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IPC-TM-650
TEST METHODS MANUAL

Number	
2.5.5.13	
Subject	
Relative Permittivity and Loss Tangent Using a Split-Cylinder Resonator	
Date	Revision
01/07	
Originating Task Group	
High Frequency Resonator Test Method Task Group (D-24c)	

1 Scope This method describes the nondestructive measurement of the relative permittivity and loss tangent of unclad dielectric substrates at microwave frequencies using a split-cylinder resonator (see Figure 1).

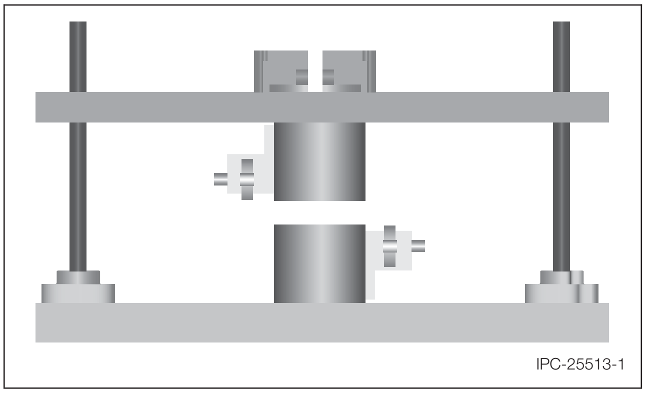

Figure 1 Split-Cylinder Resonator

This test method is directly applicable for measuring the in-plane (the plane parallel to the surface of the specimen) permittivity of the specimen because the electric field is in-plane. The permittivity of isotropic dielectrics can also be measured with this method.

Note: This measurement method does not measure the out-of-plane (direction normal to the surface of the specimen) permittivity of the specimen. However, for most printed boards the measurement uncertainties associated with this method are typically less than the difference between in-plane and out-of-plane permittivity values. Furthermore, comparison with methods measuring the out-of-plane permittivity is difficult because those methods typically do not provide measurement confidence intervals.

2 Applicable Documents See 6.2.

3 Test Specimen The test specimen is an unclad dielectric substrate. The substrate geometry can be either square or circular as long as the substrate extends beyond the diameter *2a* of the two cylindrical cavity sections as shown in Figure 2. In particular, for the 10 GHz split-cylinder resonator discussed in this method, the dimensions of the substrate should be at least 50.0 mm [1.97 in] in diameter for circular samples or 50.0 mm [1.97 in] on a side for square samples.

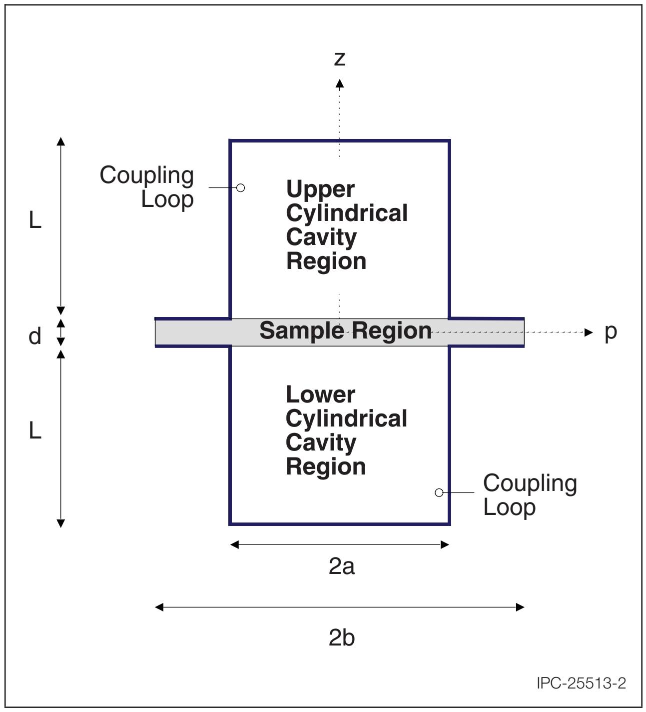

Figure 2 Split-Cylinder Resonator Diagram

Although the dielectric substrate thickness can vary from 0.05 mm to 5.0 mm [0.0020 in to 0.20 in], thin substrates may lead to larger measurement uncertainties, while the dielectric losses in thicker substrates may prevent the split-cylinder fixture from resonating properly. A substrate thickness on the order of 1.0 mm [0.040 in] is typical.

The measurement theory assumes the dielectric substrate has a uniform thickness. Therefore, to reduce the measurement uncertainty, variation and uncertainty in substrate thickness should be minimized. A typical uncertainty in thickness should be no more than 0.02 mm [0.00079 in]. In general, warped samples should also be avoided as these can lead to biases in the calculated values of the relative permittivity and loss tangent.

For the split-cylinder resonator described here, the measurement frequency of the split-cylinder resonator is a function of the relative permittivity and thickness of the substrate. Thicker substrates and higher values of relative permittivity drive the resonant frequency lower, as shown in Figure 6.

4 Measurement Apparatus

4.1 Split-Cylinder Resonator The method employs a split-cylinder resonator, which is a cylindrical cavity separated into two halves of equal length, with a dielectric substrate placed in the gap between the two cavity sections. The split-cylinder resonator must be constructed to allow an adjustable, variable gap between the two cavity sections for introduction of the dielectric substrate. Additional details about the construction of a split-post resonator are given in the references described in 6.2. Over the years there have been commercial manufacturers of this fixture.

In order to excite and detect the desired fundamental TE_{011} resonant mode in the split-cylinder resonator, a coupling loop is introduced, through a small hole in the cavity wall, in each of the two cavity regions. The plane of the coupling loop should be parallel to the plane of the sample, in order to allow maximum interaction with the vertical component of the magnetic field. Each of the coupling loops is connected to a coaxial transmission line that is connected to the input port of a network analyzer. To minimize the effect of coupling losses, the distance to which the loops extend radially into each of the cavity sections must also be adjustable. In addition to the fundamental TE_{011} mode, higher modes can be used to extend the measurement frequency. Typical measurements on fused silica with higher mode measurements are shown in Figures 3 and 4.

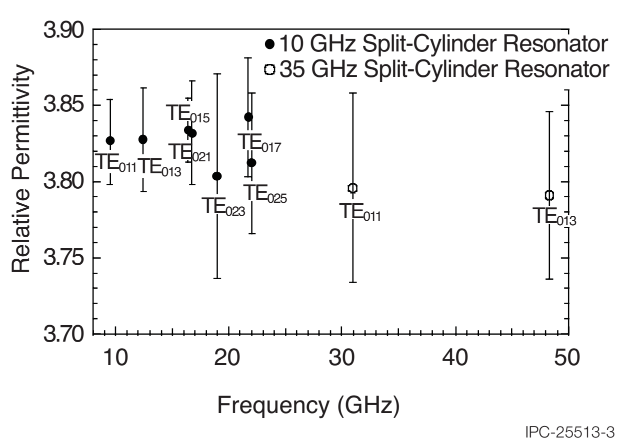

Figure 3 Typical Measurements of the Real Part of the Permittivity using 10 GHz and 35 GHz Split-cylinder Resonators including Measurements with Higher Modes

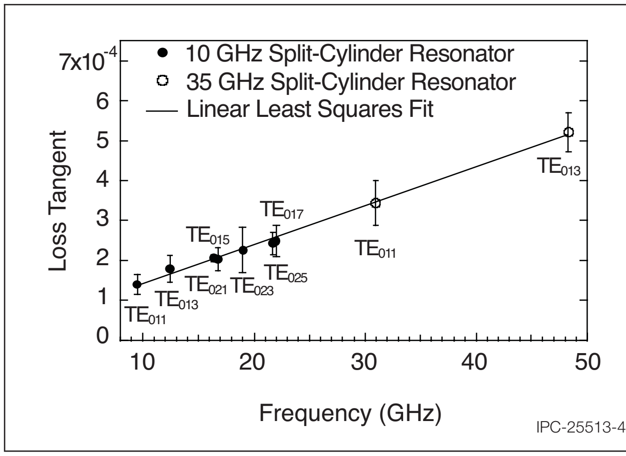

Figure 4 Typical Measurements of the Loss-tangent using 10 GHz and 35 GHz Split-cylinder Resonators including Measurements with Higher Modes

4.2 Network Analyzer A scalar or vector network analyzer is necessary to perform the measurement with the split-cylinder resonator. Commercially available network analyzers operate over various frequency ranges, so care is needed to ensure that the network analyzer covers the necessary frequency range for the particular split-cylinder resonator used.

4.3 Digital Micrometer The dielectric substrate thickness can be measured with a digital micrometer with a minimal resolution of 0.001 mm [0.000039 in].

5 Procedure

5.1 Turn on the network analyzer and allow the unit to warm-up and stabilize according to the manufacturer's instructions.

5.2 Connect the network analyzer's two input ports to the split-cylinder resonator's coupling loops using coaxial transmission lines.

5.3 Measure the thickness of the substrate over several locations using a digital micrometer, and compute the mean substrate thickness.

5.4 Determine split-cylinder resonator properties. The length, radius and conductivity of the split-cylinder resonator must be known before the substrate relative permittivity and loss tangent can be calculated. If these variables have not been already determined, the following procedure can be used:

5.4.1 Measure the length L of each of the two split-cylinder resonator sections over several locations and compute the mean length of both sections.

5.4.2 With the split-cylinder empty (no substrate) and closed (d=0), find the TE_{011} resonance with the network analyzer. To reduce the coupling losses to a negligible level, adjust the radial position of the coupling loops so that the peak of the resonance curve is less than -40 dB. For the particular 10 GHz split-cylinder resonator described in this method, the resonant frequency should be approximately 10.04 GHz. If another split-cylinder geometry is being used, use the following approximation to estimate the TE_{011} resonant frequency of an empty split-cylinder resonator:

$$f_{011} = \frac{c}{2\pi}\sqrt{\left(\frac{j_1}{a}\right)^2 + \left(\frac{\pi}{2L}\right)^2}$$

where c is the speed of light in a vacuum, j_1 is the first zero of the Bessel function of the first kind J_1, a is the split-cylinder radius in meters and L is the length, in meters, of each of the split-cylinder sections as shown in Figure 2.

5.4.3 Once the TE_{011} resonance has been identified and displayed on the network analyzer display, measure the resonant frequency f_{011} and quality factor Q of the resonance and use the following expressions to compute the radius a and the conductivity σ of the empty split-cylinder's resonator sections:

$$a = j_1\left[\left(\frac{2\pi f_{011}}{c}\right)^2 - \left(\frac{\pi}{2L}\right)^2\right]^{-\frac{1}{2}}$$

$$\sigma = \frac{2\pi f_{011}\mu_0}{2R_s^{\,2}}$$

where μ_o is the permeability of free space and

$$R_s = \frac{\sqrt{\frac{\mu_0}{\varepsilon_0}}\left[\left(\frac{j_1}{a}\right)^2 + \left(\frac{\pi}{2L}\right)^2\right]^{\frac{3}{2}}}{2Q\left[\frac{1}{2L}\left(\frac{\pi}{2L}\right)^2 + \frac{1}{a}\left(\frac{j_1}{a}\right)^2\right]}$$

5.5 Estimate the TE_{011} Resonant Frequency of Substrate-Loaded Split-Cylinder Resonator In addition to the desired TE_{011} resonant mode, other modes are excited in the split-cylinder resonator as shown in Figure 5. Depending on the thickness and relative permittivity of the dielectric substrate being measured, the resonant frequency for the split-cylinder plus substrate can be significantly lower than the resonant frequency of the empty split-cylinder resonator as shown in Figure 6.

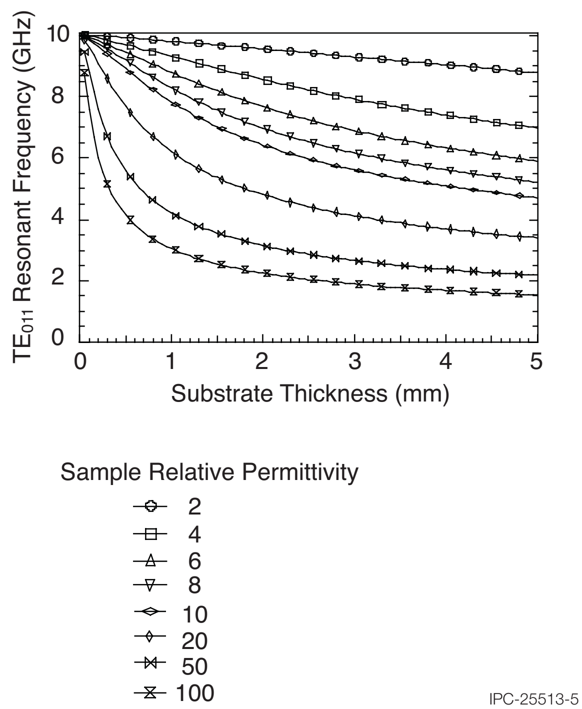

Figure 5 Frequency of the TE_{011} Resonant Mode as a Function of Permittivity and Substrate Thickness for the 10 GHz Split-Cylinder Resonator

In order to identify the correct mode, one can use Figure 6 to predict the resonant frequency of the TE_{011} resonant mode. For a more accurate estimate of this resonant frequency and the frequencies of the higher-order resonant modes, software is available from the National Institute of Standards and Technology (NIST) which calculates the split-cylinder resonator dimensions, substrate thickness, and provides an estimate of the relative permittivity of the substrate. As of the publication of this method, additional commercial vendors are developing similar software and will be listed through the IPC-TM-650 Test Methods web page.

5.6 Measure the Relative Permittivity and Loss Tangent

5.6.1 Place the substrate in the gap separating the two cavity sections of the split-cylinder resonator in such a way that

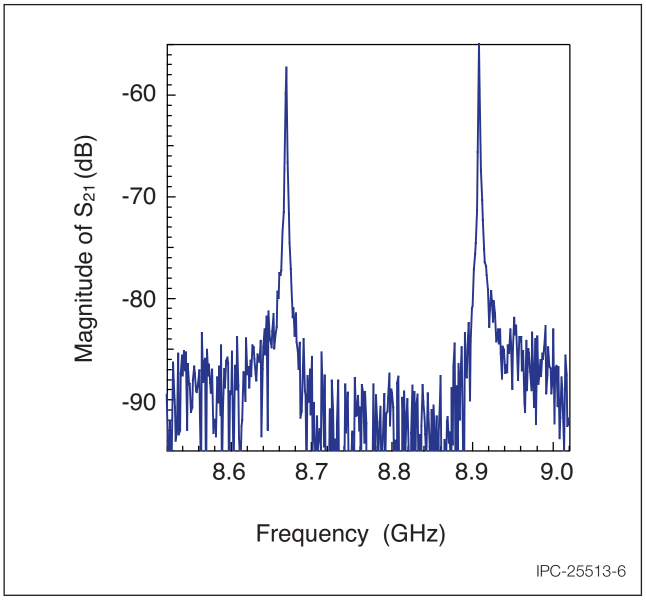

Figure 6 Typical Multiple Split-Cylinder Resonator Resonances

the substrate extends beyond the circumference of both cavity sections. Adjust the separation of the two resonator sections so that the substrate is held by the weight of the upper cavity between the two cavity sections.

5.6.2 Using the estimate calculated in 5.3, measure the resonant frequency and quality factor of the TE_{011} resonant mode using the network analyzer. Since the split-cylinder resonator is a two-port cavity, the network analyzer should be set to measure S_{21}, the scattering parameter that measures the transmission through the cavity. The resonance may have a significant amount of noise, so it may be necessary to adjust the amount of averaging performed by the network analyzer. In some cases where the resonance curve is near the noise floor, increasing the coupling level of the split-cylinder resonator may be necessary to improve the signal to noise level, although this may introduce a small amount of coupling loss.

5.6.3 When using the available software, the routine will calculate the relative permittivity and loss tangent of the dielectric substrate after properly identifying the TE_{011} resonant mode. These values are displayed in the software front panel, including an estimate of the measurement uncertainties for the relative permittivity and loss tangent.

6 Notes If additional measurements are needed at higher frequencies, the available software will provide the frequencies of the higher-order TE_{0np} resonant modes. The user must ensure that these modes are symmetric and not distorted by adjacent resonant modes.

The uncertainties in the real part and loss tangent measurement will be calculated automatically from the uncertainties in various dimensions that are specified. The major source of uncertainty will be the uncertainty in the substrate thickness.

Note that the electric field of the TE_{011} resonant mode is in the plane of the substrate. Therefore, if the substrate is anisotropic, the measured component of the relative permittivity also is in the plane of the substrate.

6.1 Software Availability Software may be available from commercial vendors and in addition executable code is available from the Electromagnetic Properties of Materials Project at the National Institute of Standards and Technology (NIST, Boulder, CO). As commercial vendor software becomes available, IPC will provide listings for these at the IPC-TM-650 web page located at www.ipc.org, under ''Standards.''

6.2 References

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