

Number 2.5.5.15	
Subject Relative Permittivity and Loss Tangent Using a Split-Post Dielectric Resonator	
Date 06/22	Revision N/A
Originating Task Group 3-11a IPC-4101 Task Group	

IPC-TM-650 TEST METHODS MANUAL

1 Scope

This test method describes a way to measure the relative permittivity (ϵ_r) and loss tangent ($\tan\delta$) (also called dielectric constant, Dk , and dissipation factor, Df) of base materials for printed boards at frequencies from 1 GHz to 20 GHz using a split post dielectric resonator (SPDR).

2 Applicable Documents

- 2.1 IPC-TM-650 Method 2.5.5.2 Dielectric Constant and Dissipation Factor of Printed Wiring Board Material – Clip Method
- 2.2 IPC-TM-650 Method 2.5.5.3 Permittivity (Dielectric Constant) and Loss Tangent (Dissipation Factor) of Materials (Two Fluid Cell Method)
- 2.3 IPC-TM-650 Method 2.5.5.5 Stripline Test for Permittivity and Loss Tangent (Dielectric Constant and Dissipation Factor) at X-Band
- 2.4 IPC-TM-650 Method 2.5.5.5.1 Stripline Test for Complex Relative Permittivity of Circuit Board Materials to 14 GHz
- 2.5 IPC-TM-650 Method 2.5.5.9 Permittivity and Loss Tangent, Parallel Plate, 1MHz to 1.5 GHz

3 Test Specimens

3.1 All base materials specimens shall have the metallic foil layer removed by etching or other suitable means and shall be thoroughly cleaned. Each specimen shall be marked in the upper left corner with an engraving pencil or equivalent.

3.2 The dimensions of the test specimen shall be larger than the outer dimension of the fixture. See Figure 1.

The size of the specimen shall be larger than the internal diameter D of the metal enclosures, and the maximum thickness of the specimen shall be smaller than the distance h_g between the metal enclosures of the fixture.

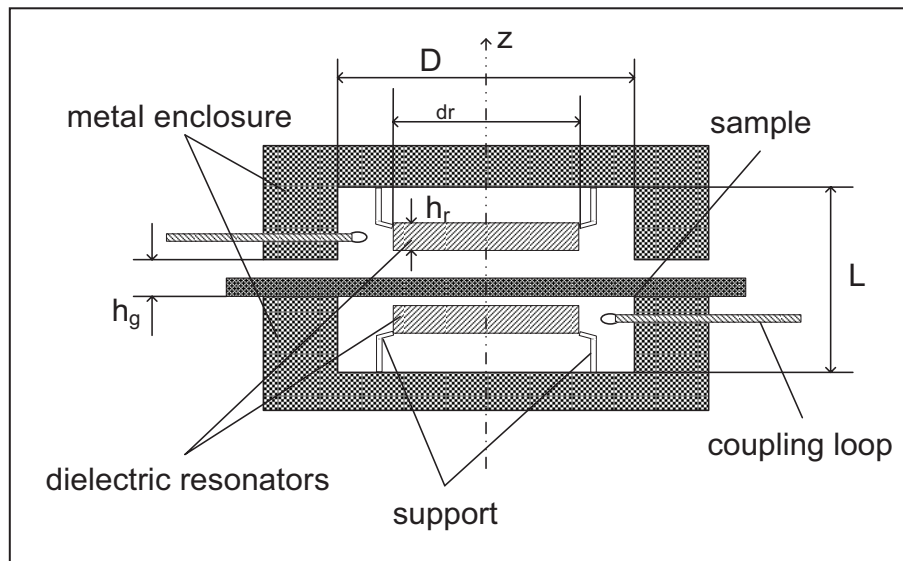


Figure 1 – Diagram of SPDR Test Fixture

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where

h_g is the distance between the metal enclosures of the fixture;

D is internal diameter of the metal enclosures;

L is internal height of the metal enclosures;

d_r is the diameter of the dielectric resonator;

h_r is the thickness of the dielectric resonator.

3.3 Specimen Thickness The thicker the specimen the less error occurs in the measurements. A thin specimen may be stacked up to a minimum of 0.4 mm [0.016 in] to improve measurement accuracy. The air gaps between the sample and the fixture do not affect the measurement.

3.4 Number of Specimens Three specimens for the test at room temperature and one specimen for the test at variable temperatures are required for each SPDR test fixture for this test. Table 1 shows the supported specimen dimensions

Table 1 – Specimen Dimensions

Nominal Frequency [GHz]	Specimen Sizes mm [inch]	Maximum Thickness mm [inch]
1	150 X 150 [5.9 X 5.9]	6.0 [0.24]
3	80 X 80 [3.2 X 3.2]	3.0 [0.12]
5 to 6	80 X 80 [3.2 X 3.2]	2.0 [0.08]
9 to 10	80 X 80 [3.2 X 3.2]	0.9 [0.035]
13 to 16	50 X 35 [2.0 X 1.4]	0.6 [0.024]
18 to 20	15 X 15 [0.6 X 0.6]	0.5 [0.020]

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4 Apparatus or Material

4.1 Test System The schematic diagram of the test system is shown in Figure 2. The test can be conducted at room temperature or an elevated temperature as indicated.

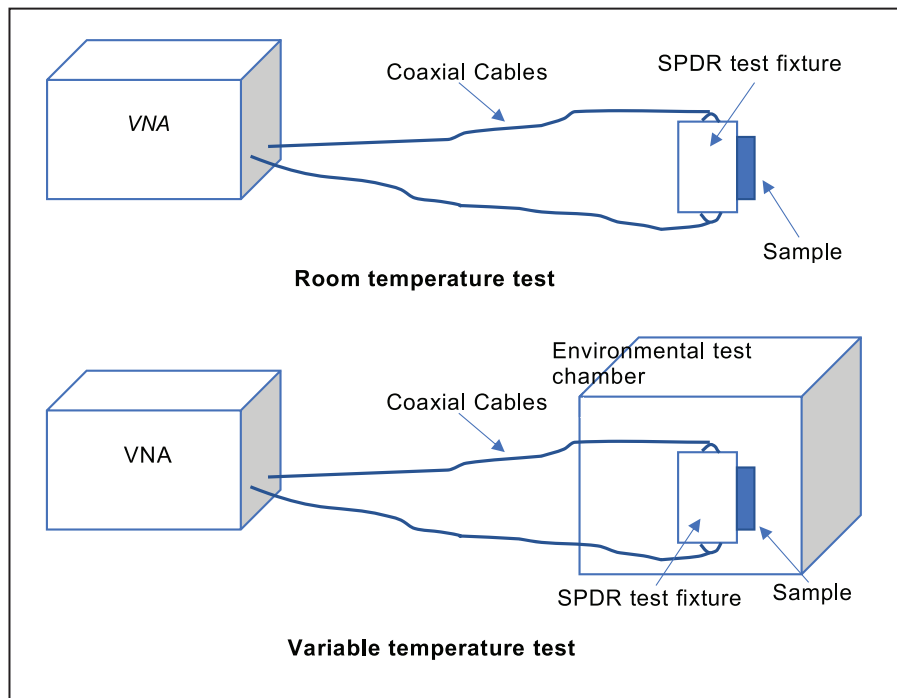


Figure 2 – Schematic Diagram of Test System

4.2 Test Fixture Parameters Table 2 shows the typical relationship between the SPDR test fixture’s nominal frequency and h_g and D . For different test frequencies, the corresponding SPDR test fixture of nominal frequency shall be used.

Table 2 – Test Fixture Configurations

SPDR Test Frequency [GHz]	D mm [inch]	h_g mm [inch]
1	120 [4.7]	6.0 [0.24]
3	50 [2.0]	3.0 [0.12]
5 to 6	30 [1.2]	2.0 [0.08]
9 to 10	22 [0.9]	0.9 [0.035]
13 to 16	15 [0.6]	0.6 [0.024]
18 to 20	10 [0.4]	0.5 [0.020]

4.3 Vector Network Analyzer (VNA) The frequency range of the VNA shall be 500 MHz to 20 GHz, The dynamic range of the VNA shall be more than 60 dB.

4.4 Calibration Reference The calibration equipment shall include a standard reference sample. For example, a single-crystal quartz or equivalent reference, and a calibration assembly for the VNA.

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4.5 Micrometer A micrometer with a minimal resolution of 0.001mm [0.00004 inch] or better.

4.6 Circulating Oven An air circulating oven with capable of a temperature of $105 \pm 1 \text{ }^\circ\text{C}$ [$221 \pm 1.8 \text{ }^\circ\text{F}$].

4.7 Test Chamber A test chamber for variable temperature testing capable of a range of $-125 \text{ }^\circ\text{C}$ to $+110 \text{ }^\circ\text{C}$ [-193 to $+230 \text{ }^\circ\text{F}$]. Other temperature ranges may be used as agreed between user and supplier. Temperature accuracy must be $\pm 1 \text{ }^\circ\text{C}$ ($\pm 1.8 \text{ }^\circ\text{F}$) of actual set point.

5 Procedure

5.1 Preconditioning All specimens shall be conditioned at $23 \pm 2 \text{ }^\circ\text{C}$ [$73.4 \pm 3.6 \text{ }^\circ\text{C}$] and $50 \pm 5 \text{ } \%$ RH for a minimum of 24 hour after etching and prior to testing.

5.2 Testing of relative permittivity and loss tangent at room temperature

5.2.1 The ambient test temperature should be $23 \text{ }^\circ\text{C} \pm 2 \text{ }^\circ\text{C}$ [$73.4 \pm 3.6 \text{ }^\circ\text{F}$]. The variation should not exceed $\pm 1 \text{ }^\circ\text{C}$ [$\pm 1.8 \text{ }^\circ\text{F}$] during the test. Allow a minimum of 30 minutes for the VNA to warm up and stabilize.

5.2.2 Select a SPDR test fixture in accordance with the test frequency. The specimen size and thickness shall comply with the requirements specified in Table 1. For example, if the test frequency is 10 GHz, a SPDR test fixture with 10 GHz nominal frequency should be selected. The supported specimen size is 80 mm \times 80 mm [$3.2 \text{ X } 3.2 \text{ inch}$] and the maximum thickness of specimens is no more than 0.9 mm [0.035 inch].

5.2.3 Connect the SPDR test fixture to VNA. The test fixture shall be kept horizontal. Set the VNA parameters according to the manufacturer's instructions and the nominal frequency of the SPDR fixture.

5.2.4 Measure resonance frequency (f_0) and Q-factor (Q_0) values of the empty resonator.

5.2.5 Utilize a micrometer to measure the thickness of the specimen and record as h . Insert the specimen into the test fixture. The side with marking is face up and the edge of this side has to be aligned with the fixture edge.

5.2.6 Measure the resonance frequency (f_s) and Q-factor (Q_s) of the resonator containing the specimen. A plot of the change of resonance frequency with or without the specimen is shown in Figure 3.

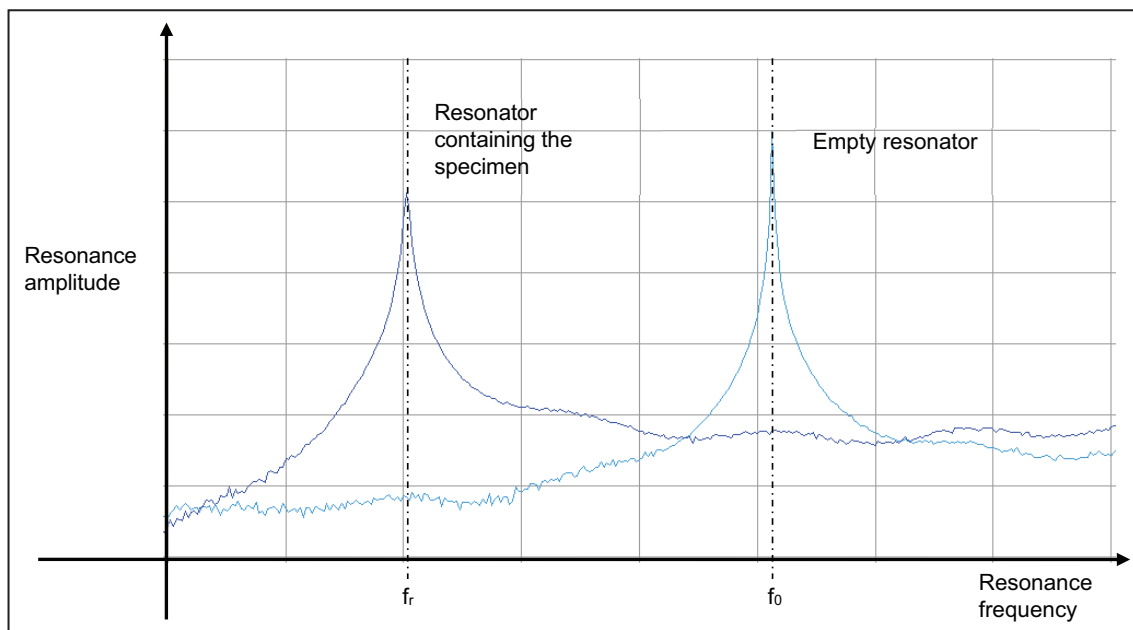


Figure 3 – Plot Showing Change of Resonance Frequency

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5.2.7 Calculation It is recommended to use the computer software provided by the equipment supplier for this calculation. If software not available, the Relative Permittivity and Loss Tangent at room temperature shall be calculated using the formula shown below.

The relative permittivity (ϵ_r) shall be calculated according to Equation (1).

$$\epsilon_r = 1 + \frac{f_0 - f_s}{hf_0 K_\epsilon(\epsilon_r, h)} \quad (1)$$

where

ϵ_r is relative permittivity;

h is the thickness of the specimen under test, mm;

f_0 is the resonant frequency of empty SPDR Fixture;

f_s is the resonant frequency of resonator with the dielectric specimen;

$K_\epsilon(\epsilon_r, h)$ is a function of ϵ_r and h . For a fixed resonant cavity, its physical parameters (size, dielectric resonators ϵ_r) should have been identified. $K_\epsilon(\epsilon_r, h)$ is pre-computed and tabulated by electromagnetic field simulation with the strict Rayleigh-Ritz method. Put the empty SPDR frequency (f_0), the resonant frequency with dielectric specimen (f_s) and the thickness of the specimen (h) under test into Equation (1). Enter a similar arbitrary value of the relative permittivity of the sample, and use a successive approximation algorithm. After several iterations, end the calculation when the relative error of the last two calculated relative permittivities is less than 0.1 %. The last calculated data is taken as the relative permittivity of the specimen.

The loss tangent shall be calculated according to Equation (2).

$$\tan \delta = \frac{(Q_s^{-1} - Q_{DR}^{-1} - Q_C^{-1})}{P_{es}} \quad (2)$$

where

$\tan \delta$ is loss tangent;

Q_s is the unloaded Q-factor of a resonant fixture containing the specimen;

Q_c is the Q-factor depending on metal losses for the resonant fixture containing the specimen;

Q_{DR} is the Q-factor depending on dielectric losses in dielectric posts for fixture containing the specimen;

P_{es} is electromagnetic energy filling factor of the specimen. After identifying the physical parameters of resonant cavity, the electromagnetic energy filling factor p_{es} can be determined by electromagnetic field simulation. For a fixed resonant cavity, p_{es} is a constant value. Some additional information is showed in Annex B.

5.2.8 Measure the two remaining specimens by repeating steps 5.2.3 through 5.2.7.

5.2.9 If another test frequency is selected, change the SPDR test fixture in accordance with the test frequency. And then repeat steps 5.2.2 through 5.2.7.

5.3 Testing of relative permittivity and loss tangent at variable temperatures

5.3.1 The ambient test temperature should be $23 \text{ }^\circ\text{C} \pm 2 \text{ }^\circ\text{C}$ [$73.4 \pm 3.6 \text{ }^\circ\text{F}$]. The variation should not exceed 1°C [$1.8 \text{ }^\circ\text{F}$] during the test. Allow at least 30 minutes for the VNA to warm up.

5.3.2 Select a SPDR test fixture in accordance with the test frequency. The specimen size and thickness shall comply with requirements specified in Table 1. For example, if the test frequency is 10 GHz, a SPDR test fixture with 10 GHz nominal frequency should be selected. The supported specimen size is 80 mm \times 80 mm [3.2 X 3.2 inch] and the maximum thickness of specimen is no more than 0.9 mm [0.035 inch]. Connect the SPDR test fixture to VNA. The test fixture shall be kept in a horizontal position in the test chamber. Set the VNA parameters according to the manufacturer's instructions and the nominal frequency of the SPDR fixture.

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5.3.3 Adjust the test temperature of the test chamber. After reaching the set temperature (T), hold it for at least 15 minutes. Measure resonance frequency $f_0(T)$ and Q-factor $Q_0(T)$ of the empty resonator.

Note: The resonance peak should be between -40 dB and -45 dB. Adjust the position of the coupling loops to achieve this range ensuring their position is symmetrical. When measuring the Q-factor, the frequency span of the VNA shall be adjusted such that it is between 110 % and 200 % of the full width at half maximum of the resonant curve.

5.3.4 Utilize a micrometer to measure the thickness of the specimen, record as h . The environmental test chamber shall be returned to room temperature. Insert the specimen into the test fixture. The side with marking is face up and the edge of this side has to be aligned with the fixture edge.

5.3.5 Repeat step 5.3.3. Measure the resonance frequency $f_s(T)$ and Q-factor $Q_s(T)$ of the resonator with the specimen at temperature T .

Note: When measuring the Q-factor, the frequency span of the VNA should be adjusted such that it is between 110 % and 200 % of the full width at half maximum of the resonant curve.

5.3.6 Calculate following the instructions in step 5.2.7, the value of the relative permittivity $Dk(T)$ and the loss tangent $Df(T)$ at temperature T .

5.3.7 If another test temperature is required, repeat steps 5.3.2 through 5.3.6 at the new temperature.

5.3.8 Thermal coefficient of relative permittivity ϵ_r (short for $TC\epsilon_r$) is the change rate of relative permittivity per temperature change. The unit of $TC\epsilon_r$ is $10^{-6}/^{\circ}\text{C}$. Generally, the relative permittivity of a specimen at its base temperature T_{ref} of 23 $^{\circ}\text{C}$ (is used as the base relative permittivity $Dk(T_{\text{ref}})$). For temperature T , $TC\epsilon_r$ shall be calculated according to Equation (3).

$$TC\epsilon_r = \frac{Dk(T) - Dk(T_{\text{ref}})}{(T - T_{\text{ref}}) \times Dk(T_{\text{ref}})} \times 10^6 \quad (3)$$

where

$TC\epsilon_r$ is thermal coefficient of ϵ_r , $10^{-6}/^{\circ}\text{C}$;
 T is test temperature, $^{\circ}\text{C}$;
 T_{ref} is base temperature, $^{\circ}\text{C}$;
 $Dk(T)$ is relative permittivity at temperature T ;
 $Dk(T_{\text{ref}})$ is relative permittivity at temperature T_{ref} .

5.3.9 The thermal coefficient of $\tan\delta$ ($TC \tan\delta$) is the change in rate of loss tangent per temperature (every increase or decrease 1°C [1.8°F]). The unit of $TC \tan\delta$ is $10^{-6}/^{\circ}\text{C}$. Generally, the loss tangent of specimen at base temperature T_{ref} of 23 $^{\circ}\text{C}$ [73.4°F] is used as the base loss tangent $Df(T_{\text{ref}})$. For temperature T , $TC \tan\delta$ is calculated according to the Equation (4).

$$TC \tan\delta = \frac{Df(T) - Df(T_{\text{ref}})}{(T - T_{\text{ref}}) \times Df(T_{\text{ref}})} \times 10^6 \quad (3)$$

where

$TC \tan\delta$ is thermal coefficient of $\tan\delta$, $\text{ppm}/^{\circ}\text{C}$;
 T is the test temperature, $^{\circ}\text{C}$;
 T_{ref} is base temperature, $^{\circ}\text{C}$;
 $Df(T)$ is loss tangent at temperature T ;
 $Df(T_{\text{ref}})$ is loss tangent at temperature T_{ref} .

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5.3.10 If another test frequency is selected, change the SPDR test fixture in accordance with the test frequency. Then repeat steps 5.3.2 through 5.3.9.

6 Report

6.1 For room temperature tests, report the following:

6.1.1 Test environment (temperature, humidity);

6.1.2 Test frequency;

6.1.3 Report the values and the average values of the relative permittivity and loss tangent at test frequency;

6.1.4 The preconditioning of the specimen;

6.1.5 Any anomalies in the test or variations from this test method.

6.2 For variable temperature tests, report the following:

6.2.1 Test temperature (T) and base temperature (T_{ref});

6.2.2 Test frequency;

6.2.3 $Dk(T)$ and $Df(T)$ at test temperature (T);

6.2.4 $TC\epsilon_r$ and $TC \tan\delta$;

6.2.5 $Dk(T_{ref})$ and $Df(T_{ref})$;

6.2.6 If more than one test temperature is necessary, report the curve diagram of the relative permittivity and loss tangent in accordance with the temperature variation ;

6.2.7 The preconditioning of the specimen;

6.2.8 Any anomalies in the test or variations from this test method.

7 Notes

7.1 Accuracy of measurements of a sample of thickness h .

7.2 Permittivity measurement: $\Delta\epsilon/\epsilon = \pm[0.0015 + \Delta h/h]$.

7.3 Loss tangent: $\Delta \tan\delta = \pm 2 \times 10^{-5}$ or $\pm 0.03 \times \tan\delta$ whichever is higher.

7.4 Clean test heads, standard materials and fixtures regularly.

7.5 To prevent damage to the test fixture because of the variable temperature tests, verify the test system regularly with a standard reference sample. For example, single-crystal quartz is used as standard reference sample of thickness 0.4 mm. The deviation of the relative permittivity measurement between the test result and the nominal value of the standard reference sample shall be less than $\pm 0.7\%$, while the deviation of the loss tangent shall be less than $\pm 2 \times 10^{-5}$.