Investigation of Measurement Techniques for the Determination of the Dielectric Constant of Substrate Boards for Microwave Circuits

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Outline

• Motivation
• Assumptions
• Method I : Capacitance Measurement.
• Method II : Full Sheet Resonance method.
• Method III : An Evaluation through a simple Microstrip Transmission Line Resonator.
• Total Results and Comparison.
• Conclusion
Motivation

• To investigate the measurement method for determination of relative dielectric constant of a substrate board:

• Example of substrate RO4003:
  - manufacturers’ result : \(3.38 \pm 0.05\)
  - recommended for use in circuit design: 3.55

- Three methods to be concerned here.
Assumptions

Stray electric field at the edge of the board.

(a) Air-filled laminate panel.

(b) Dielectric substrate filled laminate panel.
Assumptions

(a) Air-filled microstrip line with thickness of $h$.
(b) Air-filled laminate panel with thickness of $d$. ($d=2h$)
Assumptions

End-effect length $\Delta l$ (method I)

- $\varepsilon_r = 1.0$ (Air)

Fringing Capacitance (method I)

Microstrip transmission line.

Treated as open-ended transmission line resonator (method III)

Characteristic Impedance, $Z_c$
Method I: Capacitance Measurement.

- Several methods to determine the stray electric field.
- It can be represented as a Fringing / Edge capacitor or an End-effect length $\Delta l$. 
Method I : Capacitance Measurement.

Formula for the determination of the parallel-plate substrate board's capacitance $C_{\varepsilon r}$:

$$C_{\text{total/measured}} = \frac{\varepsilon_r \varepsilon_0 W \cdot L}{h} + 2C_{e1/f} + 2C_{e2/f} + C_{\varepsilon r}$$
Method I: Capacitance Measurement.

Determination of relative dielectric constant of the laminate panels (Inclusion of stray fields):

\[ \varepsilon_r = \frac{C_{\varepsilon_r} h}{\varepsilon_0 A} \]
Method II: Full Sheet Resonance method.

- Connecting probes

Modified wooden clothespin

1.5pF capacitor
Method II : Full Sheet Resonance method.

• Setup

Substrate Board (Test sample)

Probe

2-port

Probes

Connection of test sample of Substrate board to the network analyzer.

Network Analyzer
Method II: Full Sheet Resonance method.

- Determination of relative dielectric constant the substrate boards:

\[ \varepsilon_r = \frac{C_o^2}{4f_{mn}^2} \cdot \left\{ \left( \frac{m}{L} \right)^2 + \left( \frac{n}{W} \right)^2 \right\} \]

- \( C_o \): Speed of light. (2.9979x10^8 ms\(^{-1}\))
- \( f_{mn} \): Resonance frequency.
- \( (m,n) \): Corresponding resonance mode.
- \( W \): Width of the conducting.
- \( L \): Length of the microstrip line.
This method has to be carried out in few directions for the resonance frequencies measurement and the matching of resonance modes of \( m \) along the length and \( n \) along the width.
Method II : Full Sheet Resonance method.

• **Example results of RO4350 test sample:**

• Measured dimensions:
  - Length : 457.83 mm
  - Width : 305.33 mm

• Modified dimensions with inclusion of stray fields by end-effect length (Dimensions have been enlarged):
  - Length : 460.162 mm
  - Width : 307.788 mm
Method II: Full Sheet Resonance method.

• Example results of RO4350 test sample:

<table>
<thead>
<tr>
<th>Peaks</th>
<th>$f_0$ (MHz)</th>
<th>modes</th>
<th>Dielectric Constant, $\varepsilon_r$</th>
<th>Dielectric Constant, $\varepsilon_r$ (Inclusion of stray field)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>170.7</td>
<td>(1,0)</td>
<td>3.68</td>
<td>3.64</td>
</tr>
<tr>
<td>2</td>
<td>255.8</td>
<td>(0,1)</td>
<td>3.68</td>
<td>3.63</td>
</tr>
<tr>
<td>3</td>
<td>308.5</td>
<td>(1,1)</td>
<td>3.66</td>
<td>3.61</td>
</tr>
<tr>
<td>4</td>
<td>341.9</td>
<td>(2,0)</td>
<td>3.67</td>
<td>3.63</td>
</tr>
<tr>
<td>5</td>
<td>428.4</td>
<td>(2,1)</td>
<td>3.65</td>
<td>3.61</td>
</tr>
<tr>
<td>6</td>
<td>511.5</td>
<td>(0,2)</td>
<td>3.69</td>
<td>3.63</td>
</tr>
<tr>
<td>7</td>
<td>513.0</td>
<td>(3,0)</td>
<td>3.67</td>
<td>3.63</td>
</tr>
<tr>
<td>8</td>
<td>540.4</td>
<td>(1,2)</td>
<td>3.67</td>
<td>3.61</td>
</tr>
</tbody>
</table>

Average: 3.67

• Manufacturer’s results for RO4350:
  3.48±0.05
Method II : Full Sheet Resonance method.

Graph of $\varepsilon_r$ versus $f_0$ (MHz) of Sample RO4350

- A piece of substrate has been cut out and treated as a simple microstrip transmission line and open-ended transmission line resonator.

- The measured resonance frequency through S21measurement will be used to tune the corresponding dielectric constant of the substrate in a simulation (ADS).

- A simple Microstrip Transmission Line Resonator has been designed with aid of a simulation(ADS).
- Fabrication of the resonator. (Sample RO4350)
- S21 measurement has been carry out on the resonator.
- Measured resonance frequency will be used to tune the dielectric constant.

By bring near the probe to the strip line without touching it as creating a capacitive coupling to the measurement.

• The 1\textsuperscript{st} peak of resonance frequency has been measured and recorded down. It’s 251.7 MHz of resonance frequency.

• It’s 3.674 of the relative dielectric constant of the substrate (RO4350).

• Manufacturer’s results for RO4350: 3.48±0.05.
Total results of all three methods

Graph results of relative dielectric constant for sample RO4350

Average dielectric constant : 3.70
All results and comparison

- **Test sample RO4350:**
  - Average dielectric constant of three methods: 3.70
- Manufacturer’s dielectric constant: 3.48±0.05
- Recommended for use in circuit design:
  - 3.66 (from datasheet)
Conclusion

• Average relative dielectric constant of substrate boards show an improvement result with inclusion of stray electric field through these measurement techniques compared to manufacturer’s results.

• It’s suggested to include the effect in the determination methods of relative dielectric constant.
Thank You for Your attention!
Extra Slides
Method II: Full Sheet Resonance method.

- Capacitive coupling:
  - Capacitive coupling is needed to obtain more precise results of resonance frequencies measurement.
  - The of resonance frequencies will be shifted at above magnitude of -20dB.
• Resonance frequencies of high capacitive coupling have been shifted for few kHz compared to low capacitive coupling.

• Hence, Some papers have been added to reduce the capacitive coupling, in order to get more precise result of resonance frequencies.

Example:

m1
Freq= \textbf{171.6MHz}
dB(S(2,1))= -34.033

m3
Freq= \textbf{172.2MHz}
dB(S(2,1))= -34.033

It is shifted few kHz of resonance frequency.
Capacitive coupling:

<table>
<thead>
<tr>
<th>1st peak (MHz)</th>
<th>dB(S(2,1))</th>
<th>2nd peak (MHz)</th>
<th>dB(S(2,1))</th>
<th>3rd peak (MHz)</th>
<th>dB(S(2,1))</th>
<th>C1(pF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>174,22</td>
<td>-84,06</td>
<td>348,39</td>
<td>-53,83</td>
<td>522,51</td>
<td>-42,09</td>
<td>0,01</td>
</tr>
<tr>
<td>174,22</td>
<td>-72,96</td>
<td>348,39</td>
<td>-40,47</td>
<td>522,51</td>
<td>-45,30</td>
<td>0,02</td>
</tr>
<tr>
<td>174,22</td>
<td>-59,38</td>
<td>348,39</td>
<td>-42,04</td>
<td>522,51</td>
<td>-40,22</td>
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<td>174,21</td>
<td>-47,82</td>
<td>348,38</td>
<td>-36,29</td>
<td>522,50</td>
<td>-17,33</td>
<td>0,10</td>
</tr>
<tr>
<td>174,21</td>
<td>-24,01</td>
<td>348,38</td>
<td>-16,38</td>
<td>522,49</td>
<td>-8,49</td>
<td>0,20</td>
</tr>
<tr>
<td>174,20</td>
<td>-11,08</td>
<td>348,36</td>
<td>-1,16</td>
<td>522,46</td>
<td>-2,02</td>
<td>0,50</td>
</tr>
<tr>
<td>174,19</td>
<td>-8,71</td>
<td>348,33</td>
<td>-0,47</td>
<td>522,42</td>
<td>-0,15</td>
<td>1,00</td>
</tr>
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<td>174,15</td>
<td>-1,36</td>
<td>348,27</td>
<td>-0,01</td>
<td>522,34</td>
<td>-0,01</td>
<td>2,00</td>
</tr>
<tr>
<td>174,12</td>
<td>-0,28</td>
<td>348,22</td>
<td>-0,01</td>
<td>522,28</td>
<td>0,00</td>
<td>3,00</td>
</tr>
</tbody>
</table>

Limitation of capacitive coupling for the corresponding resonance frequencies.
Total results of all three methods

- **Test sample RO4350:**

<table>
<thead>
<tr>
<th>RO4350</th>
<th>Test methods</th>
<th>Relative dielectric constant, $\varepsilon_r$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Method I(A)</td>
<td>3.74</td>
</tr>
<tr>
<td></td>
<td>Method I(B)</td>
<td>3.72</td>
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<tr>
<td></td>
<td>Method I(C)</td>
<td>3.73</td>
</tr>
<tr>
<td></td>
<td>Method II</td>
<td>3.62</td>
</tr>
<tr>
<td></td>
<td>Method III</td>
<td>3.67</td>
</tr>
<tr>
<td></td>
<td><strong>Average</strong></td>
<td><strong>3.70</strong></td>
</tr>
</tbody>
</table>