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, $\varepsilon_r$, 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 $\varepsilon_r$ and $\tan \delta$ is accurate.
2) Measurement can occur at several frequencies simultaneously.
3) Measurement can be made of $\varepsilon_r$ 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.

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 $\varepsilon_r$ and low $\tan \delta$. The following are some examples of recent requirements for permittivity measurement:
1) Accurate measurement of $\varepsilon_r$ and $\tan \delta$.
2) Measurement of $\varepsilon_r$ 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 $\varepsilon_r$ 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 $\varepsilon_r$ and $\tan \delta$. The alternative microstripline resonator method employs the novel concept of using simulation software for calculating the unknown $\varepsilon_r$ of a sample material from three different $\varepsilon_r$ 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 $\varepsilon_r$ 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 $\varepsilon_r$ between the perpendicular and the parallel E directions to the DUT sheet is calculated. Here, $\varepsilon_r$ 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 \( \varepsilon_r \) 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]: \( \frac{\lambda_{a1}}{2} \), \( \lambda_{a1} = \frac{c}{f_a} \)
- \( c \): speed of light
- \( f_{s1} \) [GHz]: resonance dominant frequency of resonator \( R_s \) contacting the same material as \( R_a \)
- \( Q_{11} \): dominant Q factor of resonator \( R_s \) contacting the same material as \( R_a \)
- \( L_s \) [mm]: \( L_s \times 1.1 \)
- \( h \) [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
- \( Q_{ml} \): Q factor of resonator \( R_s \) contacting the material under test

The microstripline resonators \( R_a \) and \( R_s \) are composed of a low-\( \varepsilon_r \) and a low- \( \tan \delta \) material such as polytetrafluoroethylene (PTFE), a thin copper resonator, and are 9 \( \mu \)m 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.

\[ \Delta L : \text{fringing length} \]

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

\[
f_{a1} \left( L_a + \Delta L_a \right) = f_{s1} \left( L_s + \Delta L_s \right)
\]

\[
\therefore \Delta L_a = \frac{f_{s1} L_s - f_{a1} L_a}{f_{a1} - f_{s1}} \tag{1}
\]

\( L_s \times 1.05, L_s \times 1.1, \) and \( L_s \times 1.15 \) to \( L_s \) were tested to decide \( \Delta L \). Based on the results, \( L_s \times 1.1 \) to \( L_s \) was adopted.

4) The calculation of \( \varepsilon_{r1} \) of resonator \( R_s \) with the same dielectric material as resonator \( R_a \) is expressed by Eq. (2). Figure 3 shows the relationship between \( \varepsilon_{r1} \) 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.

\[ \varepsilon_{r2} = \varepsilon_{r1} \]

\[ 2(L_s + \Delta L_s) = \frac{c}{f_{s1}} \cdot \frac{1}{\sqrt{\varepsilon_{r1}}} \]

\[ \therefore \varepsilon_{r1} = \left( \frac{c}{2(L_s + \Delta L_s) f_{s1}} \right)^2 \tag{2} \]

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 \( \varepsilon_{r1} \), \( \tan \delta_1 \) and \( \varepsilon_{r2} \), \( \tan \delta_2 \) and effective \( \varepsilon_{r2} \). \(( \varepsilon_{r2\text{eff}} ) \) and effective \( \tan \delta_2 \). \(( \tan \delta_{2\text{eff}} ) \).

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

\(( \varepsilon_{r2\text{eff}} ) \) is calculated as follows:
2(L_s + \Delta L_1) = \frac{c}{f_{m1}} \cdot \frac{1}{\sqrt{\varepsilon_r^{\text{eff}}}}
\therefore \varepsilon_r^{\text{eff}} = \left( \frac{c}{2(L_s + \Delta L_1) f_{m1}} \right)^2 \hspace{1cm} \text{(3)}

III. CALCULATION OF $\varepsilon_{r1}$ IN THE CASE OF SEVERAL FREQUENCIES

FIG.4 HERE

In this case, $\Delta L_2$ is calculated as follows:

$$f_{a2} \left( \frac{L_s}{2} + \Delta L_2 \right) = f_{s2} \left( \frac{L_s}{2} + \Delta L_2 \right)$$
\therefore \Delta L_2 = \frac{f_{a2} L_s - f_{a2} L_f}{2(f_{a2} - f_{s2})} \hspace{1cm} \text{(4)}

By the same process,

$$\Delta L_3 = \frac{f_{a3} L_s - f_{a3} L_f}{3(f_{a3} - f_{s3})} \hspace{1cm} \text{(5)}$$

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 $\varepsilon_{r2}$ BY COMPUTER

Next, $\varepsilon_{r2}$ is calculated numerically [5].

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

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

FIG.5 HERE

$\varepsilon_{r2}$ is obtained by the following steps:
1) Computer program,

$$\varepsilon_{r2}^{\text{eff}} = \text{function} \left( \text{h} / \text{f}, \text{w}, \varepsilon_{r1} \cdot \text{d}, \varepsilon_{r2} \cdot \text{metal} \right) \hspace{1cm} \text{(6)}$$

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

2) Next, $\varepsilon_r$ is changed to 1.000 from 0 in 0.0001 steps.

Figure 6 shows the process of determining $\varepsilon_{r2}$ (the sample’s $\varepsilon_r$).

Thus, the function ($\text{h} / \text{f}, \text{w}, \varepsilon_{r1}, \text{d}, \varepsilon_{r2}, \text{metal}$) approaches $\varepsilon_{r2}$ 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 $\varepsilon_r$.

FIG.6 HERE

V. DETERMINATION OF $\tan \delta_{\text{cond}}$

$$\tan \delta_{\text{eff}} = \tan \delta_{\text{rad}} + \tan \delta_{\text{cond}} + \tan \delta_1 \hspace{1cm} \text{(7)}$$

Since

$$\tan \delta_{\text{eff}} = \frac{1}{Q_{r1}} \hspace{1cm} \text{(8)}$$

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

because the stripline does not radiate EM waves.

Symbols are as follows:
- $\tan \delta_{\text{rad}}$: $\tan \delta$ caused by radiation loss of resonator $R_s$
- $\tan \delta_{\text{cond}}$: $\tan \delta$ caused by conductor loss of resonator $R_s$
- $\tan \delta_1$: dielectric loss of resonator $R_s$

\therefore \tan \delta_{\text{rad}} + \tan \delta_{\text{cond}} = \frac{1}{Q_{r1}} - \tan \delta_1

and

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

\therefore \tan \delta_{\text{cond}} = \frac{1}{Q_{r1}} - \tan \delta_1 \hspace{1cm} \text{(9)}$$

VI. $\tan \delta_2$ CALCULATED BY EFFECTIVE $\tan \delta_2$ ($\tan \delta_{2\text{eff}}$)

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

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

$$\left[ \tan \delta_{\text{rad}} = 0 \right]$$
\[ \therefore \tan \delta_{e} = \tan \delta_{cond} + (\tan \delta_{1} \parallel \tan \delta_{2}) \quad (10) \]

\[ \tan \delta_{e} = \frac{1}{Q_{m1}} \]

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

\[ \frac{1}{Q_{m1}} = \frac{1}{Q_{s1}} - \tan \delta_{1} + (\tan \delta_{1} \parallel \tan \delta_{2}) \quad (11) \]

\[ \therefore (\tan \delta_{1} \parallel \tan \delta_{2}) = \frac{1}{Q_{m1}} - \frac{1}{Q_{s1}} + \tan \delta_{1} \quad (12) \]

If the lines of electric force are perpendicular to the material plane, then generally (\(\tan \delta_{1} \parallel \tan \delta_{2}\)) is obtained as follows:

\[ (\tan \delta_{1} \parallel \tan \delta_{2}) = \frac{\varepsilon_{r2}h \cdot \tan \delta_{1} + \varepsilon_{r1}d \cdot \tan \delta_{2}}{\varepsilon_{r2} \cdot h + \varepsilon_{r1} \cdot d} \quad (13) \]

\[ \therefore \tan \delta_{2} = \frac{(\tan \delta_{1} \parallel \tan \delta_{2})(\varepsilon_{r2} \cdot h + \varepsilon_{r1} \cdot d) - \varepsilon_{r2} \cdot h \cdot \tan \delta_{1}}{\varepsilon_{r1} \cdot d} \quad (14) \]

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

\[ \therefore \tan \delta_{2} = \frac{\varepsilon_{r2} \cdot h + \varepsilon_{r1} \cdot d \left( \frac{1}{Q_{m1}} - \frac{1}{Q_{s1}} \right) + \tan \delta_{1} + \alpha}{\varepsilon_{r1} \cdot d} \quad (15) \]

\(\alpha\) : 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 \(\varepsilon_{r}\) and \(\tan \delta\) for an isotropic material in general because the E direction of \(\varepsilon_{r}\) 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 \(\alpha\) 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, \(Q_{m1}, Q_{s1}\) is read at \(Q_{m2}, Q_{s2}\) and \(Q_{m3}, Q_{s3}\).

**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 Table 1. 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, \(\varepsilon_{r}\) 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 \(\varepsilon_{r}\) in the E direction parallel to the sheet, and the stripline resonator method can calculate the \(\varepsilon_{r}\) of the E direction perpendicular to the sheet.

The \(\varepsilon_{r} \perp \varepsilon_{r} \parallel\) ratio is almost 1.0 in 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 \(\varepsilon_{r}\).

Thus, we were able to obtain an accurate \(\varepsilon_{r}\) value by using an accurate calculation method of \(\Delta L\). 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 \(\varepsilon_{r}\) of glass is higher than that of PTFE, and thus the \(\varepsilon_{r}\) 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 $\varepsilon_r$ in the E direction is parallel to the sheet. The $\varepsilon_r$ 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 $\varepsilon_r$ 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, $\varepsilon_r \parallel$ is measured first by using, for example, a millimeter wave permittivity measurement system [7]. Then $\varepsilon_r \perp$ becomes known by calculating $\varepsilon_r \parallel \times 0.895$ 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 $\varepsilon_r$ 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 $\varepsilon_r$ and $\tan \delta$ are as follows:

1) Measurement of $\varepsilon_r$ and $\tan \delta$ is accurate.
2) Measurement can occur at several frequencies simultaneously.
3) Measurement can be made of $\varepsilon_r$ and $\tan \delta$ in the E direction perpendicular to the sheet material. In addition, $\varepsilon_r \perp / \varepsilon_r \parallel$ 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.

REFERENCES

[2] IPC-TM-650 2.5.5.5.1 “Stripline Test for Complex Relative Permittivity of circuit Board Materials to 14GHz” Institute of Printed Circuits, USA.
Fig. 1 Automatic measuring system using the stripline resonator method.

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

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

Fig. 4 Resonance at several frequencies.

Fig. 5 Photograph of the 2-layer structure.

Fig. 6 Process of determination of $\epsilon_{r2}$.
Fig. 7 Screenshots of three resonance points obtained using the stripline resonator method

Fig. 8 Apparatus of the perturbation resonator method
### Table 1

\( \varepsilon_r \) and \( \tan \delta \) of the isotropic materials PTFE, TPX and PE sheets obtained by the stripline resonator method.

<table>
<thead>
<tr>
<th>Resonator fiber [reinforced PTFE]</th>
<th>( L_f [\text{mm}] )</th>
<th>( E_{r1} )</th>
<th>( \Delta \varepsilon )</th>
<th>( \tan \delta )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( L_s [\text{mm}] )</td>
<td></td>
<td>( f_1 )</td>
<td>( f_2 )</td>
<td>( f_3 )</td>
</tr>
<tr>
<td>22.5 (W=4.2mm, h=0.8mm)</td>
<td>13.10535</td>
<td>0.89675</td>
<td>0.003300</td>
<td>0.003300</td>
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<td>21.9 (W=4.2mm, h=0.8mm)</td>
<td>13.10535</td>
<td>0.94137</td>
<td>0.003347</td>
<td>0.003300</td>
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<table>
<thead>
<tr>
<th>Samples</th>
<th>Material</th>
<th>PTFE</th>
<th>TPX</th>
<th>PE</th>
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<td>( d [\text{mm}] )</td>
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<td>1.28</td>
<td>1.28</td>
<td></td>
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<table>
<thead>
<tr>
<th>Results ( [\text{GHz}] )</th>
<th>( f_{\text{on}} )</th>
<th>( f_{\text{off}} )</th>
<th>( f_{\text{on}} )</th>
<th>( f_{\text{on}} )</th>
<th>( f_{\text{on}} )</th>
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<td>4.30369</td>
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<td>2.1052</td>
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<td>0.00150</td>
<td>0.00150</td>
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<td>0.00150</td>
</tr>
</tbody>
</table>

**Note:**
- PTFE : Polytetrafluoroethylene
- TPX : Poly(methylpentene)
- PE : Polyethylene
- \( \varepsilon_r \) \( \perp \) : \( \varepsilon_r \) of E direction perpendicular to the sheet
- \( \varepsilon_r // \) : \( \varepsilon_r \) of E direction parallel to the sheet

Calibration of \( \tan \delta \) : The \( \tan \delta \) of PTFE is adjusted to 0.0004* by controlling \( \alpha \).

### Table 2

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

<table>
<thead>
<tr>
<th>Resonator fiber [reinforced PTFE]</th>
<th>( L_f [\text{mm}] )</th>
<th>( L_s [\text{mm}] )</th>
<th>( E_{r1} )</th>
<th>( \Delta \varepsilon )</th>
<th>( \tan \delta )</th>
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<tbody>
<tr>
<td>( [\text{GHz}] )</td>
<td>( f_1 )</td>
<td>( f_2 )</td>
<td>( f_3 )</td>
<td>( f_1 )</td>
<td>( f_2 )</td>
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<td>34.55 (W=4.0mm, h=0.8mm)</td>
<td>8.76133</td>
<td>8.76133</td>
<td>8.76133</td>
<td>8.76133</td>
<td>8.76133</td>
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<td>36.15 (W=4.0mm, h=0.8mm)</td>
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<td>8.76133</td>
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<tr>
<td>( [\text{mm}] )</td>
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<td>( \Delta \varepsilon )</td>
<td>( \Delta \varepsilon )</td>
<td>( \Delta \varepsilon )</td>
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<tr>
<td>0.95861</td>
<td>0.95861</td>
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<td>0.95861</td>
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<td>0.95861</td>
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<tr>
<td>( \tan \delta )</td>
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<td>( \tan \delta )</td>
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<tr>
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<th>Material</th>
<th>Fiber-reinforced PTFE</th>
<th>Fiber-reinforced EPOXY</th>
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<td>1.50</td>
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<table>
<thead>
<tr>
<th>Results ( [\text{GHz}] )</th>
<th>( f_{\text{on}} )</th>
<th>( f_{\text{on}} )</th>
<th>( f_{\text{on}} )</th>
<th>( f_{\text{on}} )</th>
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<tr>
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</tr>
<tr>
<td>0.00150</td>
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<td>0.00150</td>
<td>0.00150</td>
<td>0.00150</td>
<td>0.00150</td>
</tr>
</tbody>
</table>

**Note:**
- Glass PTFE, Glass EPOXY: PTFE and EPOXY reinforced by glass fiber net.
- \( \varepsilon_r \) \( \perp \) : \( \varepsilon_r \) of E direction perpendicular to the sheet
- \( \varepsilon_r // \) : \( \varepsilon_r \) of E direction parallel to the sheet