Permittivity Measurements of PC Board and Substrate Materials using the HP 4291B and HP 16453A

Application Note 1300-3

Introduction

Relative complex permittivity (permittivity and loss tangent) of printed circuit (PC) board and substrate material is a critical parameter that affects circuit performance. Characterizing this parameter at RF is becoming more important because of increased clock frequencies used in today's high speed computers. Bandwidths of 10 to 20 times the clock frequency are required for good signal integrity. Thus in digital designs, analog bandwidths to 1 GHz and higher are becoming common with clock frequencies of 50 to 100MHz. In addition, performance of dielectric materials at RF is equally important for wireless communication circuits and components.

Measuring sheet dielectric material at RF has been difficult. No RF parallel plate measurement solution has existed until the recent introduction of the HP 4291B RF Impedance/Material Analyzer with the HP 16453A Dielectric Material Test Fixture. Combined with the optional material measurement firmware, the analyzer offers a simple and highly accurate solution to sheet-material permittivity measurements from 1 MHz to 1 GHz. This note summarizes the current measurement techniques and discusses the solutions now available using the HP 4291B analyzer system.
Background

Relative complex permittivity (permittivity and loss factor/loss tangent) of the dielectric material affect the bandwidth (necessary for high speed signal transmission) and circuit density.

- For high operating frequencies: High speed signal transmission and low signal attenuation are desired in many applications. The relationship of relative complex permittivity to signal transmission speed and attenuation is shown below:

  Velocity: \( V = \frac{C}{\sqrt{\varepsilon_r}} \)

  Attenuation: \( A = \frac{f \times \sqrt{\varepsilon_r \times \tan \delta}}{c} \)

  These equations show that low permittivity and low loss are required to achieve high operating frequencies. For this reason, PC boards and substrate material have lower permittivity (typically 2 to 10) and loss tangent (typically 0.01 to 0.0001) compared with other dielectric materials.

- For high circuit density: Small interconnect size is required. The equation and graph in Figure 1 show that for a constant characteristic impedance, increasing the permittivity will reduce the interconnect size. Thus for high-density interconnects (IC packages, MCM), the substrate material will have higher permittivity values, typically 6 to 10.

A range of measurements are required to characterize dielectric material used for PC boards and substrates. Table 1 shows typical material parameters and operating conditions. Note that due to the wide temperature range found in electronic applications, evaluation of permittivity over temperature (and humidity) extremes is often desired.

<table>
<thead>
<tr>
<th>Application</th>
<th>PC board</th>
<th>Substrate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material Type</td>
<td>Glass Epoxy, PI, EP</td>
<td>Alumina, Ceramic</td>
</tr>
<tr>
<td>Frequency</td>
<td>1 MHz to &gt;1 GHz</td>
<td>1 MHz to &gt;1 GHz</td>
</tr>
<tr>
<td>Permittivity</td>
<td>2 to 6</td>
<td>6 to 10</td>
</tr>
<tr>
<td>Loss Tangent</td>
<td>0.01 to 0.0001</td>
<td>0.01 to 0.001</td>
</tr>
<tr>
<td>Thickness</td>
<td>0.02 to 2 mm</td>
<td>0.5 to 2 mm</td>
</tr>
<tr>
<td>Operating Temperature</td>
<td>-55°C to 150°C</td>
<td>-55°C to 200°C</td>
</tr>
</tbody>
</table>

These are typical characteristics that may vary from substrate to substrate.

Figure 1. Characteristic impedance of a trace on a dielectric material.

Figure 2. Resonant method using a network analyzer.

Limitations of traditional sheet-material permittivity methods

In the past, two general methods were used to measure permittivity of sheet-material; a parallel-plate fixture (HP 16451B) used with an LCR meter, and resonant methods using a vector network analyzer.
The resonant method, by definition, is a single frequency technique. It requires sample preparation with tight tolerances. Relative permittivity results must be computed from other parameters, often requiring an external computer.

The LCR meter parallel-plate method has been limited by the fact that accurate impedance measurements were not possible above 30 MHz, the limit of the HP 4285A Precision LCR meter and HP 16451B fixture. Thus no simple, accurate solution was available for the frequencies from 30 MHz to over 1 GHz. See Figure 3.

**Figure 3.** Frequency coverage of two traditional PC board and substrate permittivity measurement method.

In summary, permittivity measurements of thin sheet-material in the RF range have been difficult at best, and accurate swept-frequency results nearly impossible.

**New RF measurement solution provides ease-of-use and high accuracy**

The HP 4291B system is a complete solution for relative permittivity measurements. It eliminates complex calculations, material preparation, and fixturing issues common with previous techniques. The system consists of the HP 4291B, Option 002 material measurement firmware, and the HP 16453A dielectric material test fixture.

Option 002 material measurement firmware provides direct readout of relative complex permittivity as a function of frequency, eliminating the need for an external controller. In addition, the firmware includes an easy-to-use HP 16453A fixture compensation function. The firmware uses impedance measurement data provided by the HP 4291B Impedance/Material Analyzer to calculate permittivity results.

This new analyzer is based on HP’s RF I-V method of impedance measurement. This method extends accurate, wide-range impedance measurements to 1 GHz, providing the high accuracy required to make parallel plate permittivity measurements.

In the parallel plate method, the material-under-test is sandwiched between the fixture’s two electrodes to form a capacitor. The HP 4291B measures the admittance of the capacitor, and Option 002 firmware calculates relative complex permittivity, as shown in Figure 4.

**Figure 4.** Calculating complex permittivity from admittance.

**New fixture for easy sheet-material testing**

The HP 16453A Dielectric Material Test Fixture is shown in Figure 5. It connects directly to the APC-7® connector on the HP 4291B test head, or can be used with the optional high temperature test head for use in a temperature chamber. Fixture features include:

**Figure 5.** HP 16453A dielectric material test fixture mounted on the HP 4291B test head.
Easy sample preparation: The material-under-test is simply sandwiched between the fixture electrodes. The test is non-destructive and doesn’t require extensive preparation of the material. The sample size specifications are shown in Figure 6.

Figure 6. Sheet-material dimensions for the HP 16453A fixture.

LOAD standard provided: For high accuracy results, the fixture includes a LOAD standard for fixture compensation.

High accuracy measurements up to 1 GHz

The HP 4291B system achieves high accuracy relative complex permittivity measurements up to 1 GHz (typically ±8% for permittivity and ±0.003 for loss tangent at 100MHz and $\varepsilon_r=10$). This high accuracy combined with swept-frequency measurement is ideal for PC board and substrate testing. Figure 8 shows an example of a PC board (low permittivity and low loss) measurement. The high accuracy is a result of a high basic accuracy of the impedance measurement, the fixture design, and calibration and compensation functions built into the system’s firmware.

Simplified temperature characteristic measurements

The HP 4291B is designed to be an instrument controller using HP IBASIC. As such, it can control other test equipment or an HP-IB controllable environmental chamber. Figure 9 shows the block diagram of a temperature characteristic evaluation system. The HP 4291B provides the following features and options to simplify evaluating temperature characteristics:

1. 1.8m cable to the measurement head: Convenient for system configuration. Does not affect the accuracy of the measurement.
2. High temperature high impedance test head option (Option 013): A heat-resistant cable (−55°C to 200°C) to extend the APC-7® calibration plane while at the same time maintaining high accuracy.

Figure 8. PC board relative permittivity measurement over the RF range.
Wide operating temperature range of the fixture:
The HP 16453A fixture can be used from -55°C to 200°C without loss of accuracy.

HP-IB and built-in HP IBASIC controller function: Provides an interface and controller function for automatic measurement and chamber control. A third party temperature chamber is required. Tabai Espec Corporation offers a temperature chamber (SU-240-Y) compatible with the HP 4291B. It is pictured in Figure 10.

Application program: This HP IBASIC program for temperature characteristics evaluation and chamber control is compatible with the Tabai Espec temperature chamber. It is included with the optional high temperature test head (Option 013).

Graphic display: Displays measured parameters as a function of chamber temperature. See Figure 11.

Basic measurement procedure

Figure 12 shows the basic measurement steps for dielectric material measurements.

1. Perform analyzer calibration at the APC-7® on the HP 4291B test head.
2. Connect the HP 16453A fixture to the APC-7® on the test head.
3. Perform open/short/load fixture compensation at the fixture electrodes. Note: The load standard is provided with the fixture.
4. Input the thickness of material-under-test.
5. Place the material-under-test between the fixture electrodes.
6. Select measurement parameters and display format.
7. Start the measurement. Note: The relative complex permittivity is directly displayed as shown in Figure 8.
8. Repeat the measurement for other samples.
System configuration information

• Basic relative permittivity measurement system configuration:
  - HP 4291B RF Impedance/Material Analyzer (uses high impedance test head, supplied)
    Options:
    002: Material measurement firmware
  - HP 16453A Dielectric material test fixture

• Temperature characteristics evaluation system configuration:
  - HP 4291B RF Impedance/Material Analyzer
    Options:
    002: Material measurement firmware
    013: High temperature high impedance test head*
  - HP 16453A Dielectric material test fixture
  - Temperature chamber(third party)**

* HP 4291B Option 011 is available to delete the standard high impedance test head.
** Tabai Espec Corporation offers a temperature chamber(SU-240-Y) compatible with the HP 4291B system.

Conclusion

The HP 4291B RF Impedance/Material analyzer (with Option 002 material measurement firmware) and HP 16453A dielectric material fixture system is an ideal solution for PC board and substrate measurement up to 1 GHz. The system provides accurate relative complex permittivity measurements and easy operation. It also has the capability to automatically control a compatible temperature chamber and provide direct display of temperature characteristics.

For more information

For more information, request the following literature from your local HP representative:

HP 4291B 1.8GHz Impedance/Material Analyzer Product Overview
P/N 5966-1501E

HP 4291B 1.8GHz Impedance/Material Analyzer Technical Specifications
P/N 5966-1543E

Evaluating Temperature Characteristics using a Temperature Chamber and the HP 4291B Product Note
P/N 5966-1927E

Solutions for Measuring Permittivity and Permeability Catalog
P/N 5965-9430E

Basics of Measuring Dielectric Constants, Application Note 1217-1
P/N 5091-3300E
For more information about Hewlett-Packard test & measurement products, applications, services, and for a current sales office listing, visit our web site, http://www.hp.com/go/tmdir. You can also contact one of the following centers and ask for a test and measurement sales representative.

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