is cut into two parts in the middle of the height H. A dielectric plate sample having the thickness t and the diameter d, which is larger than D, is placed between these cylinders and clamped by two clips; hence a sample to be measured can be quickly removed and replaced by another one. The axially symmetric TE_{011} modes are used for this measurement to avoid air-gap effects at the cylinder-plate interface. The cylinder parts constitute the TE_{01} mode cut-off waveguides and the dielectric plate part outside D also constitutes a radial cut-off waveguide; hence the fields decay exponentially in the axial directions to each side of the sample and in the radial direction. Wave absorbers attached at both ends are needed to eliminate the unwanted cavity modes. This resonator is excited and detected by a pair of UT-47 semi-rigid coaxial cables (outer diameter 1.2mm) with a small loop at the top, which are set near the dielectric plate sample.

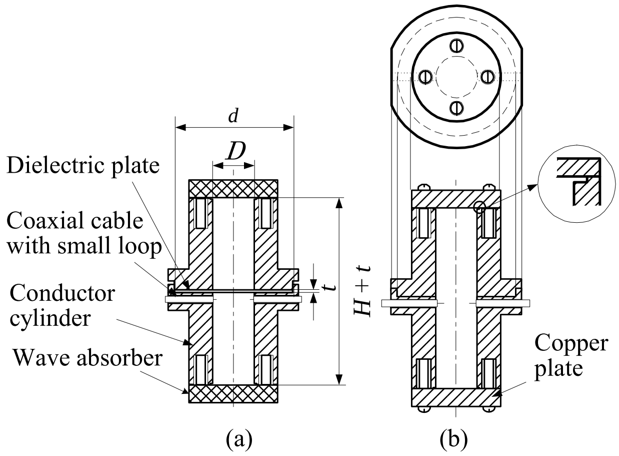

Fig. 1. Cross sectional view of a resonator structure
(a) Circular cylindrical resonator clamping a dielectric plate
(b) Circular empty cavity

The values of relative permittivity ε_r and loss tangent $\tan\delta$ of the sample, in consideration of the fringe effect at the cylinder-plate, can be calculated accurately from the measured values of the resonance frequency f_0 and the unloaded Q, Q_u of the TE_{011} mode. For ε_r measurement, the following formula is used;

$$\varepsilon_r = \varepsilon_a \left(1 - \frac{\Delta\varepsilon}{\varepsilon_a}\right) \quad (1)$$

where ε_a is a value neglecting the fringe effect and is given by

$$\varepsilon_a = \left(\frac{c}{\pi f_0 t}\right)^2 \left[X^2 - Y^2\left(\frac{t}{H}\right)^2\right] + 1 \quad (2)$$

In the above, X and Y are given by

$$X \tan X = Y \quad (3)$$

$$X = \frac{t}{2}\sqrt{\varepsilon k_0^2 - k_r^2} \qquad \left(0 < X < \frac{\pi}{2}\right) \quad (4)$$

$$Y = \frac{t}{2}\sqrt{k_r^2 - k_0^2} \quad (5)$$

where $k_0=2\pi f_0/c$, c is the velocity of light, and $k_r=2j'_{01}/D$ with $j'_{01}=3.83171$. In addition, the correction terms $\Delta\varepsilon/\varepsilon_a$ due to the fringe effect are determined from Fig.2, which is calculated from eqs. (2)-(5) and the rigorous analysis [4]. For $\tan\delta$ measurement, the following formula is used;

$$\tan\delta = \frac{A}{Q_u}\left(1+\frac{\Delta A}{A}\right) - R_s B\left(1+\frac{\Delta B}{B}\right) \quad (6)$$

where $R_s = \sqrt{\pi f_0 \mu_0 / \sigma}$ is surface resistance of the cylinder, $\sigma = \sigma_0\sigma_r$ is the conductivity, $\sigma_0 = 58\times10^6\ S/m$ is the conductivity of the standard copper, σ_r is the effective relative conductivity including influence of oxidation and roughness of the copper surface of a copper cavity, $\mu_0 = 4\pi\times10^{-7}\ H/m$ is the permeability in the vacuum and constants A and B are geometry factors and given by

$$A = 1 + \frac{W}{\varepsilon_r} \quad (7)$$

$$B = \left(\frac{j'_{01} c}{\pi f_0 D}\right)^3 \frac{1+W}{60\pi j'_{01}\varepsilon_r} \quad (8)$$

$$W = \frac{\cos^2(X - p\pi/2)}{Y + \sin^2(X - p\pi/2)} \quad (9)$$

In addition, the correction terms $\Delta A/A$ and $\Delta B/B$ due to the fringe effect are determined from Fig.3, which are calculated from A, B and the rigorous analysis [4]. Using these formulas, the calculation time is shortened greatly.

Prior to measure ε_r and $\tan\delta$ of a sample, we need to measure the values of D, H and σ_r. The values of D, H and σ_r can be measured using the TE_{01p} mode (p=1, 2, ⋯) of an empty cavity structure shown in Fig.1 (b), where copper plates are attached at both ends of the

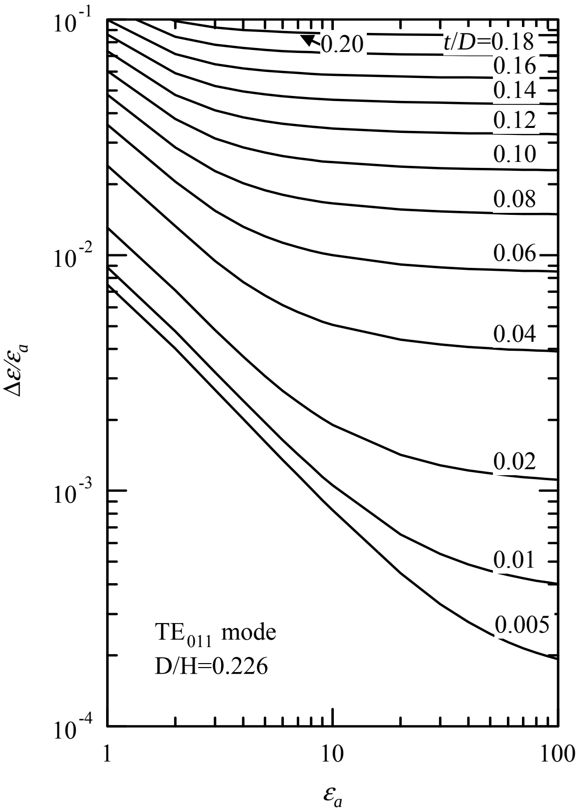

Fig. 2. Correction term $\Delta\varepsilon/\varepsilon_a$

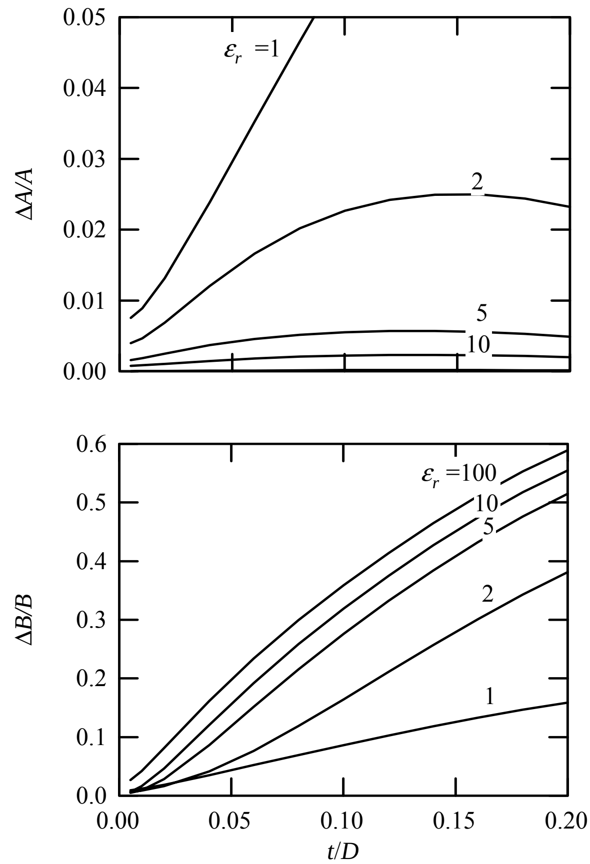

Fig. 3. Correction terms $\Delta A/A$ and $\Delta B/B$

cylinders in place of the wave absorbers shown in Fig.1 (a). The degenerate TM_{11p} mode can be separated from the TE_{01p} mode by grooves machined at each end of the cylinders. The values of *D* and *H* are calculated from some resonance frequencies f_0 for the TE_{01p} and TE_{01q} modes (p≠q, integer), and the value of σ_r is calculated from the value of Q_u measured for the TE_{01p} mode [6].

MEASURED RESULTS

Measured results for an empty cavity is shown in Table 1. The values of *D* and *H* indicate the averages of ones calculated from some sets of f_0 measured for the TE_{01p} and TE_{01q} modes. The value of σ_r of the cavity was determined from the measured Q_u value for the TE_{011} mode.

Some low-loss dielectric plates were measured to find out proper material for millimeter wave applications. The ε_r and tanδ values of some low permittivity dielectric plates were measured by using the TE_{011} mode of the 50KC01 resonator. The results are shown in Table 2, where MPO is modified polyolefin, MPS is modified polystyrene and PC is polycarbonate. For these results, it is found that the modified polyolefin has an excellent electric characteristic similar to PTFE.

MEASUREMENTS OF THE TEMPERATURE DEPENDENCE

An automatic measurement system based on this method was developed to measure the temperature dependence in our laboratory [4][5]. This system consists of Agilent technology network analyzer; 2.2mm semi-rigid coaxial cables with V connectors, Cryostat, and Windows personal computer with GP-IB. The automatic measurements of ε_r, tanδ and σ_r are performed at each temperature change of 1K, using programs developed for HT-BASIC/WINDOWS.

The temperature dependences of *D*, *H* and σ_r for the 50KC01 cavity were measured using the TE_{011} mode. The results are shown in Fig. 4(a). Then the temperature dependences of ε_r and tanδ of a PTFE plate (11x11mm^2, *t*=1.073mm and the linear thermal expansion coefficient τ_l=100ppm/K) and the MPO-A1 plate (ϕ20mm, *t*=2.050mm and τ_l=70ppm/K) were measured using the TE_{011} mode at 47GHz and 37GHz, respectively. The results are shown in Fig. 4(b) and (c). The f_0 of the PTFE plate have inflection points near 50K, 170K and 290K, because of phase transitions of crystal construction. However, the f_0 of the MPO-A1 plate have no inflection point. Moreover, the tanδ value of the MPO-A1 plate is quite lower than that of the PTFE above room temperature.

CONCLUSIONS

It was verified that the easy-to-treatment technique to correct the fringe effect from the correction charts is

Table 1. Measured result for an empty cavity at 25°C

Cavity No.	f_0 (GHz)	Q_u	*D* (mm)	*H* (mm)	σ_r (%)
50KC01	52.520 ±0.001	11230 ±80	6.991 ±0.002	30.917 ±0.079	85.7 ±1.2

Table 2. Measured results for some plates at 25°C

Sample	*t* (mm)	f_0 (GHz)	Q_u	ε_r	tanδ (x10^{-4})
PTFE	1.073 ±0.004	46.571 ±0.001	5020 ±70	2.016 ±0.005	1.65 ±0.05
Crythnex	0.823 ±0.046	46.645 ±0.003	4240 ±60	2.333 ±0.011	2.61 ±0.07
MPO-A1	2.050 ±0.001	38.010 ±0.001	3950 ±100	2.310 ±0.002	1.29 ±0.08
MPO-A2	2.040 ±0.001	38.040 ±0.001	3730 ±120	2.314 ±0.002	1.47 ±0.10
MPO-B1	1.032 ±0.001	44.746 ±0.002	2270 ±70	2.351 ±0.003	5.33 ±0.19
MPO-B2	1.035 ±0.001	44.706 ±0.002	2300 ±60	2.354 ±0.003	5.23 ±0.18
MPS-A1	1.178 ±0.001	42.833 ±0.002	3950 ±70	2.472 ±0.003	7.22 ±0.37
MPS-A2	1.175 ±0.001	42.911 ±0.004	1680 ±50	2.463 ±0.003	6.93 ±0.21
MPS-B1	1.187 ±0.001	40.097 ±0.002	1160 ±30	2.942 ±0.003	9.75 ±0.25
MPS-B2	1.190 ±0.001	40.144 ±0.002	1130 ±50	2.929 ±0.003	10.08 ±0.41
MPS-C1	1.190 ±0.002	40.209 ±0.002	1170 ±50	2.916 ±0.003	9.71 ±0.40
PC	0.978 ±0.001	42.931 ±0.005	260 ±10	2.759 ±0.003	54.7 ±1.6

useful to measure the complex permittivity of low-loss dielectric plates accurately and efficiently by the cut-off circular waveguide method. The measurement precisions of this method are 0.2~1.0 percents for ε_r=2~30 and 2~10 percents for tanδ=10^{-2}~10^{-5}. We can expect that the modified polyolefin plates have the high possibility for application to millimeter wave circuit, because of excellent electric characteristics and low price, compared with PTFE plates.

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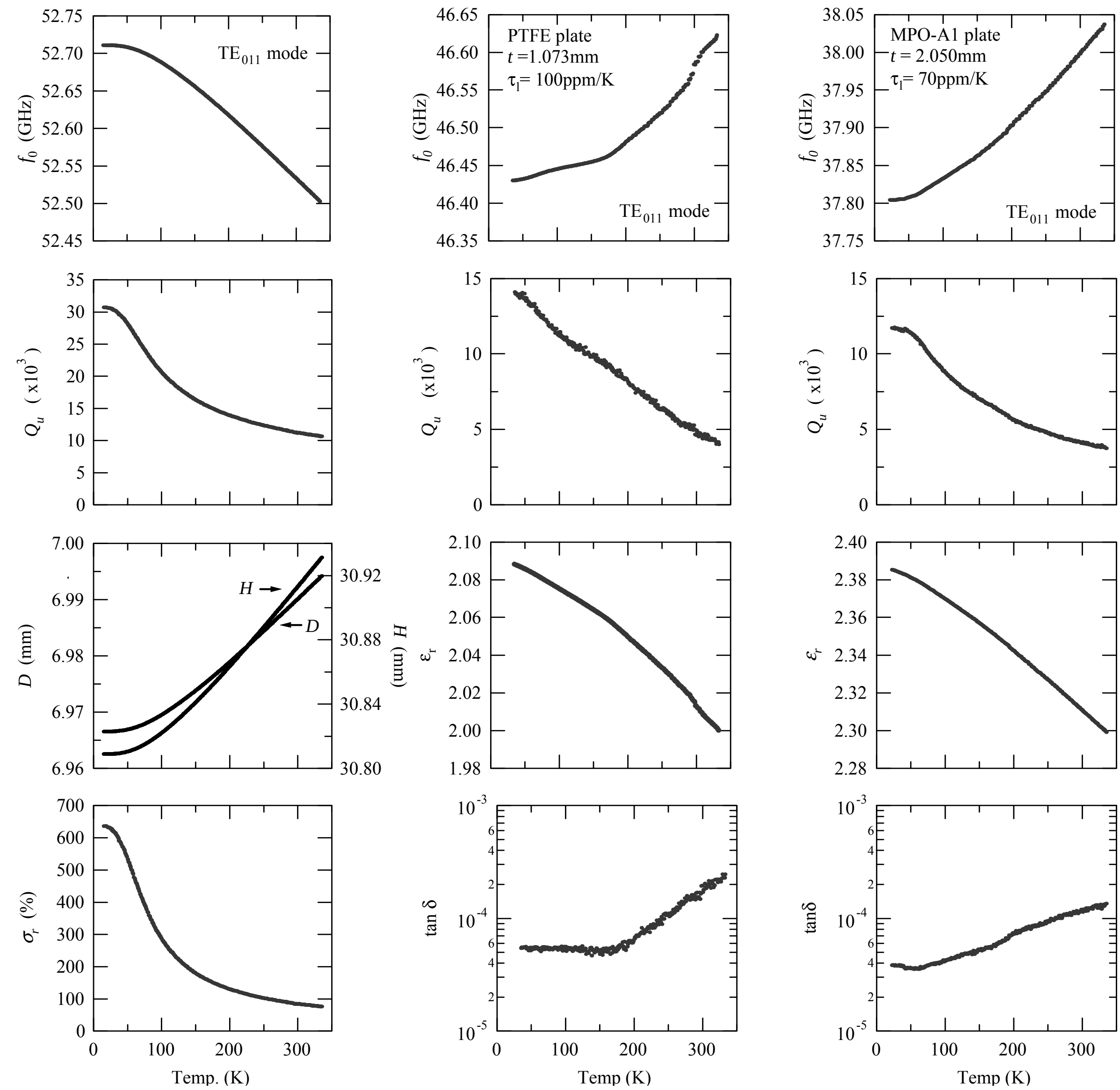

(a) empty cavity (b) PTFE plate (c) MPO-A1 plate

Fig. 4. Temperature dependences of empty cavity (50KC01), PTFE plate and MPO-A1 plate.

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