Millimeter-Wave Measurement of Complex Permittivity Using Dielectric Rod Resonator Excited by NRD-Guide

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***Abstract*—A new method for measuring complex permittivity of low-loss dielectric materials at millimeter-wave frequencies has been developed. The method uses a dielectric rod resonator excited by a nonradiative dielectric waveguide. Effective conductivity of conducting plates for short circuiting the resonator is determined by the difference of unloaded Q factors between TE_{0m1}- and $\mathrm{TE}_{0m\delta}$-mode resonators, made of the same low-loss dielectric material. Complex permittivity of the dielectric rod is determined by the resonant frequency (f_0) and unloaded Q factor (Q_u) of the TE_{0m1}-mode resonator. The complex permittivities of single crystal sapphire, polycrystalline $\mathrm{Ba(Mg_{1/2}W_{1/2})O_3}$ and $\mathrm{Mg_2Al_4Si_5O_{18}}$ (cordierite) have been obtained at 60 and 77 GHz by the new method. These results were consistent with the values measured at microwave frequencies. It was also found that the frequency dependence of the dielectric loss tangent ($\tan\delta$) for sapphire can be expressed by frequency/ $\tan\delta = 1 \times 10^6$ GHz.**

***Index Terms*—Dielectric resonator, low-loss dielectric material, millimeter wave, nonradiative dielectric waveguide (NRD-guide), permittivity measurement, sapphire.**

I. Introduction

RECENTLY, development on communication and sensing systems, operated at millimeter-wave frequencies, has been progressing at a very high speed. For designing devices and packages used in these systems, we need a reliable measurement method for relative complex permittivity $\varepsilon_r = \varepsilon' - j\varepsilon''(\tan\delta = \varepsilon''/\varepsilon')$ of dielectric materials at millimeter-wave frequencies. Several resonant methods, such as the Fabry–Perot open resonator [1]–[3], cavity resonator [4], [5], dielectric resonator excited by nonradiative dielectric waveguide (NRD-guide) [6], [7], and whispering-gallery-mode resonator [8]–[10] have been developed for measuring ε_r of the low-loss dielectric materials at millimeter-wave frequencies. Among these methods, the dielectric resonator exited by the NRD-guide is attractive. The NRD-guide [11] is widely known as a low-loss transmission guide and its dominant longitudinal section magnetic (LSM) mode can easily couple to the TE mode of the dielectric resonator. Thus, the method is especially suitable for measuring ε_r of low-loss materials used for dielectric resonators in millimeter-wave circuits.

Manuscript received November 13, 2001; revised March 19, 2002.

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Digital Object Identifier 10.1109/TMTT.2002.806932

Ishikawa *et al.* [6], [7] have originally developed the method for the ε_r measurements using a dielectric resonator exited by an NRD-guide. Their resonator was based on the $\mathrm{TE}_{0m\delta}$-mode rod resonator shielded by upper and lower parallel conducting plates. The effective conductivity σ of the conductors must be determined in advance of the measurement of ε_r. They determined the σ by measuring the difference of Q_u of the odd and even modes of their standard resonator short circuited at both ends by the conducting plates. The standard resonator is constructed by a dielectric rod and ring resonator coaxially coupled to each other. This technique enables to determine the effective conductivity by one measurement. However, the accuracy of σ measurements may not be sufficient because the difference of Q_u is small. They determined ε_r using a $\mathrm{TE}_{0m\delta}$-mode rod resonator with supports of low-permittivity material. The $\mathrm{TE}_{0m\delta}$ resonator has low conductor loss and increase resolution of $\tan\delta$ determination, supplementing their uncertainty of σ measurements. However, when the upper and lower ends of the dielectric rod are not parallel, the radiation is apt to occur in the direction of the radius of the rod resonator. Furthermore, the evaluation of ε_r is complex and needs numerical calculations.

In this paper, we propose a more efficient and simple method for measuring ε_r at millimeter-wave frequencies using a dielectric resonator exited by an NRD-guide. σ is determined by TE_{0m1}- and $\mathrm{TE}_{0m\delta}$-mode dielectric rod resonators, which are designed to enlarge the difference of Q_u. ε_r is determined by the TE_{0m1}-mode rod resonator. The resonator has relatively large conductor loss. However, the TE_{0m1}-mode resonator realizes stable measurement of Q_u, and accurate evaluations by analytic expression for ε_r [12], [13]. By the present method, ε_r of the sapphire crystal and two ceramic materials were measured at 60 and 77 GHz.

II. Measurement Method

A. Conductivity

The evaluation of conductor loss is very important for the accurate determination of $\tan\delta$ since the TE_{0m1}-mode dielectric rod resonator for measuring ε_r has relatively large conductor loss. The TE_{0m1}- and $\mathrm{TE}_{0m\delta}$-mode dielectric resonators are used for the σ measurement. Each resonator consists of low-loss material with the same ε_r. They are designed to have the same resonant frequency f_0, which is 60 or 77 GHz in this study. We used the TE_{021}- and $\mathrm{TE}_{02\delta}$-mode rod resonators of sapphire, having cylindrical axis parallel to the c-axis, as shown in

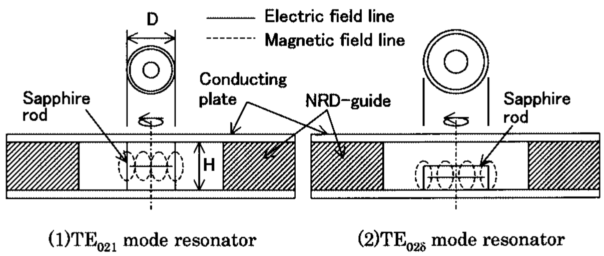

Fig. 1. Configurations of resonators for measuring effective conductivity σ and complex permittivity ε_r. Values of σ are determined using both resonators and ε_r are measured using the TE_{021} resonator.

Fig. 1. In the $\mathrm{TE}_{02\delta}$-mode resonator without support, shown in Fig. 1-(2), the conductor loss is larger than the TE_{021}-mode resonator since electronic and magnetic fields concentrate near the surface of the lower conductor because of its larger dimension ratio D/H, where D and H are the diameter and height of the resonator, respectively. High accuracy in the σ measurement is obtained by enlarging the difference of Q_u of the TE_{021} and $\mathrm{TE}_{02\delta}$-mode rod resonators.

For deriving analytical equations for the resonators, shown in Fig. 1, we assume that the conducting plates are infinitely large, and the ends of the NRD-guide for excitation are infinitely apart from the dielectric rod. To derive the equation for σ, Q_u of each resonator is firstly expressed by $\tan\delta$ and surface resistance R_s of the conducting plates as follows:

$$1/Q_{u1} = P_{e1}\tan\delta_1 + R_{s1}/G_1 \tag{1}$$

$$1/Q_{u\delta} = P_{e\delta}\tan\delta_\delta + R_{s\delta}/G_\delta \tag{2}$$

where subscripts 1 and δ represent that they belong to the TE_{0m1}- and $\mathrm{TE}_{0m\delta}$-mode resonators, respectively. Partial electric energy filling factor P_e of the dielectric rod and geometric factor G are defined in [9] as

$$P_{e1(\delta)} = \frac{\varepsilon' \iiint_{V_d} |E|^2\, dv}{\iiint_{V_t} \varepsilon'(v)|E|^2\, dv} \tag{3}$$

$$G_{1(\delta)} = \omega_{1(\delta)}\, \frac{\mu_0 \iiint_{V_t} |H|^2\, dv}{\iint_S |H_t|^2\, ds} \tag{4}$$

where V_d and V_t are the volume of the dielectric rod and the whole resonant space between the conducting plates, respectively. ε', $\varepsilon'(v)$, ε_0, and μ_0 are the relative permittivity of the dielectric rod, relative permittivity of the whole resonant space, permittivity, and permeability of the vacuum, respectively. H_t, S, and ω are the tangential magnetic field at the conductor surface, area of the conductor surface, and angular frequency.

The resonant frequencies f_1 and f_δ are slightly different in practical measurements even if they are designed to have the same resonant frequency. Since the frequency difference is very small, $\tan\delta_1$ and $\tan\delta_2$ accurately satisfy the relation of

$$f_1/\tan\delta_1 = f_\delta/\tan\delta_\delta \tag{5}$$

which is a widely known empirical low of $\tan\delta$ for dielectric ceramics composed of a paraelectric ionic crystal. The surface resistance R_{s1} and $R_{s\delta}$ are written by the effective conductivity σ, i.e.,

$$R_{s1(\delta)} = \sqrt{\omega_{1(\delta)}\mu/2\sigma} \tag{6}$$

where μ is the permeability of conducting plate. σ is assumed to be constant around the frequency of f_1 and f_δ.

We can derive equations for σ and $\tan\delta$ from (1), (2), (5), and (6) as follows:

$$\sigma = \pi\mu f_1 f_\delta \left[\frac{Q_{u1}Q_{u\delta}}{G_1 G_\delta}\cdot\frac{G_1 P_{e1}\sqrt{f_1} - G_\delta P_{e\delta}\sqrt{f_\delta}}{Q_{u1}P_{e1}f_1 - Q_{u\delta}P_{e\delta}f_\delta}\right]^2 \tag{7}$$

$$\tan\delta_1 = \frac{\sqrt{f_1/f_\delta}}{Q_{u1}Q_{u\delta}}\cdot\frac{G_1 Q_{u\delta}\sqrt{f_\delta} - G_\delta Q_{u1}\sqrt{f_1}}{G_1 P_{e1}\sqrt{f_1} - G_\delta P_{e\delta}\sqrt{f_\delta}}. \tag{8}$$

Analytic expressions of P_{e1} and G_1 are obtained as follows:

$$P_{e1} = 1/A \tag{9}$$

$$G_1 = B/A \tag{10}$$

$$A = 1 + \frac{W}{\varepsilon'} \tag{11}$$

$$B = \ell^2\left(\frac{\lambda_0}{2H}\right)^3 \frac{1+W}{30\pi^2\varepsilon'}, \qquad \ell = 1, 2, \ldots \tag{12}$$

where

$$\lambda_0 = c/f_0 \tag{13}$$

$$W = \frac{J_1^2(u)}{K_1^2(v)}\,\frac{K_0(v)K_2(v) - K_1^2(v)}{J_1^2(u) - J_0(u)J_2(u)} \tag{14}$$

$$v^2 = \left(\frac{\pi D}{\lambda_0}\right)^2\left[\left(\frac{\ell\lambda_0}{2H}\right)^2 - 1\right] \tag{15}$$

$$u\,\frac{J_0(u)}{J_1(u)} = -v\,\frac{K_0(v)}{K_1(v)}. \tag{16}$$

Here, A and B are given by Hakki and Coleman [12] for determination of $\tan\delta$ using the $\mathrm{TE}_{0m\ell}$-mode dielectric rod resonator. c is the velocity of light in the vacuum. J and K are the first- and second-kind modified Bessel functions. For any value of v, the mth solution u exists between u_{0m} and u_{1m} in (16), where $J_0(u_{0m}) = 0$ and $J_1(u_{1m}) = 0$. In this study, the values of P_{e1} and G_1 are calculated by setting $\ell = 1$ in (12) and (15) since these parameters correspond to the TE_{0m1} mode.

On the other hand, calculations of $P_{e\delta}$ and G_δ require numerical analyses. We obtained the values of $P_{e\delta}$ and G_δ by axis symmetric finite-element method (FEM) calculations. In this calculation, we set the $\mathrm{TE}_{0m\delta}$-mode resonator in a conducting cylindrical wall of diameter approximately ten times that of the dielectric rod.

Since the electronic and magnetic fields of the $\mathrm{TE}_{02\delta}$-mode resonator concentrate near the surface of the lower conductor, the greater part of the conductor loss of the $\mathrm{TE}_{02\delta}$-mode resonator is due to the lower conductor. Therefore, our measurement method gives estimation making much of σ of the lower conductor. It is desirable that the upper and lower conductors are made of the same material with the same surface roughness and, thus, those have same value of σ. However, when there is some

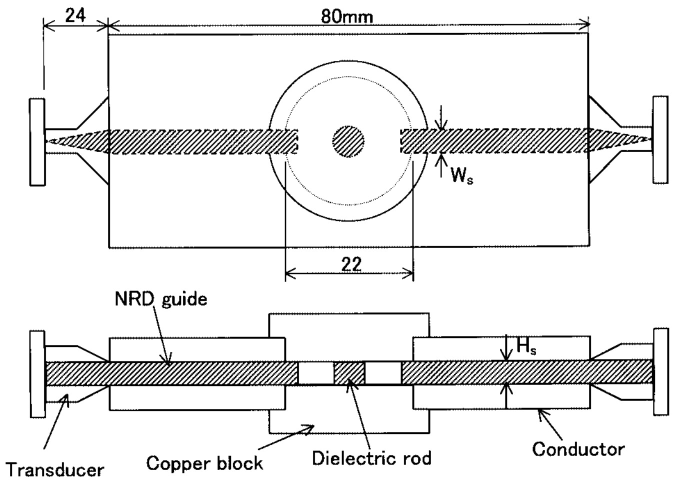

Fig. 2. Structure of measuring apparatus for complex permittivity ε_r and effective conductivity σ.

doubt that the upper and lower conductors have same value of σ, we can obtain an average value of σ of two conductors by exchanging the upper and lower conductors using our method.

B. Complex Permittivity

The TE_{0m1}-mode dielectric resonator, as shown in Fig. 1-(1), is used for the measurement of the complex permittivity of the dielectric rod made of test material [12], [13]. The value of ε' is obtained from a measured f_0 of the TE_{0m1} resonator by

$$\varepsilon' = \left(\frac{\lambda_0}{\pi D}\right)^2 (u^2 + v^2) + 1. \tag{17}$$

The value of $\tan\delta$ is obtained from a measured Q_u of the resonator by

$$\tan\delta = \frac{A}{Q_u} - BR_s \tag{18}$$

using R_s calculated by (6) from σ determined by (7).

III. Measurement System and Procedure

The TE_{0m1}-mode dielectric rod resonators, for measuring ε_r or σ, were coupled equally to the input and output NRD-guide, using an apparatus shown in Fig. 2. Dielectric strips of the NRD-guide were made of Rexolite-1422 (cross-linked styrene copolymer) of $\varepsilon' = 2.5$ and $\tan\delta = 6.6 \times 10^{-4}$ at 10 GHz. Height (H_s) and width (W_s) of the dielectric strips are 2.25 and 2.00 mm for 60-GHz measurements, and 1.80 and 1.60 mm for 77-GHz measurements. The rod sample was placed between two parallel copper blocks with facing ends of 22-mm diameter. The apparatus has transducers from the NRD-guide to waveguide at both sides. The end of dielectric strip of the NRD-guide is sharpened in the transducer. The apparatus is connected to a sweeper and a scalar network analyzer by the V-band or W-band waveguides, as shown in Fig. 3.

The height H of the dielectric rod for the ε_r measurement was fixed to 2.25 and 1.80 mm for 60- and 77-GHz measurements, respectively, which was the same as the height of the NRD-guide. The diameter D of the rod was designed using a rough

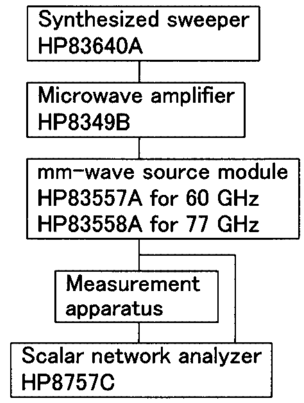

Fig. 3. Measurement system.

value of ε' so that f_0 of the TE_{0m1} mode is nearly equal to 60 or 77 GHz.

f_0, the half-power bandwidth $f_H - f_L$, and insertion loss IL_0 at f_0 were measured using a scalar network analyzer by means of the swept-frequency method. Q_u is obtained by

$$Q_u = \frac{f_o}{f_H - f_L} \Big/ \left(1 - 10^{-IL_0/20}\right). \tag{19}$$

The space between the dielectric rod and NRD-guide was adjusted so that IL_0 is 20–25 dB in 60-GHz measurement and 10–15 dB in 77-GHz measurement. The reason for use of the relatively small value of IL_0 for the 77-GHz measurement was that the dynamic range of our measuring system was limited to approximately 30 dB in the W-band.

IV. Results and Discussion

A. Characteristics of Measurement Apparatus

Transmission loss of the apparatuses for 60- and 77-GHz measurements were evaluated by connecting the input and output NRD-guide with a rexolite strip of 14-mm length. Direct coupling of the apparatuses were also evaluated by removing the rexolite strip. The transmission loss was approximately 3 dB in each apparatus, as shown in Figs. 4 and 5. The transmission loss was used as the reference level in the measurements of the resonant frequency and unloaded Q-factor of the dielectric resonator. The direct coupling appeared above 64 GHz in the evaluation of the 60-GHz measurement apparatus and above 80 GHz in that of the 77-GHz apparatus, as shown in Figs. 4 and 5. This is because the half-wavelength of free space, above these frequencies, becomes smaller than the space of the upper and lower conductor in each of the apparatuses. Here, values of space between the upper and lower conductors in the measurement apparatus were measured to be 2.310±0.001 and 1.848±0.001 mm for 60- and 77-GHz apparatuses, respectively.

B. Design of $\mathrm{TE}_{02\delta}$-Mode Resonator

The present method determines the effective conductivity σ of the conducting plate using a difference between the unloaded Q factor of the TE_{0m1}- and $\mathrm{TE}_{0m\delta}$-mode resonators. The dielectric rod for the TE_{0m1}-mode resonator can be easily designed by (17). The design of the dielectric rod for the

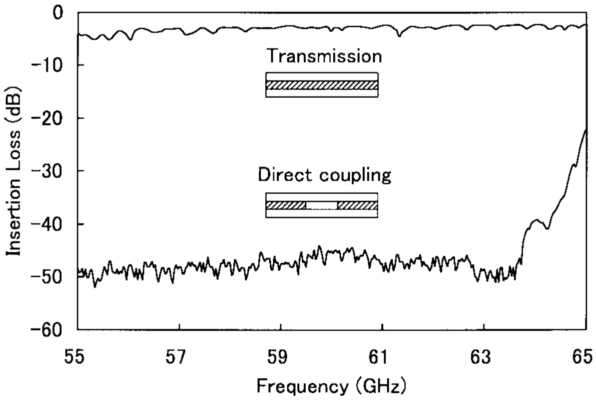

Fig. 4. Transmission and direct coupling characterization of the apparatus for 60-GHz measurements.

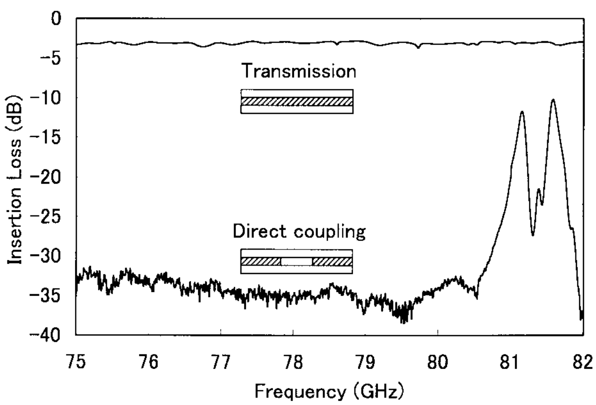

Fig. 5. Transmission and direct coupling characterization of the apparatus for 77-GHz measurements.

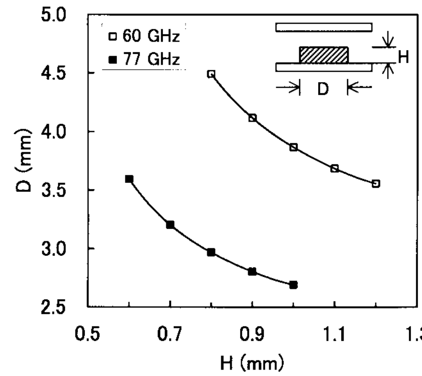

Fig. 6. Relations between diameter D and height H of a sapphire rod with $\varepsilon' = 9.4$ perpendicular to the c-axis for $\mathrm{TE}_{02\delta}$-mode resonators at 60 and 77 GHz. The spaces between two conductors in the resonators are 2.25 and 1.80 mm, respectively.

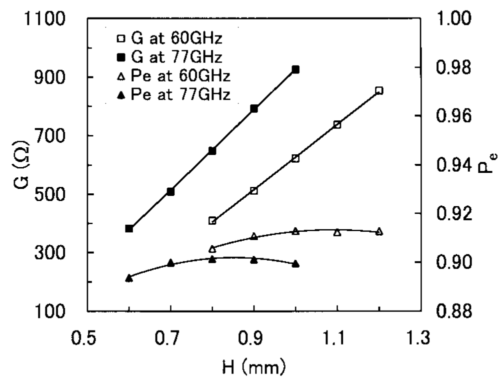

Fig. 7. Geometric factor G and partial electric energy filling factor P_e of $\mathrm{TE}_{02\delta}$-mode resonators at 60 and 77 GHz as a function of height H of a sapphire rod.

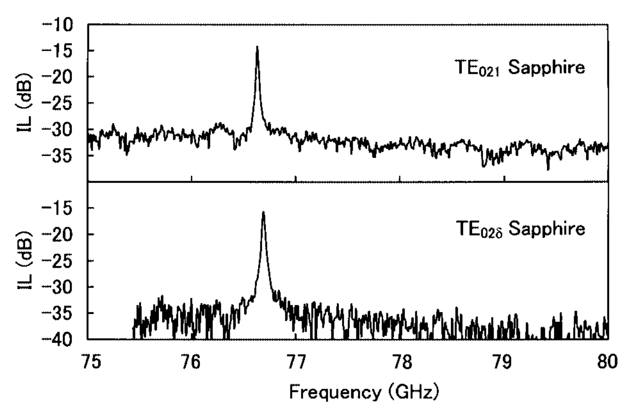

Fig. 8. Resonance peaks of TE_{021}- and $\mathrm{TE}_{02\delta}$-mode sapphire resonator.

$\mathrm{TE}_{0m\delta}$-mode resonator, however, requires numerical analysis. We calculated dimensions of the sapphire rods, geometric factor G, and partial electric energy filling factor P_e of the $\mathrm{TE}_{02\delta}$-mode resonator. Fig. 6 shows relations between diameter D and height H of sapphire rods with $\varepsilon' = 9.4$ perpendicular to the c-axis for $\mathrm{TE}_{02\delta}$-mode resonators for 60- and 77-GHz measurements. The spaces between two conducting plates in the resonators are fixed to 2.25 and 1.80 mm, respectively. Fig. 7 shows the G and P_e of the $\mathrm{TE}_{02\delta}$-mode resonators as a function of height H of the sapphire rod. Fig. 7 shows that G increases with increasing H. This is due to a fact that the field concentrates near the surface of the lower conductor when the rod is flat. On the other hand, P_e is not strongly dependent on H. The tendency of G against H in Fig. 7 supports the principle of our method, which determines the effective conductivity σ of the conducting plate using a difference between the unloaded Q factor of the TE_{0m1}- and $\mathrm{TE}_{0m\delta}$-mode resonators.

C. Effective Conductivity

The values of relative effective conductivity σ_r ($\sigma_r = \sigma/\sigma_0$, $\sigma_0 = 5.8 \times 10^7$ S/m) of mirrored ends of the copper blocks were measured at 59 and 77 GHz using the TE_{021}- and $\mathrm{TE}_{02\delta}$-mode resonators of sapphire. Resonant peaks for 77-GHz measurements are shown in Fig. 8. The measurement results are listed in Table I. The differences of the measured value of Q_u in the two resonators are sufficiently large for σ_r determination. The measured values of σ_r were 87±3% and 88±5% at 59 and 77 GHz, respectively. These values of σ_r are consistent with those measured to be 90%–100% at approximately 10 GHz in a round-robin test on the dielectric-resonator method [14].

Measurement errors of σ_r were estimated by

$$\Delta\sigma_r^2 = \Delta\sigma_{Q1}^2 + \Delta\sigma_{Q\delta}^2 \tag{20}$$

where $\Delta\sigma_{Q1}$ and $\Delta\sigma_{Q\delta}$ are errors of σ_r by the standard deviation of Q_{u1} and $Q_{u\delta}$.

TABLE I
EFFECTIVE CONDUCTIVITY σ MEASUREMENTS USING TE_{021}- AND $\mathrm{TE}_{02\delta}$-MODE SAPPHIRE RESONATORS. DIAMETER D, HEIGHT H OF DIELECTRIC ROD, RESONANT FREQUENCY f_0, UNLOADED Q FACTOR Q_u, PARTIAL ELECTRIC ENERGY FILLING FACTOR P_e, GEOMETRIC FACTOR G, RELATIVE PERMITTIVITY ε', AND $\tan\delta$ PERPENDICULAR TO THE c-AXIS OF THE SAPPHIRE CRYSTAL AND RELATIVE EFFECTIVE CONDUCTIVITY σ_r ($\sigma_r = \sigma/\sigma_0$, $\sigma_0 = 5.8 \times 10^7$ S/m) ARE LISTED

Resonator (Mode)	D (mm)	H (mm)	f_0 (GHz)	Q_u	P_e	G (Ω)	ε'(⊥c)	tanδ(⊥c) (10^{-4})	σ_r (%)
Sapphire (TE_{021})	3.205 ±.001	2.256 ±.001	58.686 ±.002	8797 ±42	0.913	1101	9.386 ±.005	0.57 ±.01	87 ±3
Sapphire ($\mathrm{TE}_{02\delta}$)	4.685 ±.001	0.810 ±.001	58.354 ±.002	4511 ±32	0.905	397	9.376 ±.007		
Sapphire (TE_{021})	2.420 ±.001	1.805 ±.001	76.594 ±.002	7439 ±47	0.888	1209	9.418 ±.008	0.80 ±.02	88 ±5
Sapphire ($\mathrm{TE}_{02\delta}$)	3.401 ±.001	0.645 ±.001	76.689 ±.026	4031 ±45	0.883	433	9.424 ±.013		

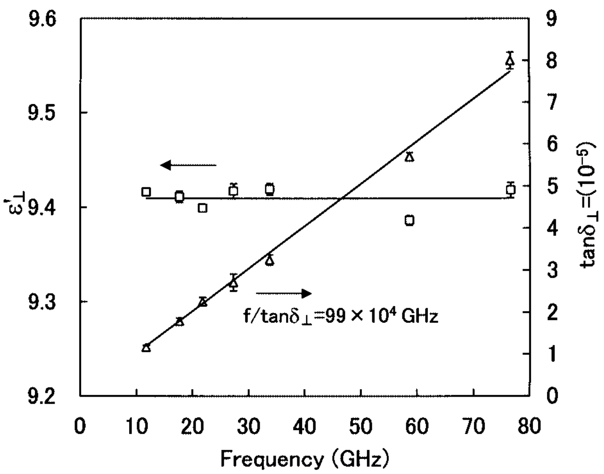

Fig. 9. Frequency dependence of ε' and $\tan\delta$ of sapphire perpendicular to c-axis.

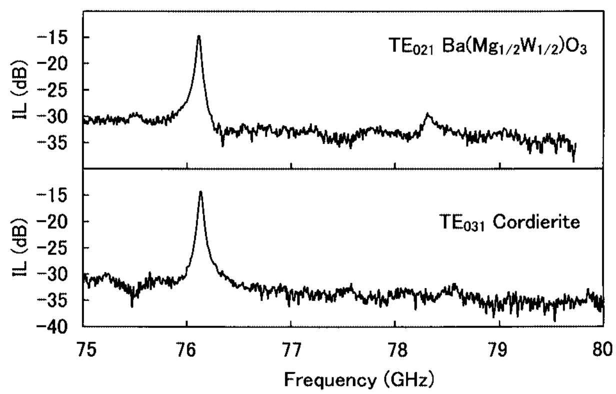

Fig. 10. Resonance peaks of $\mathrm{Ba(Mg_{1/2}W_{1/2})O_3}$ and cordierite resonators.

D. Complex Permittivity

The relative permittivity ε' and dielectric loss $\tan\delta$ perpendicular to the c-axis of sapphire, measured at 59 and 77 GHz with σ_r, are also listed in Table I. These values of $\tan\delta$ were calculated by (8). Frequency dependence of ε' and $\tan\delta$ of sapphire in the frequency range from 10 to 77 GHz are shown in Fig. 9. The values measured in the range of 10–30 GHz using the dielectric resonator exited by a loop antenna are described in [15]. Fig. 9 shows that ε' has a constant value of 9.4 in the whole range of frequency. The value of $\tan\delta$ increase with increasing frequency and its dependence can be expressed by approximately $f_0/\tan\delta = 100 \times 10^4$ GHz. These results have a good agreement with the data measured at approximately 10 GHz [14].

The complex permittivity of two polycrystalline ceramics $\mathrm{Ba(Mg_{1/2}W_{1/2})O_3}$ [16] and cordierite ($\mathrm{Mg_2Al_4Si_5O_{18}}$) [17], [18] were measured at 59 and 76 GHz using TE_{0m1}-mode ($m = 2$ or 3) resonator. In this case, the values of $\tan\delta$ were calculated by (18). The resonant peaks of 76-GHz measurements are shown in Fig. 10. The measurement results are listed in Table II with those at around 20 GHz obtained by the dielectric resonator excited by a loop antenna. The measured values of ε' and $\tan\delta$ of the two materials are plotted as a function of frequency in Figs. 11 and 12. For both materials, ε' has a constant value independent on frequency and $\tan\delta$ increases with increasing frequency. For the $\mathrm{Ba(Mg_{1/2}W_{1/2})O_3}$ ceramic, $f_0/\tan\delta = 20 \times 10^4$ GHz was found.

The total error of ε' was evaluated by

$$\Delta\varepsilon'^2 = \Delta\varepsilon_D'^2 + \Delta\varepsilon_H'^2 + \Delta\varepsilon_f'^2 \tag{21}$$

where $\Delta\varepsilon'_D$, $\Delta\varepsilon'_H$, and $\Delta\varepsilon'_f$ were errors of ε' by the standard deviations of the diameter D and height H of the sample and resonant frequency f_0. When the space H_c between two conductors of measurement apparatus is more than the height H of the sample, $\Delta\varepsilon'_H$ should be calculated from the standard deviation of the space H_c. For all samples in Tables I and II, the space H_c is more than the height H of the sample. The relative error $\Delta\varepsilon'/\varepsilon'$ of relative permittivity was less than 0.1%, as shown in Tables I and II. The error of ε' was mainly dependent on the dimensional uncertainties of D and H_c.

In advance of measuring $\tan\delta$ of test material using the TE_{0m1}-mode resonator, the effective conductivity σ of the conductors for short circuiting the TE_{0m1}-mode resonator must be determined. For this purpose, we designed the TE_{0m1}- and $\mathrm{TE}_{0m\delta}$-mode resonators of sapphire and determined σ using measured unloaded Q factors (Q_{u1} and $Q_{u\delta}$) of the two resonators by (7). In this case, $\tan\delta$ of sapphire can be simultaneously determined from Q_{u1} and $Q_{u\delta}$ by (8) and the total error of $\tan\delta$ was evaluated by

$$\Delta\tan\delta^2 = \Delta\tan\delta_{Q1}^2 + \Delta\tan\delta_{Q\delta}^2 \tag{22}$$

TABLE II
COMPLEX PERMITTIVITY MEASUREMENTS OF $Ba(Mg_{1/2}W_{1/2})O_3$ AND CORDIERITE ($Mg_2Al_4Si_5O_{18}$) CERAMICS

Sample (Mode)	D (mm)	H (mm)	f_0 (GHz)	Q_u	ε'	tanδ (10^{-4})	σ_r (%)
$Ba(Mg_{1/2}W_{1/2})O_3$ (TE_{011})	3.124 ±.001	2.254 ±.001	23.879 ±.001	3242 ±30	21.38 ±.01	1.30 ±.04	92 ±2
(TE_{021})	1.993 ±.001	2.252 ±.001	59.334 ±.001	3300 ±43	21.45 ±.02	2.89 ±.04	87 ±3
(TE_{021})	1.548 ±.001	1.799 ±.001	76.110 ±.006	2542 ±2	21.44 ±.03	3.85 ±.01	88 ±5
$Mg_2Al_4Si_5O_{18}$ (TE_{011})	10.32 ±.002	5.037 ±.002	18.320 ±.010	2845 ±37	4.893 ±.006	2.36 ±.05	92 ±2
(TE_{021})	4.805 ±.001	2.249 ±.001	58.945 ±.004	2632 ±15	4.896 ±.002	3.27 ±.03	87 ±3
(TE_{031})	5.700 ±.001	1.802 ±.001	76.135 ±.004	2504 ±11	4.880 ±.002	3.45 ±.04	88 ±5

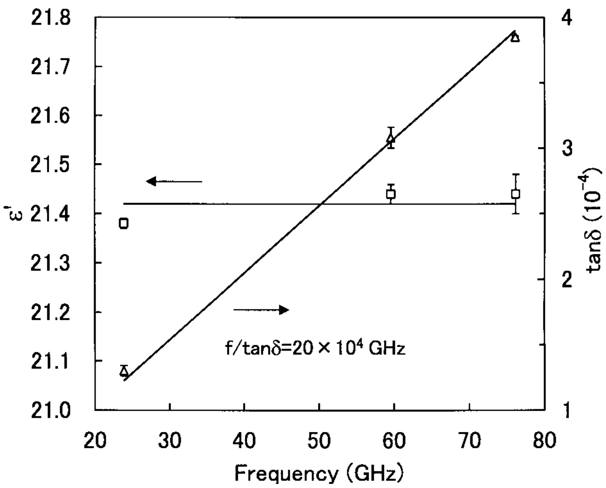

Fig. 11. Frequency dependence of ε' and $\tan\delta$ of $Ba(Mg_{1/2}W_{1/2})O_3$.

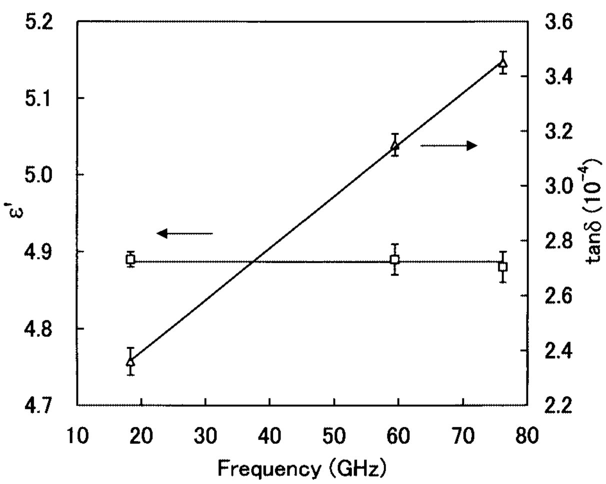

Fig. 12. Frequency dependence of ε' and $\tan\delta$ of cordierite.

where $\Delta\tan\delta_{Q1}$ and $\Delta\tan\delta_{Q\delta}$ were errors of $\tan\delta$ by the standard deviations of Q_{u1} and $Q_{u\delta}$.

Once σ is determined by (7), we can calculate $\tan\delta$ of unknown test material from only Q_u of the TE_{0m1}-mode resonator made of test material by (18). In this case, the total error of $\tan\delta$ was evaluated by

$$\Delta\tan\delta^2 = \Delta\tan\delta_\sigma^2 + \Delta\tan\delta_Q^2 \tag{23}$$

where $\Delta\tan\delta_\sigma$ and $\Delta\tan\delta_Q$ were errors of $\tan\delta$ by the standard deviations of σ of the copper blocks and Q_u of the TE_{0m1}-mode resonators, respectively. The $\tan\delta$ error was less than 5 × 10^{-6}, as shown in Table II. The $\tan\delta$ error is dependent on both of the measurement errors of σ and Q_u.

In the $\tan\delta$ determination by (18), three errors of Q_{u1}, $Q_{u\delta}$, and Q_u are origins of error of $\tan\delta$ since the error of σ comes from errors of Q_{u1} and $Q_{u\delta}$ by (20). Therefore, the determination of $\tan\delta$ by (8) has an advantage, as compared with that of (18) from a viewpoint of accuracy of measurements. However, it is actually very troublesome to make the TE_{0m1}- and $TE_{0m\delta}$-mode resonator from each test material for determination of $\tan\delta$ by (8). Therefore, the $\tan\delta$ determination by (18) is convenient for unknown test material.

E. Accuracy of FEM

The axis symmetric FEM was used for calculating the partial electric energy filling factor $P_{e\delta}$ and geometric factor G_δ of the $TE_{02\delta}$-mode resonator for the effective conductivity σ determination. We estimated the accuracy of the FEM calculations by comparing them with the exact calculations for the TE_{021}-mode resonator. Table III shows a comparison of the calculated resonant frequency f_1, P_{e1}, and G_1 for the TE_{021} resonator by an axis-symmetric FEM, with those by the exact equations [12]. The agreement between results by the FEM and those by the exact equations is very good. In this FEM calculation, we set the TE_{021} resonator at the center of a conducting cylindrical wall of diameter approximately ten times that of the dielectric rod.

F. Air-Gap Effect

The space H_c between the upper and lower conductors of the measurement apparatus and height H of the dielectric rod sample were designed to be the same value. However, an air gap of approximately 0.05 mm was generated between the upper

TABLE III
COMPARISON OF CALCULATED PARAMETERS, RESONANT FREQUENCY f_0, PARTIAL ELECTRIC ENERGY FILLING FACTOR P_e, AND GEOMETRIC FACTOR G BY THE FEM WITH THOSE BY EXACT EQUATIONS [12], FOR THE TE_{021}-MODE DIELECTRIC RESONATOR WITH $\varepsilon'_{\mathrm{rod}} = 10.00$, $D = 2.339$ mm AND $H = 1.800$ mm

Parameter	FEM	Exact Eq.	Difference
f_0 (GHz)	77.025	77.009	0.02%
p_e	0.9045	0.9046	-0.01%
G (Ω)	1260	1259	0.08%

conductor and dielectric rod. This was mainly caused by a deviation of dimension of the measurement apparatus from the designed values. It is known that a small air gap of the upper conductor and the dielectric rod does not affect the microwave measurements of relative permittivity ε' using the $\mathrm{TE}_{0m\ell}$-mode resonator, when the space H_c between two conductors is used as an effective height of the dielectric rod [13]. This is due to a fact that the electric field does not exist on the surface of the conductors in the TE-mode resonator. We also used H_c as the effective height of the dielectric rod for calculation of ε' and $\tan\delta$ in this study, ignoring the air gap. The H_c values were measured to be 2.310±0.001 and 1.848±0.001 mm for 60- and 77-GHz apparatuses, respectively. The air-gap effect on our millimeter-wave measurements is evaluated in this section via an extension of Kobayashi *et al.* [13].

We used the TE_{021}-mode dielectric rod resonators of $f_0 = 77.00$ GHz and $H = 1.800$ mm with $\varepsilon' = 5.000$, 10.000, and 20.000 as model resonators to estimate the air-gap effect. First, resonant frequency variation Δf_0 was calculated by the axis symmetric FEM when the air gap ΔH was generated by shortening H by ΔH and fixing H_c. Next, $\varepsilon'(\Delta H)$ was calculated by (17) using $f_0 = 77$ GHz $+ \Delta f_0$ and the effective rod height H_c. In a similar way, $Q_u(\Delta H)$ values were calculated for the same dielectric rods with $\tan\delta = 1 \times 10^{-5}$, 1×10^{-4}, 1×10^{-3} by (2) using the FEM in a condition that the relative effective conductivity σ_r of the conducting plate was 100%. The value of $\tan\delta(\Delta H)$ was determined by (18) using the calculated Q_u values and the effective rod heights H_c.

Fig. 13 shows the calculations of $\Delta\varepsilon'(\Delta H) = \varepsilon' - \varepsilon'(\Delta H)$ and $\Delta\tan\delta(\Delta H) = \tan\delta - \tan\delta(\Delta H)$ against the air gap ΔH. Values of the induced permittivity error $\Delta\varepsilon'(\Delta H)$ for $\varepsilon' = 5$, 10 and 20 by ignoring the air gap of 0.05 mm are 0.0005, 0.0012, and 0.0025. These values of $\Delta\varepsilon'(\Delta H)$ correspond to $\Delta\varepsilon'(\Delta H)/\varepsilon'$ of approximately 0.01%, which is negligibly small compared with errors by measurements. On the other hand, $\Delta\tan\delta(\Delta H)$ for ε' from 5 to 20 by ignoring the air gap of 0.05 mm is approximately 1×10^{-6}, which does not depend on the values of $\tan\delta$ in the case of $\tan\delta < 1 \times 10^{-3}$. This value of $\Delta\tan\delta(\Delta H)$ is also negligibly small compared with the measurement errors.

It is obvious that the gap effect in 60-GHz measurements is smaller than the results in Fig. 13 since dielectric rod for 60-GHz measurement is larger than that for 77-GHz measurement. In conclusion, the air gap of approximately 0.05 mm is negligible in our dielectric measurements at millimeter-wave frequencies and room temperature. The air gap, however, should be limited to a smaller value in the low-temperature measurements for very low-loss materials such as the sapphire crystal.

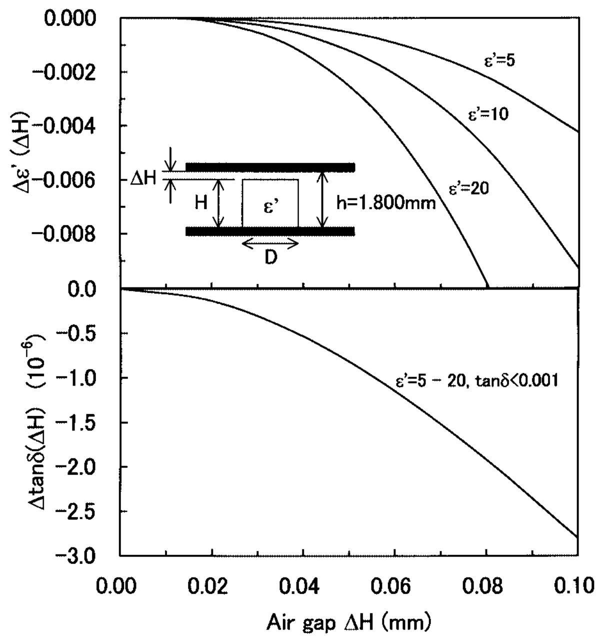

Fig. 13. Air-gap effects on ε' and $\tan\delta$ measurements by the TE_{021}-mode dielectric rod resonator of $f_0 = 77$ GHz and $H = 1.800$ with $\varepsilon' = 5$ ($D = 3.591$ mm), 10 ($D = 2.339$ mm), and 20 ($D = 1.592$ mm).

V. CONCLUSIONS

A new method for measuring the complex permittivity ε_r at millimeter-wave frequencies has been developed using the dielectric rod resonator excited by the NRD-guide. Values of ε_r of sapphire crystal sapphire, polycrystalline $Ba(Mg_{1/2}W_{1/2})O_3$ and $Mg_2Al_4Si_5O_{18}$ (cordierite) have been successfully measured at approximately 60 and 77 GHz by the new method. The results have been consistent with the values measured at microwave frequencies. The measurement error $\Delta\varepsilon'/\varepsilon'$ of relative permittivity ε' was within 0.1%, and $\Delta\tan\delta$ of dielectric loss $\tan\delta$ was within 5×10^{-6}, respectively. The main features of the presented method are as follows.

1) The TE-mode dielectric resonators for the complex permittivity ε_r and effective conductivity σ measurements are easily excited at millimeter-wave frequencies by the use of an NRD-guide.
2) The value of σ is accurately measured using the TE_{0m1} and $\mathrm{TE}_{0m\delta}$-mode resonators made of sapphire.
3) The value of ε_r is stably measured and accurately calculated by the use of the TE_{0m1}-mode resonators.

The temperature-dependence measurements of the complex permittivity at millimeter-wave frequencies by the presented method will be the subject of a future study.

ACKNOWLEDGMENT

The authors thank Assoc. Prof. F. Kuroki, Kure National College of Technology, Kure, Japan, for advice regarding the structure of transducer of NRD-guide to waveguide. The authors also thank D. A. Sagala, Kyocera Corporation, Kyoto, Japan, T. Okamura, Kyocera Corporation, and N. Hiramatsu, Kyocera Corporation, for sample preparations.

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