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Permittivity measurements at millimeter wave frequencies using dielectric rod resonator excited by NRD-guide

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Abstract

A method of measuring the relative complex permittivity ($\varepsilon_r = \varepsilon' - j\varepsilon''$, $\tan\delta = \varepsilon''/\varepsilon'$) for low-loss dielectric materials at millimeter wave frequencies has been developed, using a dielectric rod resonator excited by the nonradiative dielectric waveguide (NRD-guide). Relative permittivity (ε') and loss factor ($\tan\delta$) of the rod specimen are determined by the resonant frequency (f_0) and unloaded Q-factor (Q_u) of a TE_{0m1} mode resonator. The effective conductivity (σ) of conducting plates for short-circuiting the rod resonator is determined using TE_{021} and $TE_{02\delta}$ mode sapphire resonators. Temperature dependence of ε' and $\tan\delta$ of sapphire and cordierite ceramics were evaluated at 60 GHz. This method has been adopted as the Japanese Industrial Standard (JIS R 1660-3) and is being prepared for the IEC international standard. Several standardized specifications are presented.

Keywords: Dielectric properties; Electrical conductivity; Al_2O_3; Substrates; Millimeter wave measurements

1. Introduction

We need a reliable method for measuring ε_r of the dielectric materials for designing devices used in millimeter wave communication or sensing systems. Several methods[1–4] have been developed for measuring ε_r of the low-loss dielectric materials at the millimeter wave frequencies. Among these methods, a dielectric rod resonator method exited by the NRD-guide[5] has an advantage in that excitation of resonance is very easy. The reason is that a dominant LSM mode of the NRD-guide can be easily coupled to the TE mode of the dielectric resonator.

We have developed a simple and accurate method for measuring ε_r at millimeter wave frequencies based on the dielectric rod resonator excited by NRD-guide.[6] The values of ε' and $\tan\delta$ are determined using the TE_{0m1} ($m = 1, 2, 3$) mode resonator. The TE_{0m1} mode resonator allows us to achieve stable measurements, and accurate and simple calculations for ε' and $\tan\delta$ by analytic expression. The effective conductivity σ of the conducting plates is determined using TE_{021} and $TE_{02\delta}$ mode sapphire resonators.

2. Theory and measurement formulas

2.1. Relative permittivity ε' and loss factor $\tan\delta$

The values of ε' and $\tan\delta$ of the rod specimen are determined using the TE_{0m1} mode resonator, as shown in Fig. 1a for $m = 2$. A dielectric rod with diameter (d) and height (h) is short-circuited at both ends by two parallel conducting plates.

The values of ε' is calculated from the measured f_0, d and the space (h_c) between the upper and lower conducting plates:

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

where

$$v^2 = \left(\frac{\pi d}{\lambda_0}\right)^2 \left[\left(\frac{\lambda_0}{2h_c}\right)^2 - 1\right] \tag{2}$$

Here, $\lambda_0 = c/f_0$ is the free space resonance wavelength and c is the velocity of light. A formula for u is given elsewhere.[6,7]

Next, $\tan\delta$ is calculated from the measured Q_u:

$$\tan\delta = \frac{A}{Q_u} - BR_s = \frac{A}{Q_u} - \frac{B'}{\sqrt{\sigma_r}} \tag{3}$$

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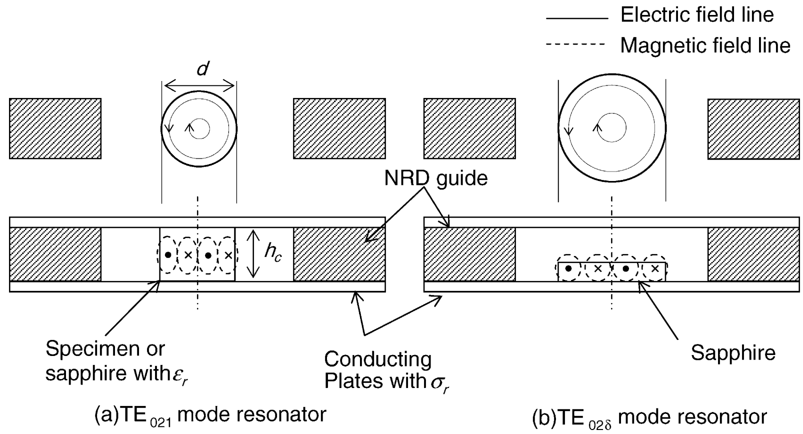

Fig. 1. Configuration of dielectric resonator for measuring ε_r and σ_r. Value of ε_r is measured using (a) and σ_r is measured using (a) and (b).

where

$$R_s(\Omega) = \sqrt{\frac{\pi f_0 \mu}{\sigma}} = \sqrt{\frac{\pi f_0 \mu}{\sigma_0 \sigma_r}} \tag{4}$$

Here, R_s and σ are the surface resistance and the effective conductivity of conducting plates, respectively. The relative conductivity is defined as $\sigma_r = \sigma/\sigma_0$ ($\sigma_0 = 5.8 \times 10^7$ S/m). Furthermore, μ is the permeability and $\mu = \mu_0 = 4\pi \times 10^{-7}$ for non-magnetic conducting plates. Formulas for A and B are given elsewhere.[6,7]

2.2. Determination of relative conductivity σ_r of conducting plates

The value of σ_r of the conducting plates must be accurately measured, to determine tan δ of low-loss dielectric specimen by (3). The TE_{021} and $TE_{02\delta}$ mode dielectric rod resonators in Fig. 1, called "standard resonators", are used for measuring σ_r. Each standard resonator is made of sapphire single crystals with the same ε_r. They are designed to have the same f_0.

The standard $TE_{02\delta}$ resonator has a large dimension ratio (*d/h*). The conductor loss of the $TE_{02\delta}$ resonator is larger than that of the TE_{021} standard resonator, since the electromagnetic field in the $TE_{02\delta}$ resonator is concentrated near the surface of the lower conductor. High accuracy measurement of σ_r is achieved by enlarging the difference in the conductor loss of the two resonators. While $f_{01} = f_{0\delta}$, Q_{u1} is higher than $Q_{u\delta}$, where subscripts 1 and δ denote each standard resonator.

The value of σ_r can be calculated from the measured f_0 ($=f_{01} = f_{0\delta}$), Q_{u1} and $Q_{u\delta}$:

$$\sigma_r = \frac{\sigma}{\sigma_0} = \pi\mu \quad f_0 \left[\frac{Q_{u1} Q_{u\delta}}{G_1 G_\delta} \frac{G_1 P_{e1} - G_\delta P_{e\delta}}{Q_{u1} P_{e1} - Q_{u\delta} P_{e\delta}} \right]^2 / \sigma_0 \tag{5}$$

where partial electric energy filling factors (P_{e1}) and ($P_{e\delta}$), and geometric factor (G_1) and (G_δ) of the resonators are defined elsewhere.[6] An example of their values is shown in Table 1.

Furthermore, tan δ of the standard resonators can be calculated:

$$\tan\delta_1 = \tan\delta_\delta = \frac{1}{Q_{u1} Q_{u\delta}} \times \frac{G_1 Q_{u\delta} - G_\delta Q_{u1}}{G_1 P_{e1} - G_\delta P_{e\delta}} \tag{6}$$

3. Preparation of dielectric specimen

Typical specifications of the standard rod resonators are described. Each rod consists of the sapphire with low tan δ. The axis of the each rod is parallel to the *C*-axis of sapphire. Table 1 shows d, h, h_c, P_e and G of the standard sapphire rods with $\varepsilon' = 9.40$ perpendicular to the *C*-axis, for measuring σ_r at 60 GHz. The factors P_{e1} and G_1 are related with A and B in (3) by $P_{e1} = 1/A$ and $G_1 = A/B$. In contrast, calculations for factors $P_{e\delta}$ and G_δ require numerical analyses. Table 1 shows values of $P_{e\delta}$ and G_δ obtained by axis symmetric FEM calculations.

The TE_{011}, TE_{021} and TE_{031} mode rod resonators are used to measure ε' and tan δ, for materials with $\varepsilon' = 2$–4, $\varepsilon' = 4$–20 and $\varepsilon' = 20$–30. Fig. 2 shows desirable values of diameter (d) of the rod specimen for 60 GHz measurement as a function of ε'.

4. Measurement apparatus

Two types of apparatus were used, as shown in Fig. 3. The dielectric rod resonator was coupled equally to the input and output NRD-guide. Space between the rod and the NRD-guide was adjusted so that insertion loss (IL_0) at f_0 was 20–25 dB. Dielectric strips of the NRD-guide with a width of 2.00 mm were made of Rexolite-1422 (cross-linked styrene copolymer) with $\varepsilon' = 2.5$,

Table 1
Dimensions, partial electric energy filling factor P_e and geometric factor G for standard sapphire rods for measuring σ_r at 60 GHz.

Space, h_c (mm)	TE_{021}				$TE_{02\delta}$			
	Diameter, d (mm)	Height, h (mm)	P_{e1}	G_1 (Ω)	d (mm)	h (mm)	$P_{e\delta}$	G_δ (Ω)
2.25	3.14	2.20–2.25	0.915	1182	4.49	0.80	0.906	409

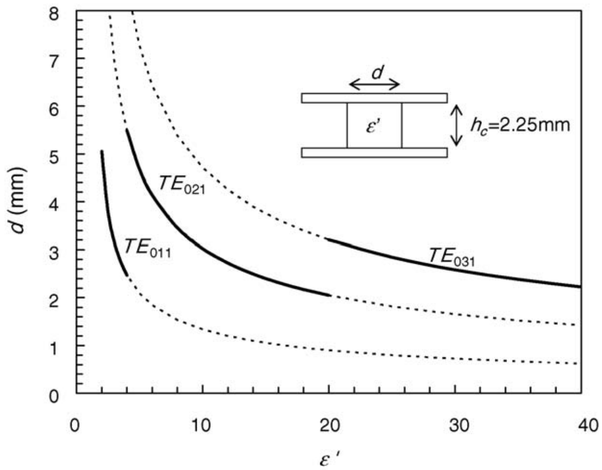

Fig. 2. Diameter d of dielectric specimen for measuring ε_r at 60 GHz, for height $h = 2.20$–2.25 mm and space $h_c = 2.25$ mm.

for 60 GHz measurements. The apparatus had transducers from the NRD-guide to the waveguide. The end of the dielectric strip was sharpened in the transducer.

A-type apparatus was used for measuring the temperature dependence of tan δ, since the $TE_{02\delta}$ standard resonator is easily constituted. The upper conducting plate was inset in the conductors of NRD-guide in the A-type apparatus. The apparatus had a small air gap (g) between the upper conducting plate and the dielectric specimen. The calculations of ε' by (1) and of tan δ by (3) are accurate for $g < 50$ μm. The error of $\Delta\varepsilon'/\varepsilon'$ for $g = 50$ μm is about 0.01% and is negligibe.[6] In contrast, B-type apparatus was used for measuring the temperature dependence of ε'. The upper conducting plate was put on the specimen in this apparatus.

The apparatus was connected to a scalar network analyzer HP-8757 system. The Q_u was calculated from f_0, the half-power band width $f_H - f_L$ and IL_0:

$$Q_u = \frac{f_0/(f_H - f_L)}{(1 - 10^{-IL_0/20})} \quad (7)$$

5. Results

The temperature (T) dependence of ε_r of sapphire and cordierite ceramics[8] was evaluated at 60 GHz by this method. First, f_0 was measured as a function of T using the B-type apparatus. Then ε' was calculated from the f_0. Fig. 4a shows ε' and f_0 of the TE_{021} standard sapphire rod ($d = 3.130 \pm 0.005$ mm, $h = 2.250 \pm 0.001$, $\alpha = 5.8$ ppm/°C). Here, α is the coefficient of thermal expansion. The values ε' of the sapphire increased linearly with increasing T. The first and second

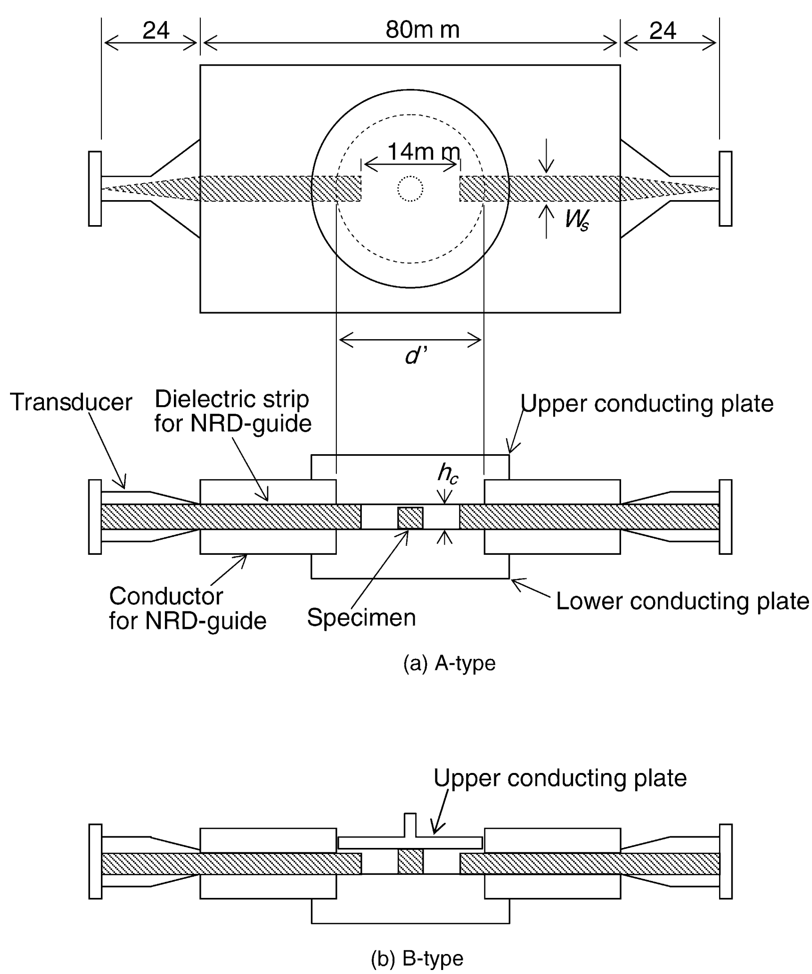

Fig. 3. Measurement apparatus.

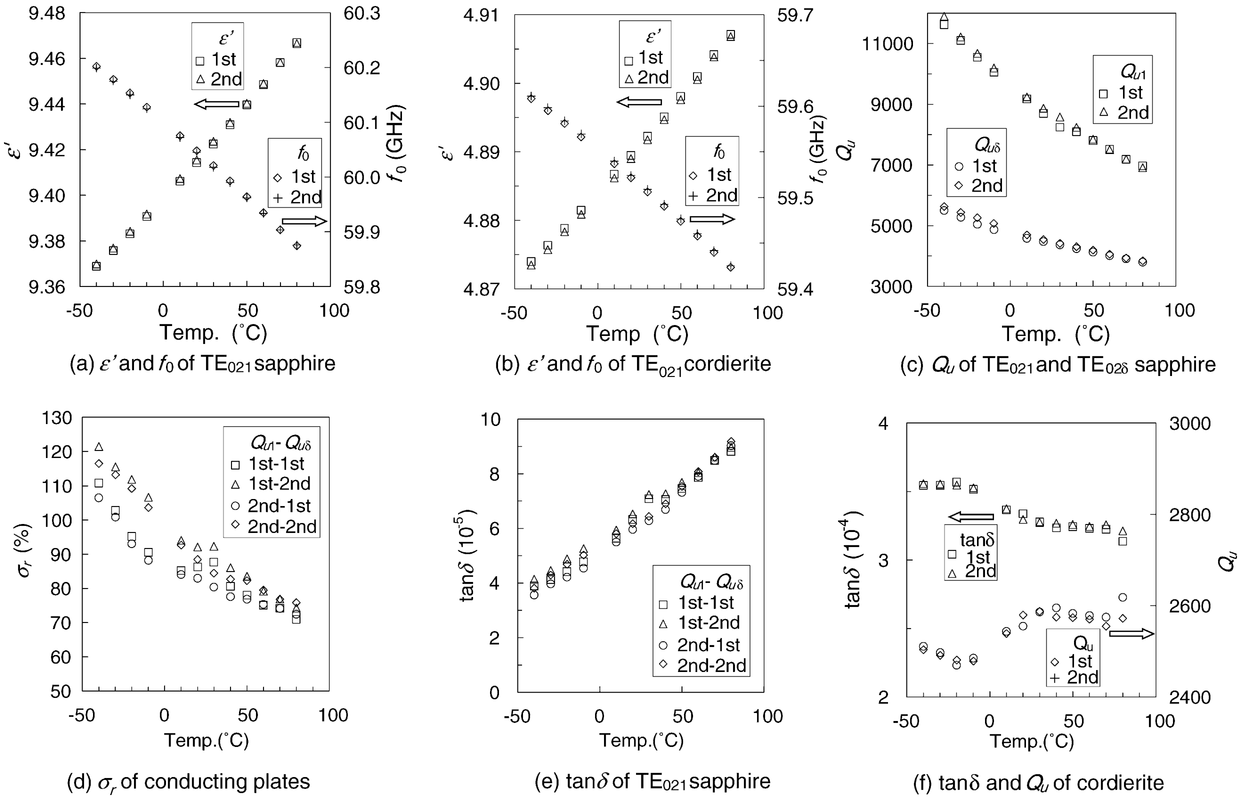

Fig. 4. Temperature dependence measurements of ε_r of sapphire crystals and cordierite ceramics, and of σ_r of conducting plates.

measurements were in agreement. The temperature coefficient of permittivity ($TC\varepsilon$) of the sapphire was calculated to be 86.4 ± 0.8 ppm/°C, which was in good agreement with a result reported elsewhere.[9] Fig. 4b shows measurements of cordierite ceramics rod ($d = 4.803$, $h = 2.253$, $\alpha = 0.5$). The values ε' of the cordierite rod also increased linearly with increasing T. The value $TC\varepsilon$ was calculated to be 56.9 ± 0.3 ppm/°C.

Next, to determine σ_r of the conducting plates of Cu and $\tan\delta$ of the standard sapphire, Q_{u1} and $Q_{u\delta}$ of standard sapphire resonators was measured twice against T as shown in Fig. 4c, using the A-type apparatus with $H_c = 2.279$ mm. Fig. 4d and 4e show σ_r of the conducting plates and $\tan\delta$ of the standard sapphire calculated by Q_{u1} and $Q_{u\delta}$. The value of σ_r decreased with increasing T. The value σ_r was 87.4% at 20 °C. The value $\tan\delta$ of the standard sapphire increased with increasing T. The value $f_0/\tan\delta = 1.04 \times 10^6$ GHz at 20 °C was in agreement with a result reported elsewhere.[6] Furthermore, Fig. 4f shows Q_u and $\tan\delta$ of cordierite ceramics. This variation of $\tan\delta$ with T was relatively small.

6. Conclusion

A method of measuring ε_r at millimeter wave frequencies has been developed, using a dielectric resonator excited by the NRD-guide. Typical specifications of the rod specimen for ε_r measurements and of the standard sapphire rods for measuring σ_r at 60 GHz were presented. The temperature dependence of ε_r of sapphire and cordierite ceramics was accurately evaluated at 60 GHz by this method. The repeated measurements showed the error of $TC\varepsilon$ was less than 1 ppm/°C.

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