Measured results of some low-loss dielectric plates by cut-off circular waveguide method in millimeter wave region

Takashi Shimizu Yoshio Kobayashi

Dept. Electrical and Electronic System, Saitama University
Shimo-ookubo 255, Saitama 338-8570, Japan
Phone: +81-48-858-3477, Fax: +81-48-857-2529
E-mail: shimizu@reso.ees.saitama-u.ac.jp

Abstract — In order to investigate accuracy of a cut-off circular waveguide method, the round robin test, which is needed to establish JIS standard, is performed by using three cavities and eight sapphire plates. Some low-loss dielectric plates were measured by this method to find out good 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. The measurement precisions of this method are 0.2~1.0 percents for ε_r=2~30 and 2~10 percents for $\tan\delta$=10^{-2}~10^{-5}.

I. 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]-[3]. We also have developed a circular cut-off waveguide method [4]-[6] to measure the temperature dependence of complex permittivity of low-loss dielectric plates accurately and efficiently.

In this paper, the round robin test, which is needed to establish JIS standard, is performed by using three cavities and eight sapphire plates to investigate accuracy of this method. These measured results of the round robin test are discussed. Then the measured results of some low-loss dielectric plates by this method to find out good material are reported.

II. 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). This 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$_{0m1}$ (m: integer) modes are used for this measurement to avoid air-gap effects at the cylinder-plate interface. The cylinder parts constitute the TE$_{0m}$ mode cutoff waveguides and the dielectric plate part outside *D* also constitutes a radial cutoff 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

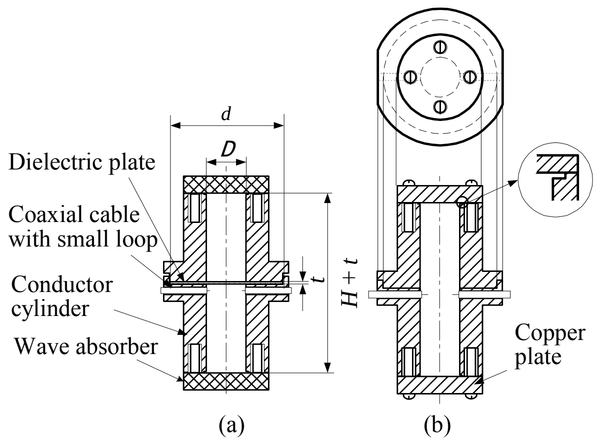

Fig. 1. Cross sectional view of a resonator structure

(a) Circular cylindrical resonator clamping a dielectric plate
(b) Circular empty cavity

the unwanted higher order modes. These resonators are 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.

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$_{0m1}$ mode, by using measurement formulas derived on the basis of the rigorous analysis by the Rits-Galerkin technique. For ε_r measurement,

$$\det H\left(f_0;\varepsilon_r,\varepsilon_g,t,g,D,H,d\right)=0 \tag{1}$$

where *g* is a gap distance between the sample and the cylinder and ε_g is relative permittivity of the gap, which is ε_g =1 usually. For $\tan\delta$ measurement,

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

where $R_s = \sqrt{\pi f_0 \mu_0 / \sigma}$ is surface resistance of the cylinder, $\sigma = \sigma_0 \sigma_r$ is the conductivity, $\sigma_0 = 58 \times 10^6$ 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 and $\mu_0 = 4\pi \times 10^{-7}$ H/m is the permeability in the vacuum. Also A and B are constants calculated from the frequency changes due to each perturbation of ε_r, D, H and g for ε_g =1 by using eq. (1) [4], that is,

$$A = -\frac{f_0}{2\varepsilon_r} \frac{\Delta\varepsilon_r}{\Delta f_{0\varepsilon}} \quad (3)$$

$$B = \frac{1}{120\pi k_0 \varepsilon_r} \frac{\Delta\varepsilon_r}{\Delta f_{0\varepsilon}} \left(\frac{\Delta f_{0D}}{\Delta D} + \frac{\Delta f_{0H}}{\Delta H} + \frac{\Delta f_{0g}}{\Delta g} \right) \quad (4)$$

The values of D, H and σ_r of a copper cavity are 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 cylinders in place of the wave absorbers. The degenerate TM_{11p} mode can be separated from the TE_{01p} mode by grooves machined at each end of the cylinders. The D and H values are calculated from some-resonance frequencies f_0 for the TE_{01p} and TE_{01q} modes (p ≠ q, integer), and the σ_r value is determined from the unloaded Q, Q_u measured for the TE_{01p} mode [7].

III. Measured Results of Round Robin Test

Three cavities numbered as 50KC01, 50KA02 and 60KA02 were manufactured to investigate the accuracy of this method.

Measured results for these empty cavities are 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 values of σ_r of these cavities were determined from the measured Q_u value for the TE_{011} mode.

The round robin test was performed using these three

Table 1. Measured results for three empty cavities 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
50KA02	52.640 ±0.001	10870 ±900	6.985 ± 0.002	26.117 ± 0.105	80.4 ± 1.3
60KA02	56.735 ±0.002	11230 ±80	6.482 ± 0.004	24.276 ± 0.282	73.6 ± 1.1

Table 2. Dimensions of eight sapphire plates

Sample No.	d (mm)	t (mm)
Sapphire-1	9.958±0.003	0.216±0.001
Sapphire-2	9.958±0.002	0.213±0.001
Sapphire-3	9.947±0.017	0.209±0.003
Sapphire-4	9.957±0.008	0.304±0.002
Sapphire-5	9.949±0.012	0.295±0.002
Sapphire-6	9.948±0.022	0.298±0.001
Sapphire-7	□10×10	0.506±0.001
Sapphire-8	□10×10	0.524±0.001

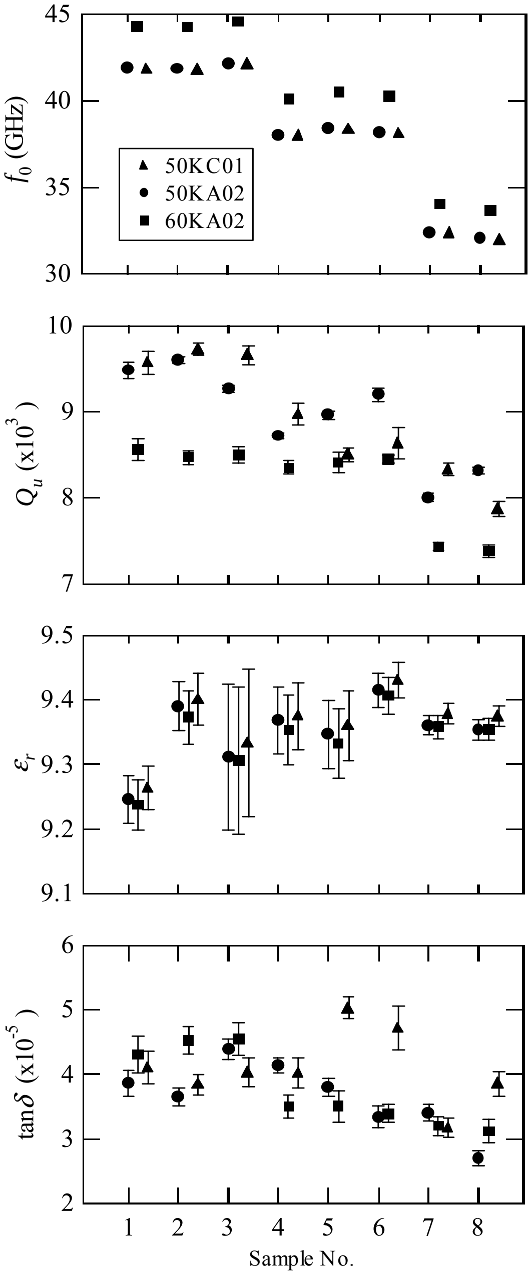

Fig. 2. Measured results for eight sapphire plates

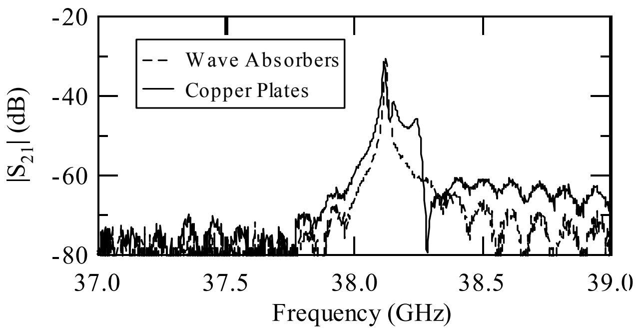

Fig. 3. The frequency responses for the 50KC01 resonator with a sapphire-6 plate attaching wave absorbers or copper plates

cavities and eight sapphire plates [8]. The dimensions of them are shown in Table 2. The measured results are shown in Fig. 2.

The ε_r value of the sapphire is in the range of 9.3~9.4. In particular, ε_r for the sapphire-1 is smaller than them and the sapphire-6 is little higher than them. It is concluded that the measured results for ε_r of the sapphire-1 and the sapphire-6 show the individual differences of the sapphire plates due to off-c-axis and a lattice defect, since the ε_r values of each samples measured with these three cavities agree within the measurement errors. As the thickness is thin, the measurement error of ε_r increases, because the major factor of ε_r error is due to the measurement error of thickness.

The $\tan\delta$ value of sapphire is in the range of about (3~4)x10^{-4}. In particular, the $\tan\delta$ values of the sapphire-5 and the sapphire-6 measured using the 50KC01 resonator are considerably higher than them. We performed the following experiment to investigate this phenomenon. In the two cases of wave absorbers and copper plates attached both ends of the cylinder, the frequency responses for the 50KC01 resonator with the sapphire-6 plate are shown in Fig. 3.

When the wave absorbers are attached, other degenerate modes are not observed. However the measured Q_u value is lower than one measured for the 50KA02. When the wave absorbers are exchanged to the copper plates, it is found that the unwanted cavity mode exists. As a result, the measured Q_u value decreases due to the influence of the unwanted cavity mode because these wave absorbers do not have sufficient attenuation to suppress them completely. By the reason, it is concluded that the $\tan\delta$ values measured for the sapphire-

Table 3. Measured results for some low ε_r plates at 25°C

Sample	t (mm)	f_0 (GHz)	Q_u	ε_r	$\tan\delta$ (x10^{-4})
PTFE	0.930 ±0.004	47.197 ±0.001	5430 ±70	2.078 ±0.005	1.61 ±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

Table 4. Measured results for some high ε_r plates at 25°C

Sample	t (mm)	f_0 (GHz)	Q_u	ε_r	$\tan\delta$ (x10^{-4})
Sapphire-3	0.209 ±0.003	42.095 ±0.015	9660 ±110	9.333 ±0.115	0.39 ±0.03
Sapphire-7	0.506 ±0.001	32.396 ±0.002	8000 ±50	9.361 ±0.017	0.29 ±0.03
Sapphire-8	0.524 ±0.001	32.032 ±0.001	8310 ±40	9.354 ±0.015	0.22 ±0.05
GaAs-1	0.607 ±0.001	26.416 ±0.001	3210 ±40	12.944 ±0.016	2.27 ±0.06
GaAs-1 (TE_{021})	0.607 ±0.001	39.310 ±0.001	2980 ±40	12.956 ±0.016	2.36 ±0.05
GaAs-2	0.108 ±0.001	45.050 ±0.001	4970 ±9	12.785 ±0.107	2.77 ±0.08
GaAs-3	0.107 ±0.001	45.192 ±0.001	4990 ±130	12.709 ±0.108	2.78 ±0.12
GaAs-4	0.110 ±0.001	44.895 ±0.001	4910 ±70	12.772 ±0.105	2.78 ±0.07
GaAs-5	0.110 ±0.001	44.939 ±0.001	4680 ±140	12.716 ±0.105	3.01 ±0.14
$LaAlO_3$-1	0.521 ±0.001	21.054 ±0.002	6770 ±50	24.044 ±0.039	0.32 ±0.03
$LaAlO_3$-2	0.510 ±0.002	21.224 ±0.003	6700 ±50	24.060 ±0.078	0.35 ±0.03
LSAT-1	0.484 ±0.001	22.091 ±0.008	3530 ±10	23.070 ±0.081	1.83 ±0.03
LSAT-2	0.499 ±0.001	21.751 ±0.001	3970 ±20	23.249 ±0.039	1.47 ±0.03

5 and the sapphire-6 using 50KC01 resonator are higher than other one and are incorrect. It is a future research subject how unwanted modes can be eliminated.

IV. MEASURED RESULTS FOR SOME LOW-LOSS DIELECTRIC PLATES

Some low-loss dielectric plates were measured, after confirming disappearance of the unwanted cavity mode described in the above section.

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 3, where MPO is modified polyolefin, MPS is modified polystyrene, and PC is polycarbonate. The modified polyolefin has an excellent electric characteristic similar to PTFE.

Similarly, the ε_r and tanδ values of some high permittivity dielectric plates were measured by using the same resonator. The results are shown in Table 4, where LSAT is $(LaAlO_3)_{0.3}$-$(SrAl_{0.5}Ta_{0.5}O_3)_{0.7}$. The resonance frequency of the TE_{011} mode decreases considerably when a sample plate with high permittivity is thick. Then, the GaAs-1 plate was also measured using the TE_{021} mode, which makes the resonance frequency close to a resonance frequency where σ_r is determined from the measured Q_u for a circular empty cavity. It is available to use the higher order mode to measure the high permittivity plate in millimeter wave region.

V. TEMPERATURE DEPENDENCE OF LOW-LOSS DIELECTRIC PLATES

An automatic measurement system based on this method was developed to measure the temperature dependence in our laboratory [5][6]. 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, $\tan\delta$ and σ_r are performed at each temperature change of 1K, using programs developed for HT-BASIC/WINDOWS.

Prior to measure the temperature dependences of ε_r and $\tan\delta$, the temperature dependences of D, H and σ' are measured for the empty cavity set in Cryostat. Then the dependences of ε_r and $\tan\delta$ are measured for a plate sample. The temperature dependences for a PTFE plate of t=0.930mm, a Crythnex plate of t=0.832mm and a GaAs plate of t=0.607mm have been measured in 40~50GHz range. These results are given in [5][6].

VI. CONCLUSIONS

It was verified that this method is useful to measure the complex permittivity of low loss dielectric plates accurately and efficiently in millimeter wave region. The measurement precisions of this method are 0.2~1.0 percents for ε_r=2~30 and 2~10 percents for $\tan\delta = 10^{-2} \sim 10^{-5}$.

The modified polyolefin plates have excellent electric characteristics similar to PTFE plates in the millimeter wave region.

ACKNOWLEDGEMENT

The authors wish to thank Shinkosha Co. Ltd. for providing single crystal plates, Dr. H. Kondo, Hitachi Co. Ltd. for providing GaAs plates, Dr. Y. Hirachi, Fujitsu Quantum Device Co. Ltd. for providing Crythnex plates.

The authors are also grateful to Mr. S. Harigai for assisting the measurements and Mr. M. Kato for fabricating the measurement apparatus.

REFERENCES

[1] A.L.Cullen and P.K.Yu, "The accurate measurement of permittivity by mean of an open resonator," *Proc. Roy Soc. A*, Vol.325, pp493-509, 1971

[2] Y.Kogami and K.Matsumura "Dielectric constant measurements in millimeter wave region by the whispering-gallery mode resonator method." *2000 China-Japan Joint Meeting on Microwave* (CJMW' 2000)

[3] Y.Ishikawa, "Non-Destructive Precise Measurement of Dielectric Substrate for Millimeter-Wave Circuits", *2001 Microwave Workshop Digest*, pp.163-168, Dec. 2001.

[4] Y.Kobayashi, and T.Shimizu, "Millimeter wave measurements of temperature dependence of complex permittivity of dielectric plates by the cavity resonance method," *1999 IEEE MTT-S Int. Microwave Symp. Digest*, pp.1885-1888, June 1999.

[5] T.Shimizu and Y.Kobayashi, "50GHz measurements of temperature dependence of complex permittivity of dielectric plates by a cut-off circular waveguide method", *2001 Topical Symposium on Millimeter Waves. Digest*, P-10, Mar. 2001.

[6] T. Shimizu and Y. Kobayashi, "Millimeter wave measurements of temperature dependence of complex permittivity of GaAs plates by a circular waveguide method", *2001 IEEE MTT-S Int. Microwave Symp. Digest*, THIF-51, pp.2195-2198, Jun. 2001.

[7] Y.Kobayashi and J.Sato, "Millimeter wave measurement of complex permittivity by improved dielectric disk resonator method," 13th Int. Conf. Infrared and Millimeter Waves: Conf. Digest, pp302-303, Dec. 1988.

[8] S.Harigai, T.Shimizu and Y.Kobayashi, "A study on measured results of complex permittivity by circular cut-off waveguide method in millimeter wave region", (*in Japanese*) *ibid*, MW2001-137, pp.85-90, Dec. 2001.