

Wideband Millimeter-Wave Complex Permittivity Measurement Technology

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[Summary]

Circuit designs for wideband millimeter-wave signals must properly handle the dispersion properties of dielectric materials comprising the circuit, and technologies to easily and accurately measure the complex permittivity of these materials is urgently needed. Generally, resonance-based systems for measuring complex permittivity are very accurate, but can be cumbersome, are limited to resonance modes suitable for measurement, and require multiple resonators covering a wide bandwidth. This article introduces a complex permittivity measurement system based on the balanced circular disk resonator (BCDR) method facilitating wideband measurement covering 10 to 145 GHz without changing equipment. In addition, we discuss the impact of resonator shape inaccuracies on measurements accuracy.

1 Introduction

Use of the millimeter-wave (mmWave) band is being promoted to secure adequate bandwidth for mobile network communications suffering from limited available frequency resources, and the 300-GHz frequency range is a promising candidate. Circuit design for such high-frequency bands requires basic information on complex permittivity, specifically the relative permittivity (hereafter referred to simply as permittivity) and the dielectric loss tangent. On the other hand, the 60-GHz band is being used for the development of automobile millimeter-wave radar and the complex permittivity of resin materials is being measured to quantify reflection characteristics. High-precision complex permittivity measurements at high frequencies over wide bandwidths are required for various applications.

Figure 1 shows typical permittivity measurement methods. The capacitance method determines the permittivity by measuring the capacitance of a parallel-plate capacitor with the test dielectric material (MUT) sandwiched between electrodes^{1), 2)}. This method is used mainly for low-frequency bands because the resonance between parallel-plate electrodes at higher frequencies cannot be ignored. The transmission method calculates the permittivity by loading the test material on part of a transmission line, such as a waveguide, and measuring its scattering matrix (S-parameters)^{1) to 3)}. Although the transmission method can measure wideband permittivity, the accuracy depends on the transmission line dimensional precision, and gaps between the line and test material cannot be ignored. In particular, dimensional

accuracy requirements approach the limits of manufacturing precision in the millimeter-wave band at wavelengths less than a millimeter. The resonance method calculates the permittivity by loading the test dielectric into a resonator and measuring resonance frequency. The dielectric loss tangent can also be determined from the Q value of the resonance. The measurement frequency of the permittivity is limited to the resonance frequency. Therefore, measuring permittivity over a wide bandwidth requires either making sequential measurements using multiple resonators or using different resonant modes. The resonator requires high mechanical precision to measure the permittivity accurately, and the cavity resonator method is used to accurately evaluate the permittivity of dielectric substrates, etc., at limited frequencies⁴⁾.

However, the Balanced Circular Disk Resonator (BCDR) method can calculate the permittivity from resonant frequencies measured using a symmetrical resonator configured as a sandwich of two outer identical dielectric plates of the test material and an inner conductive circular disk positioned between sufficiently wide parallel conducting plates. As explained in section 2, this method is often used by selectively exciting and utilizing resonant modes where the electric field becomes maximum at the central axis of the disk. Although measurement is discrete, the permittivity can be measured over a wide frequency range by using resonant modes up to about the 10th order. Moreover, while many other methods measure the permittivity for electric fields parallel to the surface of plate-shaped dielectrics, the BCDR

method also measures the permittivity for electric fields perpendicular to the surface. The BCDR method was proposed by Kobayashi in the 1970s and is used widely to measure the permittivity of substrates used by the millimeter-wave band^{5) to 14)}. Recently, it is being used for higher frequency bands and permittivity measurements up to 170 GHz using waveguide coupling have also been conducted¹⁵⁾.

This paper introduces practical examples of permittivity measurements using the BCDR method. Section 2 covers the measurement principle and section 3 describes the constructed measurement system. Section 4 explains some measurement examples and section 5 considers the impact of resonator shape inaccuracies on measured values.

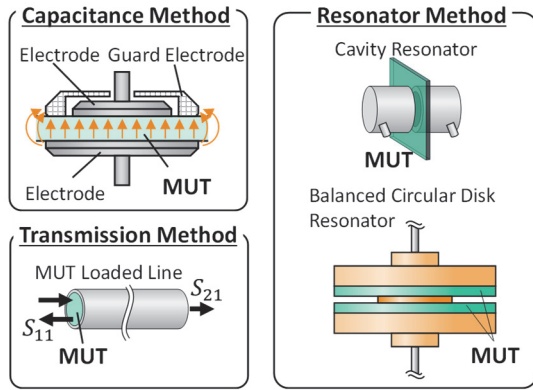


Figure 1 Typical permittivity measurement methods

2 Balanced Circular Disk Resonator Method

2.1 Resonator Structure and Resonance Mode

The (BCDR) method was described by Kobayashi *et al.* in 1974^{5), 6)}. Figure 2 shows the structure. The resonator is configured by layering a conducting flange, the test dielectric material (MUT: material under test), and conducting circular disk. It is excited from an excitation port that is fed by a coaxial line or from the side by a strip line (Figure 2(b)). The crosshatched region sandwiched between the conducting wall and conducting circular disk area (Figure 2(a)) can be considered as a cylindrical resonator. If the thickness of the resonator is limited to less than half the wavelength, the electric field becomes uniform in the thickness direction, and the resonance is limited to TM modes^{5), 13)}. TM modes are identified by the number of nodes in each direction, and are expressed as TM_{nm0} , with subscripts representing the circumferential direction, radial direction, and thickness direction (always 0 since there are no nodes), respectively. The TM_{nm0} resonance frequency is expressed as,

$$f_r = \frac{c}{\sqrt{\epsilon_r}} \frac{x_{nm}}{2\pi R} \quad (1)$$

where, c is the velocity of light in vacuum, ϵ_r is the permittivity, and R is the resonator radius. Also x_{nm} is the eigenvalue corresponding to TM_{nm0} and is determined by the resonators structural parameters and permittivity of the MUT. Therefore, the permittivity of the MUT at that frequency can be derived by substituting the resonator dimensions, resonance mode, and measured resonance frequency into Eq. (1). This requires identifying the resonance mode, which is achieved by selectively exciting only TM_{0m0} modes as described in the next section. Figure 3 shows a calculation example for resonance frequency versus permittivity, when conducting circular disk diameter = 12 mm, dielectric thickness = 0.2 mm, excitation port diameter = 0.9 mm, excitation port depth = 0.3 mm, and conducting disk thickness = 50 μm ¹⁵⁾. The multiple solid lines in the figure represent TM_{0m0} modes ($m = 1, 2, \dots$) from the left. For example, if the permittivity is 3 regardless of frequency, resonance occurs at multiple frequencies indicated by the dots.

As described above, the eigenvalue x_{nm} in Eq. (1) is calculated from the dimensions of each resonator part and the permittivity. The simplest model for the BCDR is the cylindrical region above or below the conducting disk, as shown by the crosshatched region in Figure 2(a), and the eigenvalue is expressed by the root of the derivative of the Bessel function. However, in reality, the electromagnetic field extends outside this cylindrical region and to the excitation port, so the eigenvalue differs from that of a simple cylinder. Since this eigenvalue cannot be obtained analytically, the mode analysis method described in section 2.3 has been reported^{5) to 10), 15)}.

Figure 4(a) shows an example calculation for the BCDR reflection and transmission spectrum using finite element analysis, and Figure 4(b) shows the electric field distribution of each resonant mode. Figure 4(a) shows the case when the excitation port is intentionally set at a position offset from the center of the conducting disk, and there are numerous TM_{nm0} modes other than $n = 0$. The TM_{0m0} modes among these are modes where the electric field becomes maximum at the center of the cylindrical resonator and can be excited by applying an electric field in the thickness direction at the center of the resonator. The circular waveguide described in the next section is used to perform this selective excitation^{11) to 14)}.

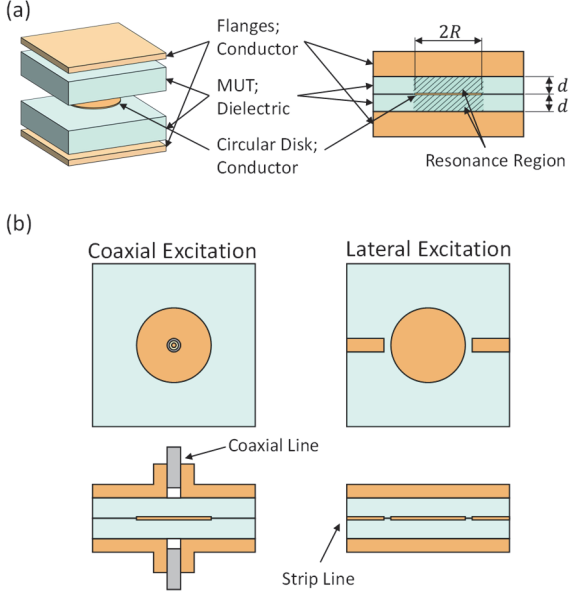


Figure 2 (a) Balanced circular disk resonator, (b) Two types of balanced circular disk resonators with different excitation structures

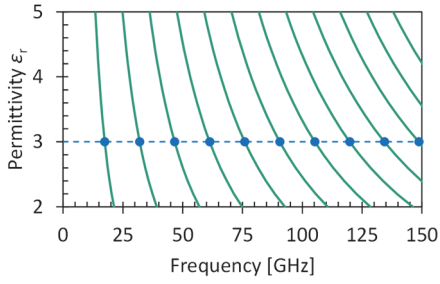


Figure 3 Relationship between resonance frequency and permittivity

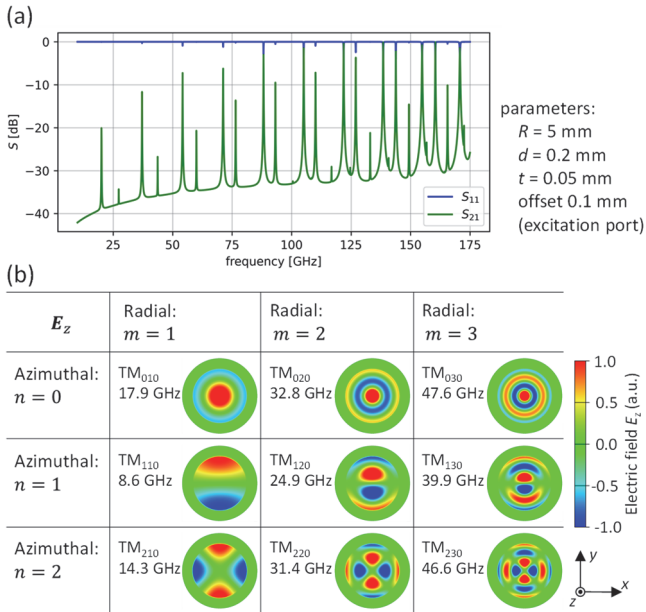


Figure 4 (a) Resonator transmission spectrum S_{21} and reflection spectrum S_{11} , (b) Electric field distribution in thickness direction of TM_{nm0} mode. Here, the thickness direction of the measurement target is defined as the z -axis.

2.2 Excitation Port Shape

An electric field must be applied in the thickness direction of the dielectric at the center of the conductive disk to selectively excite the TM_{0m0} mode. This is achieved by coupling with a thin circular waveguide with a cutoff frequency sufficiently higher than the measurement frequency band¹³⁾. Furthermore, the lateral excitation shown in Figure 2(b) makes it difficult to read the resonance because the Q value decreases compared to coaxial excitation¹⁴⁾. Figure 5(a) shows the coaxial excitation structure. The excitation port is a circular waveguide with a diameter of $2a$ such that the following relationship is satisfied:

$$f_{c, TM_{01}} = \frac{p_{01}c}{2\pi a} \gg f_{\max} \quad (2)$$

where, $f_{c, TM_{01}}$ is the cutoff frequency of the lowest order propagating mode TM_{01} , and $f_{\max}$ is the maximum value of the measurement frequency. Also, p_{01} is the first root of the zeroth-order Bessel function of the first kind, $J_0(x)$ such that $J_0(p_{01}) = 0$. Figure 5(b) shows the geometry of the excitation port and the electric field. A non-propagating field is generated in the cylindrical excitation port, and the BCDR TM_{0m0} mode is excited in this way.

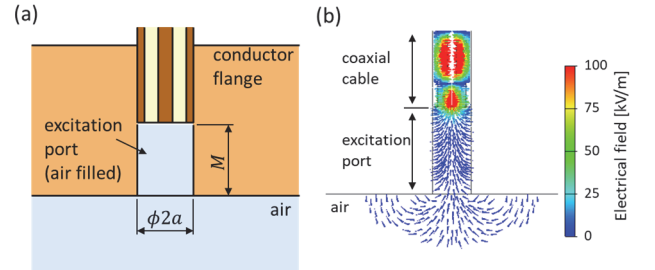


Figure 5 Excitation port and the electric field behavior (a) Port geometry, (b) Electric field

2.3 Relationship between Resonance Frequency and Permittivity

Figure 6(a) shows the BCDR structure. As described in section 2.1, the BCDR can be represented most simply by a cylindrical model like Figure 6(b), with the upper and lower surfaces being conductors and the outer circumferential surface being a magnetic wall. At this time, the eigenvalue in Eq. (1) becomes $x_{nm} = p'_{nm}$. Here, p'_{nm} denotes the m th root of the derivative of the Bessel function of the first-kind and order n , i.e., $J'_n(p'_{nm}) = 0$. However, in reality, the true eigenvalue differs from the simple cylindrical model due to the spread of the electromagnetic field beyond the outer circumferential surface and the spread of the electromagnetic field into the spatial

part of the excitation port. To incorporate these effects, we developed calculation methods for eigenvalues using the models shown in Figures 6(c), (d), and (e). Since these derivations are complex, we leave the details to original papers^{5), 6), 8), 9), 15)} and only briefly describe the general concept here.

As is widely known, the solution to the Helmholtz equation with symmetry around the central axis can be expanded into modes expressed as the product of a Bessel function in the radial direction, a trigonometric function in the circumferential direction, and a trigonometric function in the axial direction. Figure 6(c) is a model considering the spread of the electromagnetic field beyond the cylinder^{5), 6)}. Taking this as an example, in the cylindrical region within radius R (called region I), the upper and lower surfaces are electrical walls; in the outside region (called region II), the lower surface is an electrical wall, and the upper surface is a magnetic wall. These boundary conditions must be satisfied and the electromagnetic field that is continuous across regions I and II becomes the solution for the entire region. Following the general procedure of the mode matching method, for example, in the case of TM_{0m0} , if the electric field in the height (thickness) direction is represented as $\mathbf{E}_z$, then $\mathbf{E}_z$ expressed as a linear combination of modes in region I and $\mathbf{E}_z$ expressed as a linear combination of modes in region II are equated. Similarly, if the magnetic field in the circumferential direction is represented as $\mathbf{H}_\theta$, equations for this can also be obtained in the same way as for $\mathbf{E}_z$. These can be organized with the unknown coefficients of the linear combination (vector) $\mathbf{a}$ and coefficient matrix $\mathbf{M}$, which can be written in the form $\mathbf{M}\mathbf{a} = \mathbf{0}$. For the unknown coefficient vector $\mathbf{a}$ to have solutions other than zero vector $\mathbf{0}$,

$$\det \mathbf{M}(f_{ra}; \varepsilon_{ra}, R, d) = 0 \quad (3)$$

must be satisfied, where f_{ra} is the resonance frequency, R is the radius of the circular conduction disk, and d is the sample thickness. The permittivity ε_{ra} can be found numerically by determining f_{ra} through measurement and substituting R and d into Eq. (3).

Although even more complex, eigenvalues can also be determined using the mode matching method when using the models in Figures 6(d) and (e)^{8), 9), 15)}.

On the other hand, the dielectric loss tangent is calculated from the Q -value of the measured resonance. The unloaded Q -value Q_u , the Q -value of conductor loss Q_c , and the Q -value of dielectric loss Q_d have the following relationship

$$\frac{1}{Q_u} = \frac{1}{Q_c} + \frac{1}{Q_d} \quad (4)$$

The dielectric loss tangent $\tan \delta$ and Q_d have an inverse relationship (Eq. 5))

$$Q_d = \frac{1}{\tan \delta} \quad (5)$$

Conductor loss, Q_c can be calculated from the electromagnetic field distribution^{7), 15)}. Generally, the energy and conductor losses of the electromagnetic field in the spatial region outside the cylinder and in the excitation port are small compared to those inside the cylinder. From this, if we consider a cylindrical model like Figure 6(b) for the TM_{nm0} mode, Q_c can be approximated as follows¹⁶⁾:

$$Q_c \approx d \sqrt{\pi \mu_0 f_r \sigma} = \frac{d}{\delta_s} \quad (6)$$

Here, μ_0 is the permeability of vacuum ($1.26 \times 10^{-6} \text{ N/A}^2$), σ is the conductivity of the conductor surrounding the resonator, and δ_s is the skin depth. Finally, the dielectric loss tangent $\tan \delta$ is determined as follows:

$$\tan \delta = \frac{1}{Q_u} - \frac{1}{d \sqrt{\pi \mu_0 f_r \sigma}} \quad (7)$$

In actual measurements, the coupling between the resonator and excitation port is made sufficiently loose, and the Q -value read from the width of the resonance peak is used as Q_u .

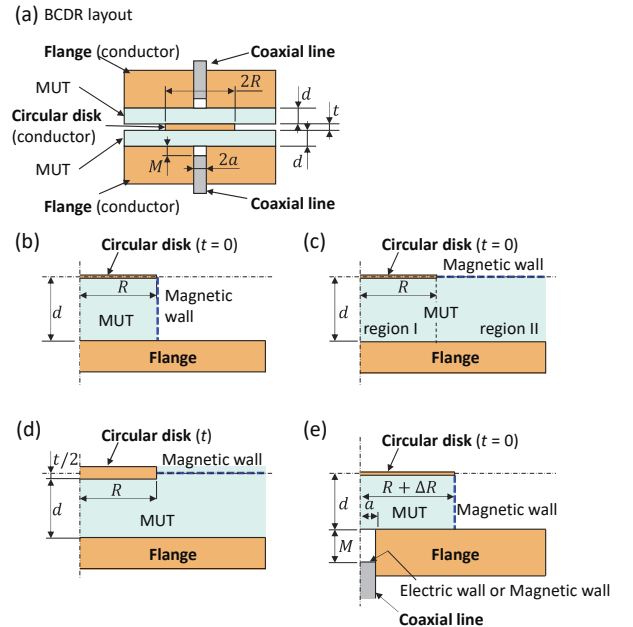


Figure 6 Resonator analysis models (a) BCDR structure, (b) Cylindrical model surrounded by magnetic walls, (c) Model considering spread from edges, (d) Model considering thickness of conductor disk, (e) Model considering influence of excitation port.
MUT: Material Under Test

3 Measurement System Configuration

This study constructed a device to make batch permittivity measurements in the millimeter waveband with an upper limit of 145 GHz. Figures 7(a) and (b) show the configuration and external appearance of the device. The BCDR has 0.8-mm coaxial connectors as input and output ports, which are connected to a wideband vector network analyzer (VNA, ME7838D) with a maximum frequency of 145 GHz. This measurement system eliminates the need to reconfigure or reconnect equipment for each frequency band, making it possible to read a series of resonance peaks at once.

Figure 7(c) shows the resonator configuration. A copper disk is sandwiched between two pieces of MUT that are held between copper flanges. Excitation is via a semi-rigid coaxial cable (155 GHz max. operating frequency, 0.89-mm outer diameter) inserted into two circular excitation ports (0.92-mm inner diameter) in the copper flange, and is loosely coupled to the resonator with a gap, M , of 0.3 mm. The two excitation ports are aligned with the center axis with an accuracy of $\pm 5 \mu\text{m}$. On the other hand, the center position of the copper disk relative to the excitation ports is adjusted along with the two MUT plates sandwiching the copper disk.

The measurement procedure is as follows: ① Calibrate VNA at 0.8-mm coaxial connector at resonator input. ② Measure MUT thickness. ③ Install MUT and copper disk. ④ Apply pressure to conductor flange. ⑤ Capture transmission spectrum (S_{21}). ⑥ Check for higher-order modes and if present, adjust position of copper disk. ⑦ Acquire and analyze spectrum.

Spectrum measurement calibration is performed at the 0.8-mm coaxial connector terminal at the resonator input. To assure accuracy across a wide bandwidth, calibration is divided into two frequency bands. SOLT calibration is used for frequencies below 70 GHz, while offset short calibration was performed and synthesized for frequencies above 70 GHz where load termination matching is difficult.

First-peak detection is performed at spectrum analysis and the resonance frequency and Q -value are determined by fitting a Lorentz function to each peak. The permittivity ϵ_r is obtained by solving Eq. (3) from the obtained resonance frequencies. On the other hand, the dielectric loss tangent δ is obtained by substituting the Q -value into Eq. (4).

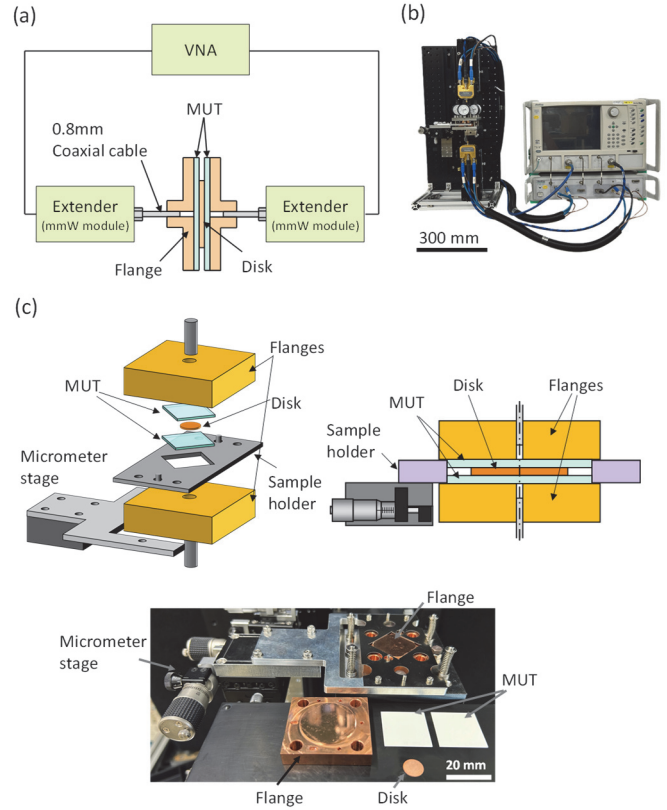


Figure 7 Measurement system configuration (a) Block diagram, (b) External appearance, (c) Resonator structure

4 Measurement Results

4.1 Measurement of Complex Permittivity of Typical MUT

Complex permittivities of typical MUT were measured to verify the operation of the prototype measurement system. The measured MUT samples were cyclo-olefin polymer sheet (CoP, Zeon Corporation, ZF-14, 0.188-mm thick), synthetic quartz plate (Covalent Inc., T-4000, 0.124-mm thick), and millimeter wave composite substrate (Megtron 7, R-5775N, Panasonic Industry Co., Ltd., 0.200-mm thick). A 9.902-mm diameter, 50- μm thick copper conductor disk (cut from 99.99% pure copper foil manufactured by Nilaco Corporation) was used for the CoP sheet and synthetic quartz plate measurements. A 11.994-mm diameter, 12- μm thick copper disk formed from the laminated copper foil on the substrate was used for the millimeter wave composite substrate measurement. Figure 8 shows transmission spectra obtained by measuring each MUT and the complex permittivity analysis results. Almost periodic TM_{0m0} mode resonances are observed up to about 140 GHz in each transmission spectrum. Permittivities shown in Figure 8 represent the mean and the standard deviation measured

after five cycles of mounting and dismounting for each MUT. In addition, results measured at the Kanagawa Institute of Industrial Science and Technology (KISTEC) are also shown for comparison. The standard deviation of the permittivity was within $\pm 0.3\%$ of the mean value across the entire frequency band, and matching KISTEC measured values were within this repeatability range.

4.2 Changes in Resonance Peaks Depending on Conductor Disk Diameter

The measurement frequency upper limit is restricted by the signal-to-noise ratio (SNR) of the transmission spectrum near the resonance peak¹⁴⁾. On the other hand, increasing the BCDR conductor disk diameter can increase both the density of the spacing between resonance peaks and the number of measurement points, but the resonance peaks decrease because higher-order resonances suffer greater losses. Therefore, the conductor disk diameter should be set to the appropriate size to obtain sufficient resonance peak values even at high frequencies, as well as an adequate number of resonance modes across the entire bandwidth. The change in resonance peaks when changing the resonator diameter was confirmed using this measurement setup. The millimeter wave composite substrate was used as the MUT sample, and copper disks (8.990, 11.994, and 14.998-mm diameter, 12- μm thick) were formed using the laminated copper foil on one side of the substrate. Figure 9 shows the measured results. As shown by Eq. (1), the diameter of the conductor disk determines the resonator size, and the spacing between resonance peaks becomes narrower as the resonator size increases. The measured results show a similar trend. The permittivity and dielectric loss tangent derived from each peak frequency are 3.19 ± 0.02 and 0.005 ± 0.002 , respectively, near 75 GHz. These values are consistent with the measured results in section 4.1. When comparing results by diameter, although modes up to $m = 6$ can be read for a resonator diameter of 9 mm, the peak values of the transmission spectrum at mode $m > 6$ decrease for diameters of 12 and 15 mm, suggesting the possibility that peak estimation cannot be performed normally due to the impact of noise. Accordingly, when evaluating samples with unknown complex permittivities, it is necessary to use a moderately small resonator diameter so that each resonance peak value does not decrease too much.

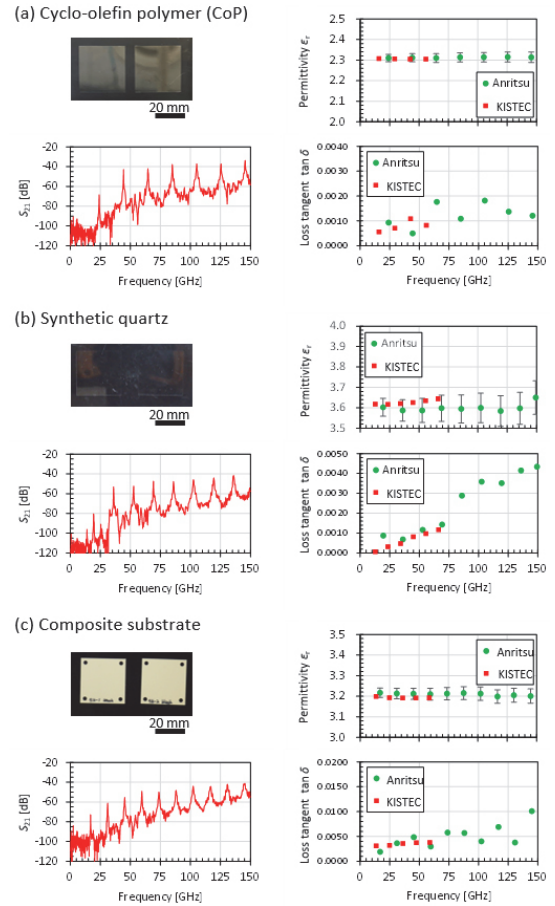


Figure 8 Measured complex permittivity results. (a) Cyclo-olefin polymer (CoP) sheet, (b) Synthetic quartz plate, (c) Millimeter wave composite substrate

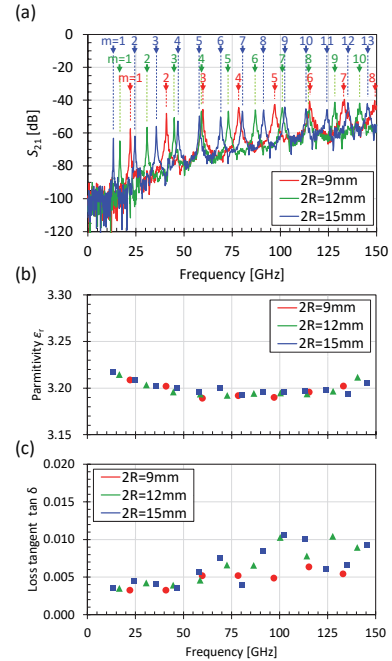


Figure 9 Measured complex permittivity results using circular conductor disks of different diameters for same MUT (a) Resonator transmission spectrum, (b) Estimated permittivity values, (c) Estimated dielectric loss tangent values

5 Impact of Feed Port Position Accuracy on Resonance Modes

The BCDR method determines permittivities from resonance frequencies based on a rigorous model. However, if the model differs from the actual resonator shape, the accuracy of permittivity measurements is limited. Consequently, the resonator mechanical dimensions must be precisely controlled. While several potential dimensional errors can be anticipated, this study examined the positioning accuracy of the excitation ports.

As described in section 2.3, avoiding BCDR excitation modes other than TM_{0m0} requires aligning the center of the excitation port with the center of the conductor disk. This positioning must be done carefully while maintaining accuracy by establishing an external mechanical reference. If the center is misaligned, TM_{nm0} modes (hereafter called high-order TM_{nm0} modes) will be excited, and the magnitude of the excitation port correction described in section 2.3 will probably change. To consider this effect, we verified the impact of positioning accuracy on the BCDR resonance modes experimentally.

Figure 10(a) models BCDR with an eccentric excitation port by reusing the MUT used in section 4.2 (Panasonic Megtron7, 0.200-mm thick). An 11.994-mm diameter, 12- μ m thick copper foil circular pattern formed on the MUT was used as the conductor disk. The center was offset by fine-tuning the moving stage holding the MUT (Figure 7(c)), making the excitation port center eccentric relative to the conductor disk center. We scanned the eccentricity from -250 to 250 μ m in 50 - μ m steps using the mechanical center position calculated from the external dimensions of the resonator as a reference. The mechanical center was set by installing the conductor disk within a tolerance of ± 100 μ m relative to the conductor disk center.

Figure 10(b) shows the transmission spectra when changing the eccentricity. The TM_{0m0} mode resonances (black arrows in figure) appeared when the eccentricity was within 100 μ m. On the other hand, above 100 μ m, resonance peaks due to higher-order TM_{nm0} modes appeared at the positions indicated by blue triangles in the figure. Mode identification is impossible if the higher-order TM_{nm0} mode peaks cannot be distinguished from the TM_{0m0} modes. Furthermore, the intensity decreases for TM_{0m0} modes, and the resonance

frequency shifts for the 5th order and above. If the peak intensity decreases, the measured Q-value is lower, and the measured dielectric tangent is higher. Also, the resonance frequency shift causes an offset in the measured permittivity. From the characteristics of the above spectra, precise positioning of the excitation port center is important not only to avoid exciting unintended higher-order TM_{nm0} modes, but also to ensure that the resonance conditions of the fundamental vibration mode TM_{0m0} match the strict model.

Figure 10(c) shows the measured resonance frequencies for TM_{020} , TM_{050} , and TM_{080} . The top panel in Figure 10(c) shows the changes in resonance frequency with respect to the eccentricity of the conductor disk; the bottom panel shows the permittivity calculated from the resonance frequency. The resonance frequency peaked at an eccentricity of -50 μ m from the center, and the characteristic frequency shift toward the lower frequency side occurred as the absolute eccentricity increased from that position. In this case, as shown in the bottom panel of Figure 10(c), the calculated permittivity increases as the eccentricity moves away from -50 μ m. The measured permittivity is lowest at all resonance peaks when the eccentricity is -50 μ m, and it is thought that this position corresponds to the electrical center of the resonator. Also, when comparing TM_{020} , TM_{050} , and TM_{080} , the higher the resonance frequency, the greater the impact on the measured permittivity with increasing eccentricity. Achieving an accuracy of $\pm 0.5\%$ under the current permittivity measurement conditions requires positioning the excitation port within ± 0.15 mm of the resonator center.

Based on above-observed changes in resonance high-resolution, positioning adjustment of the excitation port is possible using the following procedure. First, adjust so that the higher-order TM_{nm0} modes are sufficiently small and only the TM_{0m0} modes are excited. Next, monitor the resonance frequency of the higher-order TM_{0m0} modes and adjust to maximize the resonance frequency. By using this procedure, positioning can achieve an accuracy of $\geq \pm 50$ μ m for the MUT and resonator used in this study, and the resulting uncertainty in the permittivity can be expected to be $\leq \pm 0.1\%$.

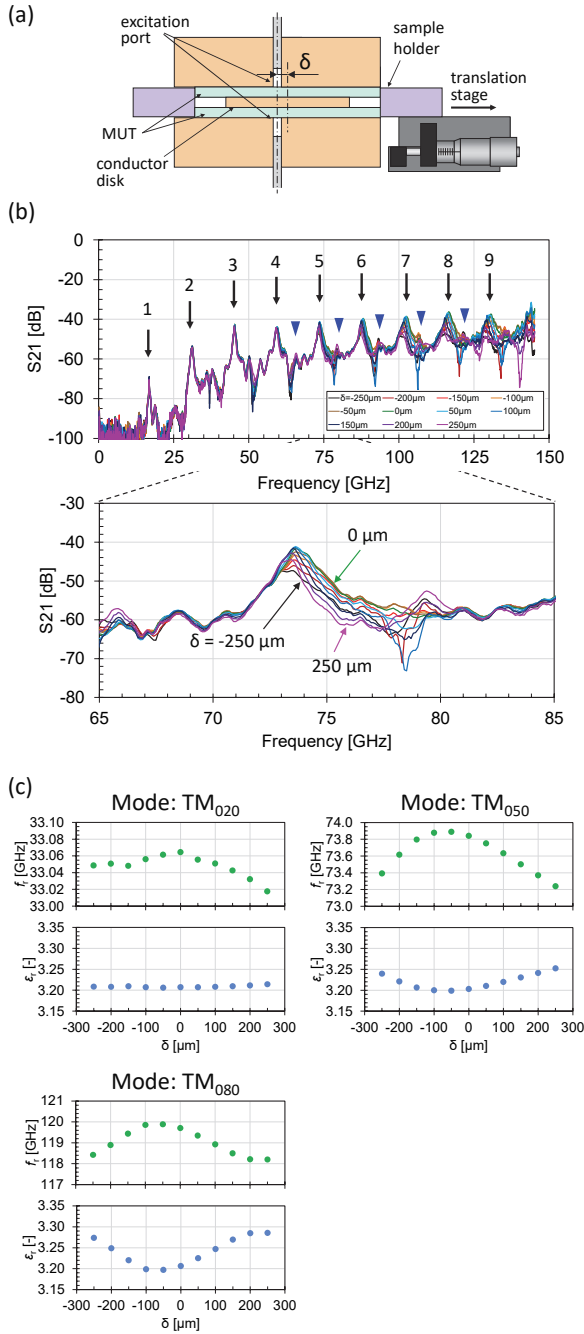


Figure 10 (a) Excitation of modes other than basic resonance mode due to eccentricity of excitation port, (b) Transition of resonance frequencies of basic resonance modes, where blue triangles indicate resonance peaks of higher-order TM_{nm0} modes, (c) Changes in resonance frequency and estimated permittivity due to eccentricity of conductor disk center relative to excitation port. TM_{020} (fr ~ 32 GHz), TM_{050} (~ 76 GHz), and TM_{080} (~ 120 GHz) modes shown as examples.

6 Conclusions

We built a system to measure complex permittivity using Anritsu's wideband VNA to take advantage of the inherent

wideband nature of the BCDR method. Generally, the measurement frequency range of the BCDR method is determined by the resonator size, excitation port size, and VNA measurement bandwidth, and this study measured permittivity up to 145 GHz. To our knowledge, this is the widest bandwidth implementation of permittivity measurement that does not require reassembly or reconnection of equipment for each frequency band. Furthermore, we used this measurement system to experimentally demonstrate the effect of the relative position of the excitation port center axis and the conductor disk on measurement accuracy, and proposed a method for adjusting their relative positions. In addition to describing wide bandwidth, accuracy, high maximum measurable frequency, and simplicity, we describe general requirements for a permittivity measurement system. Future research on the BCDR method is expected to extend measurement to higher frequency bands beyond 300 GHz by scaling down the excitation port etc., to develop more accurate and simpler measurement system.

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