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Author(s)	Suzuki, Hirosuke; Hotchi, Tomio; Nojima, Toshio
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A new Measurement system for the perpendicular complex permittivity to DUT-sheet by stripline simulation

Hirosuke SUZUKI, *Member, IEEE,* Tomio HOTCHI and Toshio NOJIMA, *Member, IEEE*

***Abstract*—The relative dielectric constant, ε_r , is calculated by quasi-static and frequency-dependent hybrid-mode analysis of two layers of dielectric materials (a sample material and a resonator base material) after measuring the rate of change of the resonating frequency of a sheet material under test sandwiched between sheet metal and a calibrated stripline resonator. This method corrects the fringing effect of the resonator by using two resonators that have slightly different resonating frequencies. In the present study, $\tan\delta$ is calculated by balancing the conductor loss.**

The features of this method are as follows:

1) **Measurement of ε_r and $\tan\delta$ is accurate.**
2) **Measurement can occur at several frequencies simultaneously.**
3) **Measurement can be made of ε_r and $\tan\delta$ in the E direction perpendicular to the sheet material, e.g., a printed circuit board.**
4) **A metal pattern is not required. Only the sheet material under test is necessary.**
5) **Measurement provides accurate data since there is no radiation loss.**

This method is useful for measurement in the range 0.5–14 GHz, calculated at multiple frequencies. Fully automatic calculation can be achieved by computer analysis through connection to a network analyzer.

Keywords— **Complex permittivity, Stripline resonator, Simulation, Non-pattern fabrication, Multi frequency measurement.**

Hirosuke SUZUKI and Tomio Hotchi are with the Development and Technology Division, KEYCOM Corp., 3-40-2 Minamiotsuka, Toshima-ku, Tokyo 170-0005, Japan (e-mail: suzuki@keycom.co.jp; hotchi@keycom.co.jp; TEL: +81-3-5950-3101)

Toshio NOJIMA is with the Division of Media and Network Technologies, Graduate School of Information Science and Technology, Hokkaido University, Sapporo 060-0814, Japan (e-mail: nojima@wtemc.ist.hokudai.ac.jp)

I. INTRODUCTION

Many types of devices with a printed circuit antenna, resonator and circulator, such as mobile phones and automobile collision avoidance radar systems, have been developed. The printed circuit board requires accurate values of the relative dielectric constant ε_r and low $\tan\delta$.

The following are some examples of recent requirements for permittivity measurement:

1) Accurate measurement of ε_r and $\tan\delta$.
2) Measurement of ε_r and $\tan\delta$ in the E-H field direction of materials used in testing, e.g., printed circuit boards.
3) Non-metal pattern fabrication for measurement of ε_r and $\tan\delta$.
4) Measurement at several frequencies simultaneously.
5) Easy measurement or shortened measuring time (within 5 minutes).
6) Measurement that provides accurate data.

While the stripline resonator method [1][2] satisfies item 2), metal fabrication of a stripline is very difficult and requires many hours for testing ε_r and $\tan\delta$. The alternative microstripline resonator method employs the novel concept of using simulation software for calculating the unknown ε_r of a sample material from three different ε_r materials: air, the sample sheet material, and the microstripline resonator [3]. However, the value of measured $\tan\delta$ is not accurate because the microstripline suffers radiation loss. The problem of measured $\tan\delta$ has been improved, however, by a method we outlined in a previous publication [4].

Although the cavity perturbation method is highly accurate for measuring complex permittivity [5], the E direction of ε_r and $\tan\delta$ is parallel to the sheet material. In the present paper, to overcome the problems of measurement at different frequencies, the measurement ratio of ε_r between the perpendicular and the parallel E directions to the DUT sheet is calculated. Here, ε_r is accurately calculated by quasi-static and frequency-dependent hybrid-mode analysis of two layers of dielectric materials (a sample material and a resonator base material) after measuring the rate of change of the resonating frequency of a sheet material under test sandwiched between sheet metal and a calibrated stripline resonator. The method corrects the fringing effect of the resonator by using two resonators that have slightly different resonating frequencies. In addition, $\tan\delta$ is accurately calculated by balancing the conductor loss.

This method is useful for the accurate measurement of ε_r and $\tan\delta$ in the E direction perpendicular to the sheet material (e.g., printed circuit board) and in the range 0.5–14 GHz, calculated simultaneously at multiple frequencies. Fully automatic calculation can be achieved by computer analysis through connection to a network analyzer.

II. Outline of the New Approach

Figure 1 shows the newly developed automatic measurement system using the stripline resonator technique.

To ensure close contact of the sample sheet with the microstripline resonator, a weighted metal plate is placed on the sample.

FIG.1 HERE

Symbols are as follows:

f_{a1}[GHz]: resonance dominant frequency of resonator R_a for fringing effect correction contacting the same material as R_s

L_a[mm]: $\frac{\lambda_{a1}}{2}, \lambda_{a1} = c/f_a$

c: speed of light

f_{s1} [GHz]: resonance dominant frequency of resonator R_s contacting the same material as R_a

Q_{s1}: dominant Q factor of resonator R_s contacting the same material as R_s

L_S [mm]: $L_a \times 1.1$

h [mm]: thickness of material of resonators R_a and R_s

d [mm]: thickness of material under test

w [mm]: metal pattern of R_a and R_s

f_{m1} [GHz]: resonance dominant frequency of resonator R_s contacting the material under test

Q_{m1}: Q factor of resonator R_s contacting the material under test

The microstripline resonators R_a and R_s are composed of a low-ε_r and a low- $\tan\delta$ material such as polytetrafluoroethylene (PTFE), a thin copper resonator, and are 9 μm in thickness. The 2 GHz resonators are shown in Fig.2.

FIG.2 HERE

The dielectric materials of resonator R_a for fringing effect correction and resonator R_s for measurement must be the same.

1) f_{a1} is measured by a network analyzer or similar device.
2) f_{s1} is measured by the same device.
3) Electromagnetic waves expand slightly from the edge of the resonator; a phenomenon known as the fringing effect.

ΔL : fringing length

The difference between f_{a1} and f_{s1} is only 10%. Thus, the dominant fringing lengths ΔL_1 of L_a and L_s are identical. So,

$$f_{a1}(L_a + \Delta L_1) = f_{s1}(L_s + \Delta L_1)$$

$$\therefore \Delta L_1 = \frac{f_{s1}L_s - f_{a1}L_a}{f_{a1} - f_{s1}} \qquad ...(1)$$

L_a x 1.05, L_a x 1.1, and L_a x 1.15 to L_s were tested to decide ΔL . Based on the results, L_a x 1.1 to L_s was adopted.

4) The calculation of ε_{r1} of resonator R_s with the same dielectric material as resonator R_a is expressed by Eq. (2). Figure 3 shows the relationship between ε_{r1} and $\tan\delta_1$ of the material above and of the material below in the case where both top and bottom materials are the same.

$$\varepsilon_{r2} = \varepsilon_{r1}$$

$$2(L_s + \Delta L_1) = \frac{c}{f_{s1}} \bullet \frac{1}{\sqrt{\varepsilon_{r1}}}$$

$$\therefore \varepsilon_{r1} = \left(\frac{c}{2(L_s + \Delta L_1) f_{s1}} \right)^2 \qquad ...(2)$$

Note: the dominant mode of resonance is half wave.

FIG.3 HERE

5) Resonator R_s with the material under test is written as below. Figure 3 shows the relationship between ε_{r1}, $\tan\delta_1$ and ε_{r2}, $\tan\delta_2$ and effective ε_{r2}, (ε_{r2eff}) and effective $\tan\delta_2$, ($\tan\delta_{2eff}$).

Here, f_{m1} and Q_{m1} are measured by resonator R_s with the material under test.

(ε_{r2eff}) is calculated as follows:

$$2(L_s + \Delta L_1) = \frac{c}{f_{m1}} \bullet \frac{1}{\sqrt{\varepsilon_{r2eff}}}$$

$$\therefore \varepsilon_{r2eff} = \left(\frac{c}{2(L_s + \Delta L_1)\, f_{m1}} \right)^2 \qquad ...(3)$$

III. Calculation of ε_{r1} in the Case of Several Frequencies

FIG.4 HERE

In this case, ΔL_2 is calculated as follows:

$$f_{a2}\left(\frac{L_a}{2} + \Delta L_2 \right) = f_{s2}\left(\frac{L_s}{2} + \Delta L_2 \right)$$

$$\therefore \Delta L_2 = \frac{f_{s2} L_s - f_{a2} L_f}{2\left(f_{a2} - f_{s2} \right)} \qquad \ldots(4)$$

By the same process,

$$\therefore \Delta L_3 = \frac{f_{s3} L_s - f_{a3} L_f}{3\left(f_{a3} - f_{s3} \right)} \qquad \ldots(5)$$

Symbols are as follows:

f_{a2}, f_{a3}: second and third resonance frequencies of f_{a1}

f_{s2}, f_{s3}: second and third resonance frequencies of f_{s1}

$\Delta L_2, \Delta L_3$: fringing length of second and third resonance frequencies

Note that the method is not limited to 3 frequencies.

IV. Calculation of ε_{r2} by Computer

Next, ε_{r2} is calculated numerically [5].

Coupled strips with an overlay structure (Fig.8 of Reference [5]) are used to calculate ε_{r2}.

The layer structure is illustrated in Fig.3 and photographs of the layer structure are shown in Fig.5.

FIG.5 HERE

ε_{r2} is obtained by the following steps:

1) Computer program,

ε_{r2eff} = function (h/f_2, w, ε_{r1}, d, ε_{r2}, metal) $\cdots$(6)

Note that the upper area of the sample is composed of metal.

2) Next, ε_r is changed to 1,000 from 0 in 0.0001 steps.

Figure 6 shows the process of determining ε_{r2} (the sample's ε_r).

Thus, the function (h/f_2, w, ε_{r1}, d, ε_{r2}, metal) approaches ε_{r2} in a step-by-step manner, and when the left-hand side of Eq. (6) becomes equal to the right-hand side, we have

$\varepsilon_r = \varepsilon_{r2}$

In this equation, the function increases or decreases monotonically with ε_r.

FIG.6 HERE

V. Determination of $\tan\delta_{cond}$

$$\tan\delta_{1eff} = \tan\delta_{rad} + \tan\delta_{cond} + \tan\delta_1 \qquad \ldots(7)$$

Since

$$\tan\delta_{1eff} = \frac{1}{Q_{s1}} \qquad \ldots(8)$$

$$\tan\delta_{rad} = 0$$

because the stripline does not radiate EM waves.

Symbols are as follows:

$\tan\delta_{rad}$: $\tan\delta$ caused by radiation loss of resonator R_s

$\tan\delta_{cond}$: $\tan\delta$ caused by conductor loss of resonator R_s

$\tan\delta_1$: dielectric loss of resonator R_s

$$\therefore \tan\delta_{rad} + \tan\delta_{cond} = \frac{1}{Q_{s1}} - \tan\delta_1$$

and

$$\tan\delta_{rad} = 0$$

$$\therefore \tan\delta_{cond} = \frac{1}{Q_{s1}} - \tan\delta_1 \qquad \ldots(9)$$

VI. $\tan\delta_2$ Calculated by Effective $\tan\delta_2$ ($\tan\delta_{2eff}$)

If the ε_r of the material is small, ($\tan\delta_{rad}$ + $\tan\delta_{cond}$) hardly changes before and after measurement when the material under test is placed on the stripline resonator.

$$\therefore \tan\delta_{2eff} = \tan\delta_{rad} + \tan\delta_{cond} + (\tan\delta_1 // \tan\delta_2)$$

$$\left[\tan\delta_{rad} = 0 \right]$$

$$\therefore \tan\delta_{2eff} = \tan\delta_{cond} + (\tan\delta_1 // \tan\delta_2) \qquad \ldots(10)$$

$$\tan\delta_{2eff} = \frac{1}{Q_{m1}}$$

and by inserting Eq. (9) into Eq. (10).

$$\frac{1}{Q_{m1}} = \frac{1}{Q_{s1}} - \tan\delta_1 + (\tan\delta_1 // \tan\delta_2) \qquad \ldots(11)$$

$$\therefore (\tan\delta_1 // \tan\delta_2) = \frac{1}{Q_{m1}} - \frac{1}{Q_{s1}} + \tan\delta_1 \qquad \ldots(12)$$

If the lines of electric force are perpendicular to the material plane, then generally ($\tan\delta_1 // \tan\delta_2$) is obtained as follows:

$$\left(\tan\delta_1 // \tan\delta_2\right) = \frac{\varepsilon_{r2} h \bullet \tan\delta_1 + \varepsilon_{r1} d \bullet \tan\delta_2}{\varepsilon_{r2} \bullet h + \varepsilon_{r1} \bullet d} \qquad \ldots(13)$$

$$\therefore \tan\delta_2 = \frac{\left(\tan\delta_1 // \tan\delta_2\right)\left(\varepsilon_{r2} \bullet h + \varepsilon_{r1} \bullet d\right) - \varepsilon_{r2} \bullet h \bullet \tan\delta_1}{\varepsilon_{r1} \bullet d} \qquad \ldots(14)$$

Equation (14) can be substituted by Eq. (12).

$$\therefore \tan\delta_2 = \frac{\left(\frac{1}{Q_{m1}} - \frac{1}{Q_{s1}} + \tan\delta_1\right)\left(\varepsilon_{r2} \bullet h + \varepsilon_{r1} \bullet d\right) - \varepsilon_{r2} \bullet h \bullet \tan\delta_1}{\varepsilon_{r1} \bullet d}$$

$$= \frac{\varepsilon_{r2} \bullet h + \varepsilon_{r1} \bullet d}{\varepsilon_{r1} \bullet d}\left(\frac{1}{Q_{m1}} - \frac{1}{Q_{s1}}\right) + \tan\delta_1 + \alpha \qquad \ldots(15)$$

α : correction number

When PTFE is used for calibrating $\tan\delta$, we measure $\tan\delta_2$ of the PTFE by employing another measurement technique, namely, either the perturbation resonator method [5] or the open-type resonator (Fabry-Perot resonator) method [7]. These methods are useful to measure ε_r and $\tan\delta$ for an isotropic material in general because the E direction of ε_r and $\tan\delta$ is parallel to the sheet material.

Using the perturbation resonator method, we determined $\tan\delta$ of PTFE to be 0.0004 in the range 1–15GHz. Further, we control α to achieve $\tan\delta_2$ which is equal to $\tan\delta$ as determined by the other measuring technique.

In the case of the second and third resonance frequencies, Qm1, Qs1 is read at Qm2, Qs2 and Qm3, Qs3.

VII. Results

Screenshots showing the three resonance points are shown in Fig.7, and we can see the dielectric constant relationship that exists between these frequencies.

FIG.7 HERE
Table 1 HERE

The results for an isotropic dielectric sheet using the stripline resonator method are shown in Table 1. The results for the perturbation resonator method are given one row from the bottom of Table1. The perturbation resonator method is a standard method and an accurate measurement method of complex permittivity. Figure 8 shows the apparatus of the perturbation resonator method. In the new method, ε_r of PTFE is calculated to be 2.08 at 4.4GHz, 2.05 at 8.8GHz and 2.11 at 13GHz.

The perturbation resonator method can measure the dielectric constant ε_r in the E direction parallel to the sheet, and the stripline resonator method can calculate the ε_r of the E direction perpendicular to the sheet.

The $\varepsilon_r \perp$ to $\varepsilon_r //$ ratio is almost 1.0in the case of the measurement of isotropic materials, as shown in the last row of Table 1.

The result suggests that the new method also provides a highly accurate measurement of ε_r.

Thus, we were able to obtain an accurate ε_r value by using an accurate calculation method of ΔL. The resulting $\tan\delta$ as measured by the new method is almost the same as that as determined by the perturbation resonator method, and we realized accurate measurement of $\tan\delta$ by conductor loss calculation. These two accurate calculation methods employed by the new measuring method mark improvement on the conventional stripline resonator method [1][2].

FIG.8 HERE

The results for the anisotropic dielectric sheets using the stripline resonator method are shown in Table 2.

Table 2 HERE

In the case of fiber-reinforced PTFE, the sheet material consists of glass fiber net and immersed PTFE resin. The ε_r of glass is higher than that of PTFE, and thus the ε_r in the E direction parallel to the sheet will be higher than in the E direction perpendicular to it. In the case of using the perturbation resonator, the ε_r in the E direction is parallel to the sheet. The ε_r of fiber-reinforced PTFE determined by the perturbation resonator method is 2.42, which is higher than that of the new stripline resonator method (2.17).

Fiber-reinforced EPOXY has a similar property. The ratios of ε_r between the E directions perpendicular and parallel to the DUT sheet are shown at bottom of Table 2. The obtained values of 0.895 in the case of a fiber-reinforced PTFE and 0.930 in the case of a fiber-reinforced EPOXY at 2.7GHz are extremely important information to the electronic engineering field. As an illustration, when designing a printed circuit antenna made with fiber-reinforced PTFE for an automobile collision avoidance radar system at 76.5GHz, $\varepsilon_r \perp$ at 76.5GHz is needed. So, $\varepsilon_r //$ is measured first by using, for example, a millimeter wave permittivity measurement system [7]. Then $\varepsilon_r \perp$ becomes known by calculating $\varepsilon_r // \times 0.895$ which overcomes the difficulty at present of not being able to measure $\varepsilon_r \perp$ directly at millimeter wave frequencies.

VIII. CONCLUSIONS

The dielectric constant ε_r and loss $\tan\delta$ of a sheet material can be measured with high accuracy and very easily by employing the new stripline resonator method. The features of the proposed method for measuring ε_r and $\tan\delta$ are as follows:

1) Measurement of ε_r and $\tan\delta$ is accurate.

2) Measurement can occur at several frequencies simultaneously.

3) Measurement can be made of ε_r and $\tan\delta$ in the E direction perpendicular to the sheet material. In addition, $\varepsilon_r \perp / \varepsilon_r //$ of some anisotropic materials can be measured.

4) A metal pattern is not required. Only the sheet material under test is necessary.

5) Measurement provides accurate data since there is no radiation loss.

Future plans to improve this method aim at the development of a new, thinner film material by changing the $\tan\delta$ calculation method.

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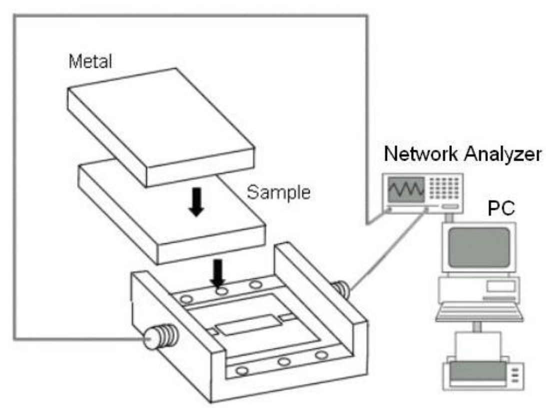
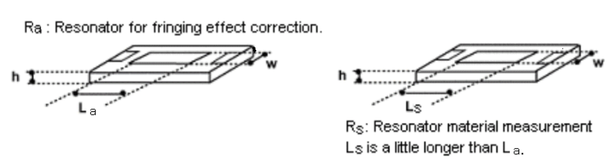
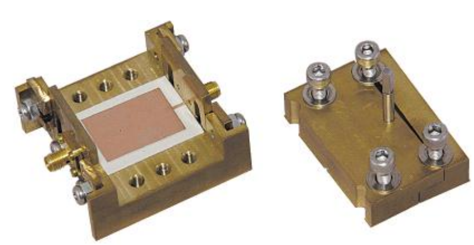






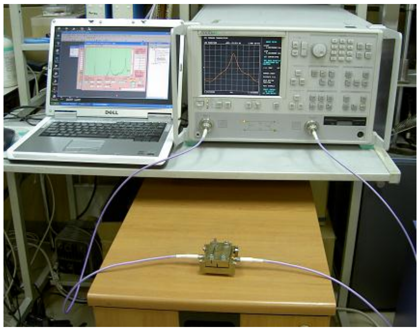


Fig.1 Automatic measuring system using the stripline resonator method.

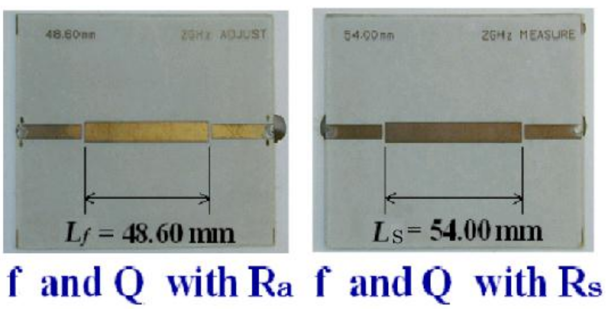


Fig.2 2 GHz resonators for fringing effect correction and for material measurement.

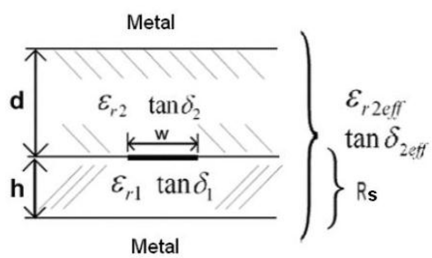


Fig.3 Relationship between ε_{r1}, $\tan\delta_1$, ε_{r2}, $\tan\delta_2$, ε_{r2eff} and $\tan\delta_{2eff}$

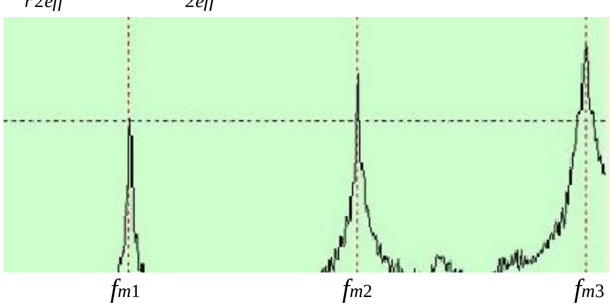


Fig.4 Resonance at several frequencies

Fig.5 Photograph of the 2-layer structure

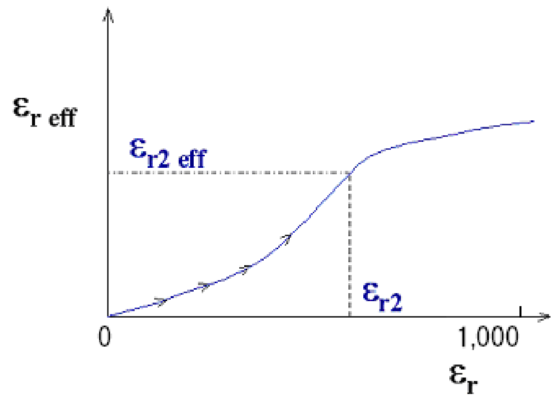
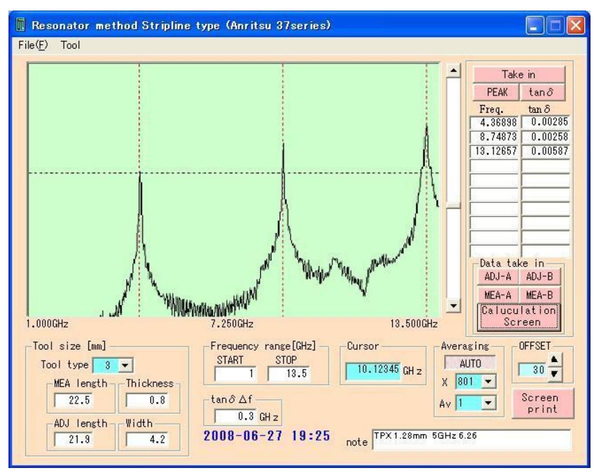


Fig.6 Process of determination of ε_{r2} .



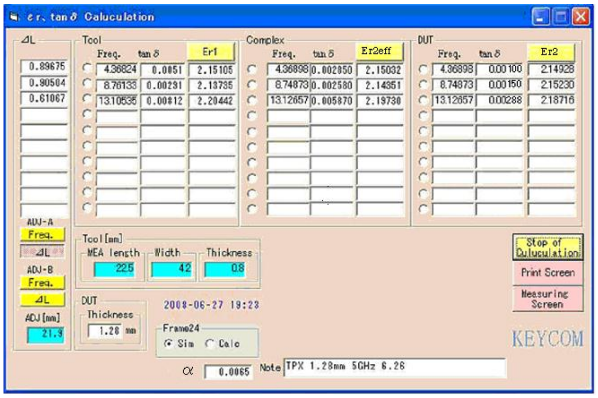


Fig.7 Screenshots of three resonance points obtained using the stripline resonator method

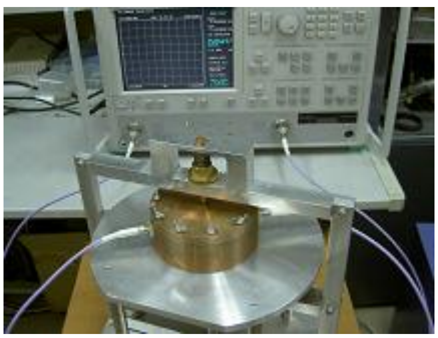


Fig.8 Apparatus of the perturbation resonator method

Table 1

ε_r and $\tan\delta$ of the isotropic materials PTFE, TPX and PE sheets obtained by the stripline resonator method.

Resonator [fiber -reinforced PTFE]	L_f [mm]	21.9 (W=4.2mm, h=0.8mm)								
	L_s [mm]	22.5 (W=4.2mm, h=0.8mm)								
	[GHz]	f_{s1}	f_{s2}	f_{s3}	f_{s1}	f_{s2}	f_{s3}	f_{s1}	f_{s2}	f_{s3}
		4.36824	8.76133	13.10535	4.36842	8.76133	13.10535	4.36842	8.76133	13.10535
	[mm]	ΔL_1	ΔL_2	ΔL_3	ΔL_1	ΔL_2	ΔL_3	ΔL_1	ΔL_2	ΔL_3
		0.89675	0.86606	0.94137	0.89675	0.86606	0.94137	0.89675	0.86606	0.94137
	ε_{r1}	2.15105	2.14449	2.14266	2.15105	2.14449	2.14266	2.15105	2.14449	2.14266
	$\tan\delta_{1eff}$	0.003300	0.003350	0.003470	0.003300	0.003350	0.003470	0.003300	0.003350	0.003470
Samples	Material	PTFE			TPX			PE		
	d[mm]	1.074			1.28			1.48		
Results	[GHz]	f_{m1}	f_{m2}	f_{m3}	f_{m1}	f_{m2}	f_{m3}	f_{m1}	f_{m2}	f_{m3}
		4.39921	8.83208	13.23251	4.36898	8.74873	13.12657	4.30369	8.62748	12.90333
	ε_{r2eff}	2.12087	2.11027	2.10168	2.15032	2.15067	2.13574	2.21606	2.21154	2.21028
	$\tan\delta_{2eff}$	0.002630	0.002937	0.002970	0.002940	0.003054	0.003232	0.004390	0.004697	0.004861
	α	0.00150	0.00150	0.00150	0.00150	0.00150	0.00150	0.00150	0.00150	0.00150
Final data $(\varepsilon_r \perp)$	ε_{r2}	2.08306	2.06738	2.05032	2.14928	2.15949	2.12586	2.31905	2.31774	2.31741
	$\tan\delta_2$	0.00035	0.00045	0.00064	0.00092	0.00102	0.00111	0.00323	0.00363	0.00370
Results obtained by the perturbation resonator method $(\varepsilon_r //)$		4GHz ε_r : 2.06 $\tan\delta$: 0.0004*	8GHz ε_r : 2.06 $\tan\delta$: 0.0004*	13GHz ε_r : 2.06 $\tan\delta$: 0.0004*	4GHz ε_r : 2.15 $\tan\delta$: 0.0012	8GHz ε_r : 2.14 $\tan\delta$: 0.0012	13GHz ε_r : 2.12 $\tan\delta$: 0.0013	4GHz ε_r : 2.31 $\tan\delta$: 0.0031	8GHz ε_r : 2.29 $\tan\delta$: 0.0035	13GHz ε_r : 2.28 $\tan\delta$: 0.0040
$\dfrac{\varepsilon_r \perp}{\varepsilon_r //}$		1.011	1.004	0.9953	1.000	0.9624	1.0028	1.004	1.0121	1.0164

Note; PTFE : Polytetrafluoroethylene
TPX : Polymethylpentene
PE : Polyethylene
$\varepsilon_r \perp$: ε_r of E direction perpendicular to the sheet
$\varepsilon_r //$: ε_r of E direction parallel to the sheet

Calibration of $\tan\delta$: The $\tan\delta_2$ of PTFE is adjusted to 0.0004* by controlling α .

Table 2

ε_r and $\tan\delta$ of the anisotropic materials fiber-reinforced PTFE and fiber-reinforced EPOXY sheets obtained by the stripline resonator method.

Resonator [fiber -reinforced PTFE]	L_f [mm]	34.55 (W=4.0mm, h=0.8mm)					
	L_s [mm]	36.15 (W=4.0mm, h=0.8mm)					
	[GHz]	f_{s1}	f_{s2}	f_{s3}	f_{s1}	f_{s2}	f_{s3}
		2.74424	5.50683	8.26232	2.74424	5.50683	8.26232
	[mm]	ΔL_1	ΔL_2	ΔL_3	ΔL_1	ΔL_2	ΔL_3
		0.95861	0.96544	0.97655	0.95861	0.96544	0.97655
	ε_{r1}	2.16661	2.15140	2.14904	2.16661	2.15140	2.14904
	$\tan\delta_{1eff}$	0.003870	0.004126	0.004337	0.003870	0.004126	0.004337
Samples	Material	Fiber-reinforced PTFE			Fiber-reinforced EPOXY		
	d[mm]	0.80			1.50		
Results	[GHz]	f_{m1}	f_{m2}	f_{m3}	f_{m1}	f_{m2}	f_{m3}
		2.74424	5.50683	8.26232	2.39175	4.79853	7.20347
	ε_{r2eff}	2.16661	2.15140	2.14904	2.85229	2.83340	2.82725
	$\tan\delta_{2eff}$	0.00387	0.004126	0.004337	0.01067	0.01232	0.01419
	α	0.00150	0.00150	0.00150	0.00150	0.00150	0.00150
Final data $(\varepsilon_r \perp)$	ε_{r2}	2.16660	2.15141	2.14902	3.95226	3.92746	3.91520
	$\tan\delta_2$	0.0015	0.0015	0.0015	0.01492	0.01767	0.02093
Results obtained by the perturbation resonator method $(\varepsilon_r //)$		2.5GHz ε_r : 2.42 $\tan\delta$: 0.0011	5GHz ε_r : 2.40 $\tan\delta$: 0.0013	8GHz ε_r : 2.39 $\tan\delta$: 0.0014	2.5GHz ε_r : 4.24 $\tan\delta$: 0.0178	5GHz ε_r : 4.22 $\tan\delta$: 0.0210	8GHz ε_r : 4.20 $\tan\delta$: 0.0250
$\dfrac{\varepsilon_r \perp}{\varepsilon_r //}$		0.895	0.896	0.899	0.930	0.930	0.932

Note; Glass PTFE, Glass EPOXY: PTFE and EPOXY reinforced by glass fiber net.
$\varepsilon_r \perp$: ε_r of E direction perpendicular to the sheet
$\varepsilon_r //$: ε_r of E direction parallel to the sheet