Permittivity Measurements of Frequency Dependent Electronics Materials

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Introduction

There is a significant gap developing between device speed and performance, and overall system performance. Many devices have on-chip speeds 2 to 4 times that of the system. This limitation can be partly due to the design of the interconnect system. In many cases, however, the materials used to interconnect the components can be the determining factor in final system speeds.

This paper will present the following:

- The different materials used in a system to interconnect components.
- How the materials individually effect signal and power management.
- How this collectively inter-relates to overall system performance.
- The composition of the materials used in the interconnect components (in both the IC packages and the printed circuit boards) will be described.
- Finally, guidelines and suggestions on how to test, when to test, and what to do with the data will be proposed. The intent is to provide an insight into an area that could lead to a competitive edge in production and technology.

Electronics Materials

Besides the materials used for semiconductor manufacturing, such as silicon or gallium arsenide, there are a number of different types of materials used in an electronic system. Many of us consider those materials to be part of the system, and believe them to be well-behaved and understood, as in the case of the semiconductor. Unfortunately, those of us on the electronics side of the industry do not consider any part of the system other than the IC's to be "high tech." This occurs simply because the rest of the system is some form of interconnect, and therefore a passive component. Thus, it is left to the system integrators: the mechanical, layout, routing, assembly, and manufacturing engineers to determine what materials will be used in the system. As with most systems, cost is the primary driver, followed by reliability and finally functionality.

For those engineers who have worked in the microwave and above frequency range, functionality is of primary concern. Typical devices operating at these frequencies are very specific in function. Therefore, they are designed with minimal functionality per chip. This inevitably leads to many devices in a system communicating at very high frequencies. This means that the rest of the system needs to operate at very high frequencies.

Now that the digital electronics world is reaching into the realm of very high frequency, system integration becomes the limiting factor in overall performance. This means that the electronics engineer must now decide which materials to use for the integration. Let's take a look at some materials to get a better understanding of how their composition actually makes a difference in the overall system performance.

Table 1 lists a number of materials used in typical electronics systems and two parameters associated with that material. Each material has an associated complex permittivity. The permittivity value determines the quality of the material with respect to its applications.

Material Selection	Dielectric Constant, εr	Loss Tangent, Tan δ
Vacuum (air)	1.0	0
PTFE (TEFLON)	2.0 - 2.3	0.0002 - 0.0008
Polyethylene	2.2 - 2.5	0.0002 - 0.001
DUROID	2.7 - 3.0	0.00035 - 0.001
Silicone	3.0 - 3.3	0.001 - 0.01
BT Resin	2.9 - 4.3	0.003 - 0.012
Nylon	3.0 - 3.4	0.01 - 0.05
Polyimide	2.8 - 3.5	0.004 - 0.02
Silica (quartz)	3.8 - 4.2	0.0006 - 0.005
Polyimide/Glass	3.8 - 4.5	0.003 - 0.01
Epoxy/Glass (FR4)	4.1 - 5.3	0.002 - 0.02
Beryllia	6.5 - 7.0	0.001-0.002
Mica	7.2 - 7.8	0.0014 - 0.007
Aluminum Nitride	8.7 - 8.9	0.0002 - 0.001
Alumina	9.0 - 10.0	0.0005 - 0.001
Silicon	11.7-12.2	0.001 - 0.002
Gallium Arsenide	15.5-16.2	0.001 - 0.002
Titania (rutile)	90 - 600	0.0001 - 0.004

Table 1. List of various materials used in today's electronic systems.

The equation for complex permittivity is:

$$K = \varepsilon_r = \frac{\varepsilon}{\varepsilon_\circ}$$

$$K^* = \varepsilon_r{*}= \frac{\varepsilon^*}{\varepsilon_\circ} = \varepsilon_r{'} - j\varepsilon_r{''}$$

where K is the dielectric constant, εr is the relative permittivity, and ε_o is the permittivity of free space (8.854 pF/m).

In complex form, permittivity has two components. The real component of permittivity (εr') is the dielectric constant of the material, which connotes the material's capacity to hold a charge. This value is relative to that of free space, which has a dielectric constant of 1. The imaginary component (εr") is the dielectric loss, which indicates how much energy is lost in the material due to dissipation. Tan delta is the term used to describe the tangent of scalars of the dielectric loss to dielectric constant. For free space, this number is 0, meaning there is no loss of energy in the medium. Note: Using the term dielectric constant connotes that the material is constant. In reality, all electronics materials have properties that are both frequency ***and*** temperature dependent.

Materials Effects

So, what does all this mean, and how does it effect the system? Two different areas in system design and performance affected by the materials are related to noise and timing. The ideal interconnect system generates no noise and creates no timing problems between components. Everyone knows this is not the case. Contributors to the noise budget are:
a) switching noise, b) crosstalk, c) power/ground IR drop, and
d) impedance discontinuities. Two contributors to timing problems, created by the types of materials used in the system, are e) wiring delay, and
f) clock skew.

Realizing the effects that materials can have on system performance is the first step towards applying the information about the materials used in the system towards creating a better design. The question now becomes: how can I best get the information about the electronic materials used in my system? There are two possible avenues of approach. One is to ask for and rely on the materials vendors to supply that information. The second is to make measurements yourself.

There are a couple of issues concerning the first approach. First, the board, package, substrate, or interconnect supplier is typically not the same manufacturer as the raw material laminate supplier. Therefore, you must either have your supplier obtain that information for you, or get it from the raw materials supplier(s) directly. Second, most laminate suppliers do not measure and/or intentionally control the permittivity properties of the material. If it is measured, typically the material is measured at 1 MHz, and almost never with any type of accuracy specified, or even mention of the method used. Third, if the material is obtained from multiple sources, there can be variability between suppliers. Each of these concerns is legitimate when it comes to determining the permittivity properties of any electronics material.

The advantage to the second approach is obvious. Not only will the information be readily available, and accurate, it will also help determine the quality of the material used in the system. Let's take a look at a very good approach to materials measurements. This approach does not require an expert in the area of material science, electrical engineering, mechanical engineering, physics, or chemistry. In fact, the system used in this approach can be configured so that a person with a basic technical background can be proficient at measuring materials.

Materials Measurements and Techniques

Issues to address when deciding to make measurements on any type of electronic component or system include: how much time, effort, skills, equipment, accuracy, or money do I need. For those of you with experience, you know that one of the oldest and most applicable adages of today is "the right tool for the job." With the dynamics of this industry changing ever faster, it makes sense to get exactly what you need, not just something that is handy. There are at least four different measurement/instrument approaches to extracting permittivity values from electronics materials available and used in industry today. I have used all them in one form or another. Each has its area of usefulness involving the question of "how much" above. The four different approaches are:

1. High frequency vector network analysis.
2. Low frequency impedance analysis.
3. Time domain reflectometry.
4. High frequency impedance/material analysis.

The technique I prefer for high speed digital applications is the high frequency impedance/materials analysis approach. (See Figure 1.) Here are a few reasons for this preference:

1. Minimal preparation of the material under test (MUT) is needed to perform the measurement. It only requires a flat, relatively small substrate with no circuitry in the area to be tested.

2. Embedded firmware provides direct extraction of the permittivity properties from the analyzer. There is no need to buy or develop external software.

3. A calibration kit and fixture are already tailored for this type of measurement. Some techniques require special fixtures that are custom and very expensive, not to mention very unconventional and non-standard. It is always better to go with known good fixturing, especially the type that is designed for a test system. It ensures compatibility and is typically designed by someone who is very familiar with the technique.

4. The frequency spectrum in which the material can be measured coincides with that of today's high speed electronic systems. Low frequency solutions provide information about the material that is safe to assume is stable for low performance systems. But, it is important to know the properties of the materials at operating frequencies, because the material itself is frequency dependent. This is especially true of the dielectric loss of the material.

5. This system is also configured to interface with test chambers and capable of measuring temperature dependent material properties. This is important for materials, such as resin-based printed circuit boards.

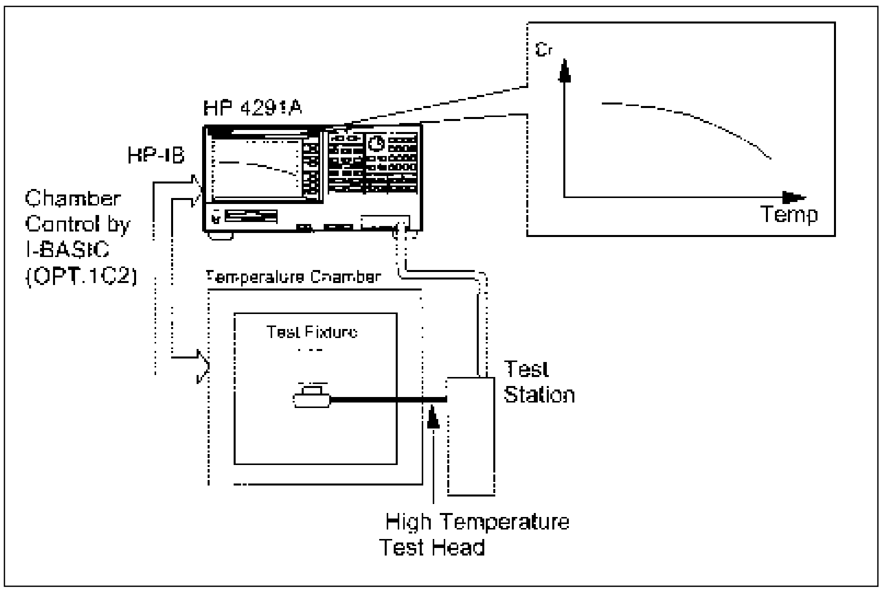


Figure 1. System configured for temperature dependent measurements.

By understanding the dielectric behavior of a material across a frequency spectrum, it is easier to understand if and how it affects the overall system. Some materials may be stable across the frequency band. Yet, the value of the material may be significantly different from the data published by vendors, journals, or reference books. It is very common to find material information published by sources that only make a single frequency measurement at 1 MHz. This is unacceptable for today's high speed systems.

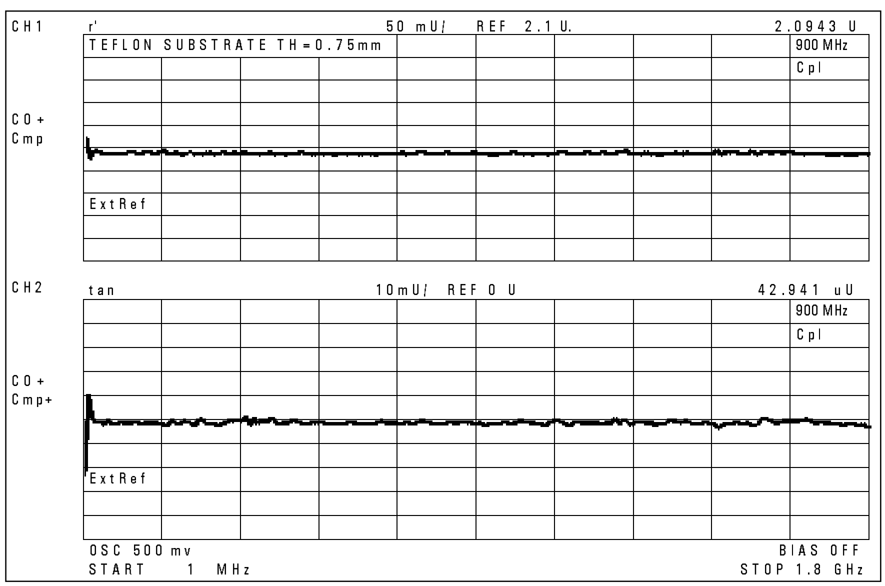
How accurate is the measurement system? Good question. I have found that the most reliable way to determine accuracy in any measurement system is to break the system down into two parts. The first is quantitative accuracy and the second is qualitative accuracy. Combined, these two values determine the overall accuracy of the system. The quantitative accuracy relates to the instrument, interface, and fixturing. For highly sophisticated, complex, sensitive, and expensive systems, accuracy can be achieved to the nth degree. This usually requires the highest in qualitative accuracy, meaning, a single, highly-trained, highly-skilled, and highly-paid technical person. The sliding scale goes to the other end of the spectrum that requires low technology and low technical skills to achieve results that are, at best, questionable. Most people are somewhere in-between. We want accuracy, speed and simplicity. Therefore, we want a system that requires minimal technical training, yet produces results that are both reasonable, and agree with known quantities.

Examples

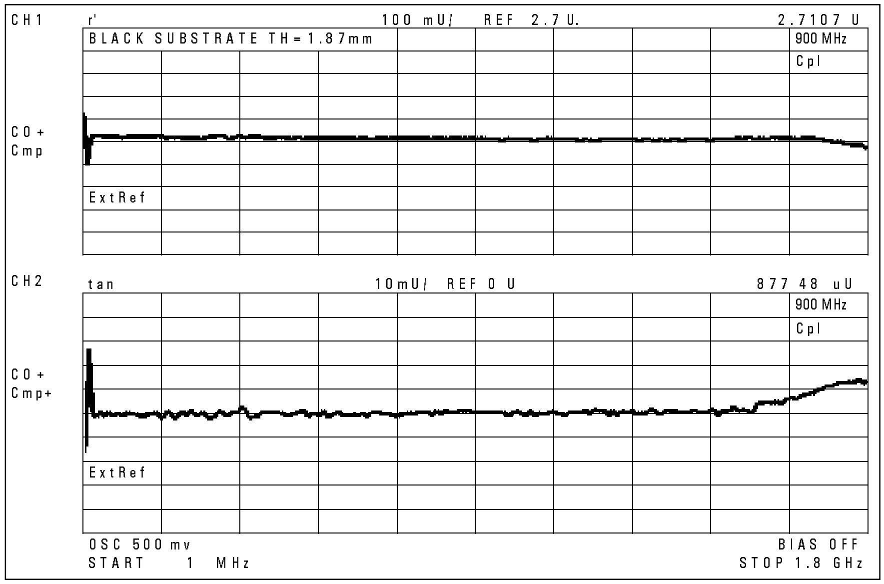
When reviewing the measured responses, the following is consistent among all graphs. The CH1 indicator in the upper left of the top graph indicates the dielectric constant measurement, ($\varepsilon r'$), whereas the CH2 indicator in the upper left of the bottom graph indicates the loss tangent measurement, ($\varepsilon r''$). The measured results are displayed in the upper right of the graph, and the measurements were made at 900 MHz, unless otherwise indicated. TEFLON® was used as a reference for fixture de-embedding.

If we take a look at a number of different types of materials, we may see some commonalties that can help determine the capability of a measurement system. Each material has a flat region that indicates stability within that frequency band. There is a frequency dependent anomaly at the very low end and very high end of the broadband frequency responses. Additional contributing factors of this phenomenon include the inherent nature of the broadband sweep, the number of frequency points selected, and fixturing.

Graph 1 shows the dielectric constant and loss tangent of a TEFLON sample. The absolute value and variation across the frequency band are the important characteristics to look for. TEFLON is a well known, well understood and well behaved material. Graph 2 shows the behavior of DUROID®, another well known material. Note the stability of the material through 1.5 GHz. Beyond this frequency, the dielectric constant response begins to decrease, indicating frequency dependent instability. The loss tangent response begins to increase at about the same frequency, which agrees with well understood theory.

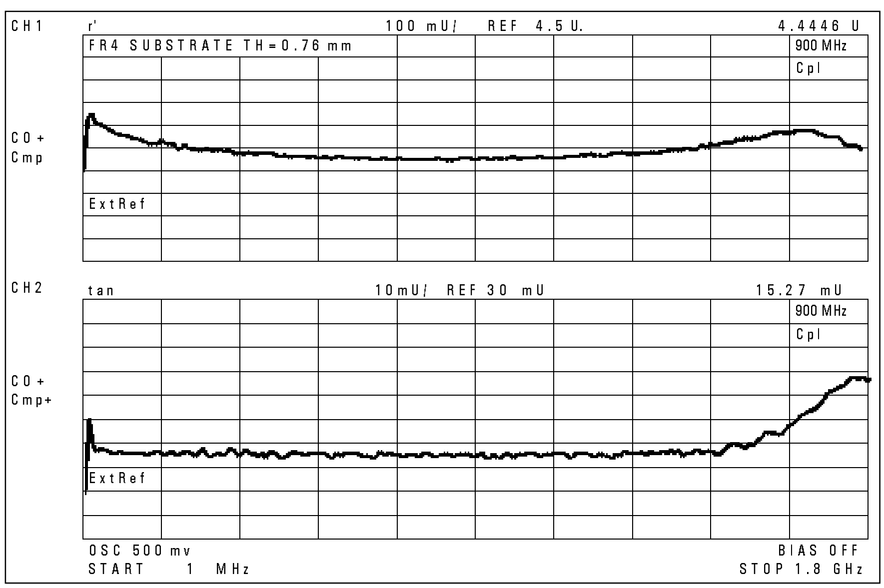


Graph 1. TEFLON Glass with thickness = 0.75 mm.

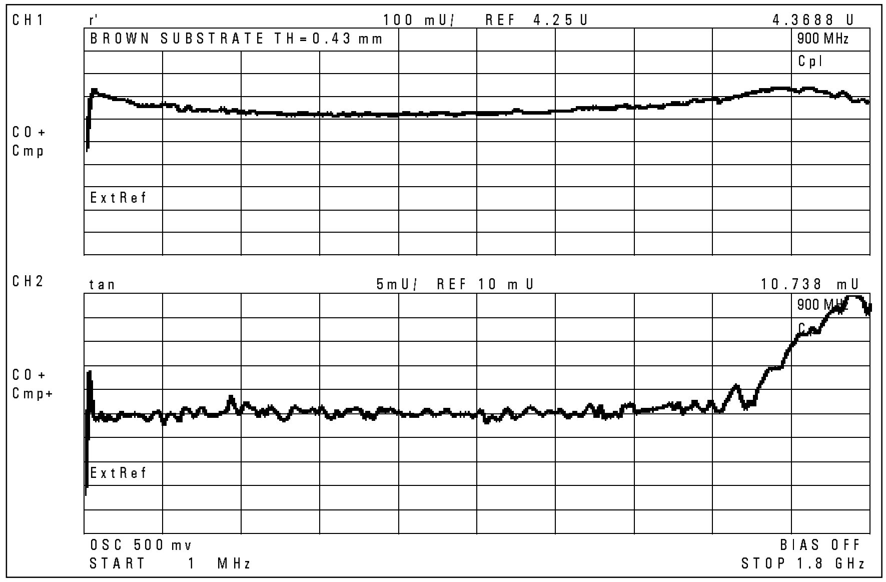


Graph 2. DUROID with thickness = 1.67 mm.

Graph 3 shows the measured response of an FR4 substrate. The elliptical behavior of the dielectric constant measurement indicates some inaccuracy introduced by a possible combination of MUT preparation and fixture contact pressure. These two variables can produce false, and/or, inaccurate readings of the material across the frequency band. In cases like this, as shown again in Graph 4, it is best to obtain a material sample that has a surface flatness that adheres to the recommended specifications of the system.

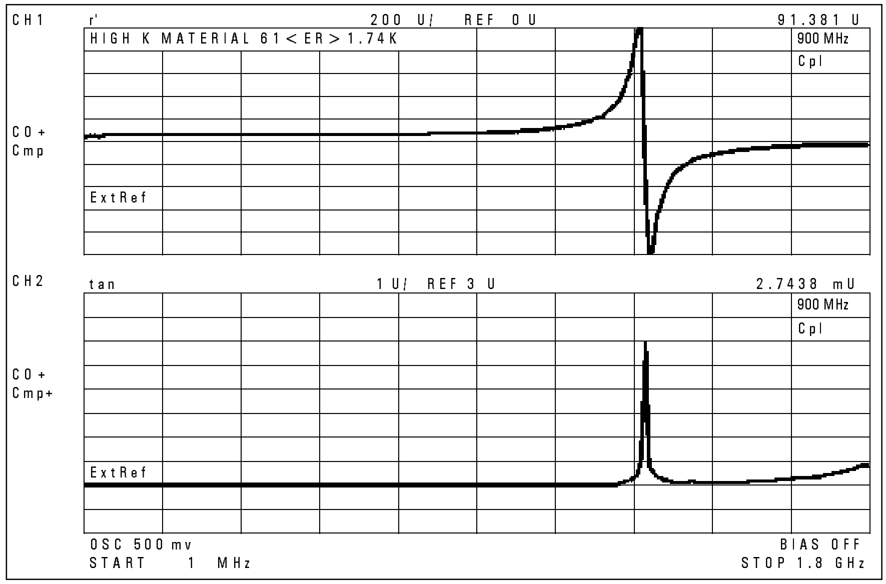


Graph 3. FR4 material with thickness = 0.76 mm.

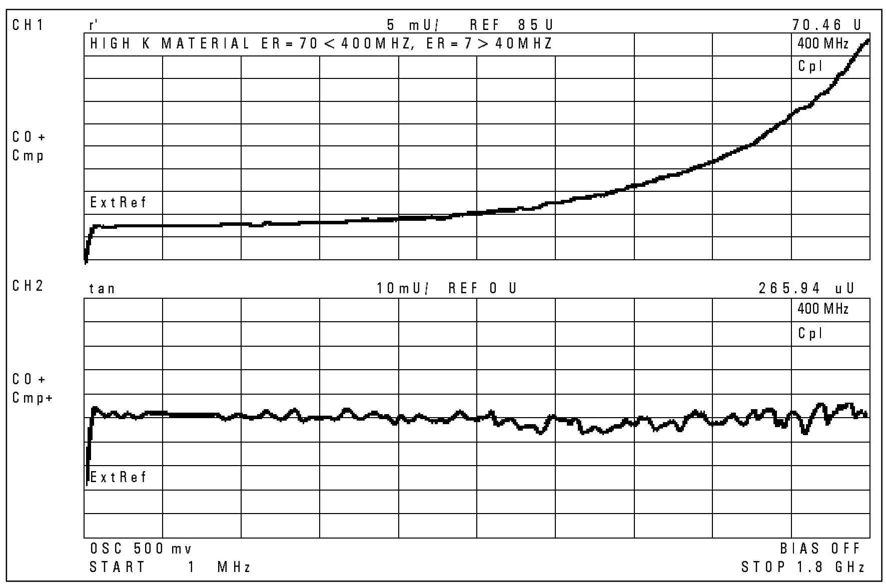


Graph 4. BT Resin material with thickness = 0.43 mm.

A final set of examples highlighting the capability of the measurement system and the importance of making materials measurements is shown in Graphs 5 and 6. The material measured was a high K substrate made of titania. Applications include integrating the material into multilayer boards between power and ground planes as a decoupling capacitor for high speed switching. The problem with titania is in its capacity to hold a charge. It can be very unstable as a function of frequency, as shown in Graph 5. Notice the resonance that occurs just under 1.2 GHz. This behavior will definitely have an adverse effect on a system that is operating around that bandwidth. Across the measurement spectrum, the dielectric constant value varied from 61 to 1740. Graph 6 emphasizes the main point about certain materials being frequency dependent. The titania was remeasured from 1 MHz to 1 GHz, well below the resonance. Yet, looking at the response within a reasonable scale shows that the material becomes unstable beyond 400 MHz. Therefore, for high speed or high frequency electronics, which require operating bandwidths greater than 400 MHz, this material could create unstable behavior in the system.



Graph 5. High K material measured across frequency band.



Graph 6. High K material measured up to first resonance.

Conclusions

From my experience, it is sometimes difficult to decide when to make an engineering investment in test and measurement. Usually, that time comes when failures occur and the only remaining approach to a solution involves testing. For some companies, experience with many types of electronics materials has been gained over the years through continuous evaluation. They see the long term advantage of building an internal body of knowledge of materials, finished products, and vendors. Some of our customers have used this information to gain a competitive edge by reducing design, manufacturing, and evaluation time.