Presented at IPC Printed Circuits Expo®
SMEMA Council APEX®
Designers Summit 04

Electrical Characteristics of High Speed Materials

Eric Montgomery
Northrop Grumman
Springfield, MO

Abstract
This paper will discuss the two primary transmission components that concern designers today. These components affect the signal integrity of all high-speed transmissions in printed circuit boards (PCBs).

The dissipation factor (Df) is a laminate material parameter that determines the losses assigned to the laminate surrounding the transmission line. For a good dielectric, the conductivity, which determines Df, should approach zero. Signal processing at high speed requires that the dielectric constant (Dk) that is perceived static and the effective dielectric constant (Er') that is perceived active, be measured so that the designers have an accurate model to predict delays and impedances. For these high-speed signals, the delay (phase or propagation) is critical to the success of any high-speed transmission path. Delays through the transmission line can affect skew, influence noise immunity and may reduce eye widths. An accurately measured Er' obtained from signal delay is needed to ensure that no impedance mismatches associated with laminates are found along the transmission path.

Objectives
In this paper, we describe methods of measuring propagation delay, phase delay or group delay, modeling, and calculating Er' using measured delay through a strip-line transmission line. This paper will present methods of measuring and techniques for determining the loss tangent and the Df of materials. All data collected will be correlated to the manufacturers data sheets. The objective of this paper is to provide electrical design criteria of the material tested to our customers. The material evaluated for this paper is: Nelco 4000-6, Nelco 4000-13, Nelco 4000-13si, Megtron Standard, Megtron 5, Isola 406, Isola 408, Isola 410, Isola 420, Rogers 4350, Nelco 9200, and Nelco 9300.

Introduction
This paper describes the methods of measuring propagation delay, phase delay or group delay, modeling, and calculating Er' using measured delay through a strip-line transmission line. This paper also presents methods of measuring and techniques for determining the loss tangent and the Df of materials. All data collected will be correlated to the manufacturers data sheets.

The Device Under Test (DUT) is a test coupon with:
1. 16 inch transmission line (single ended)
2. Trace width = 0.0010”
3. Trace height = 0.0012”

The launch and receive connectors for the DUT are surface mounted compression coax connector. The delay through the transmission line is measured on ten (10) DUTs for each material. The average of these ten measurements are then used to calculate Er’. Er’ is also calculated using this same methods when measuring phase or group delay.

Time Domain Reflection (TDR), Time Domain Transmission (TDT) and Group Delay Techniques for Calculating Er’
Table 2 provides the predicted Er’ for lossy categories of materials. Graphs and DUT are available for all materials tested.

Test Equipment Configuration for Measuring Delay
Correlating the measured data to the modeled data is critical to the success of any testing and modeling methods used in determining the electrical elements or components of a high-speed transmission line. The calibration method is a very important first step in this process. Calibration procedures are provided in the equipment manufacturers manual. Listed below in Table 1 are the basic testing configurations.

Table 1 - Equipment Configuration

TDR test configuration		
Time Base	***Time Delay***	***Volts/Division***
0.7 nanoseconds/div	28 nanoseconds/div	50 millivolts/div
TDT test configuration		
0.7 nanoseconds/div	28 nanoseconds/div	50 millivolts/div
Network Analyzer configuration		
Frequency bandwidth	time or phase/division	N/A
50 Mhz to 20 Ghz	50 ps/div or .5degs/div	

Figures 1 and 2 illustrate time and frequency domain test setup for both phase and time delay measurements using a digital sampling scope and a network analyzer.

Photos of the DUT -

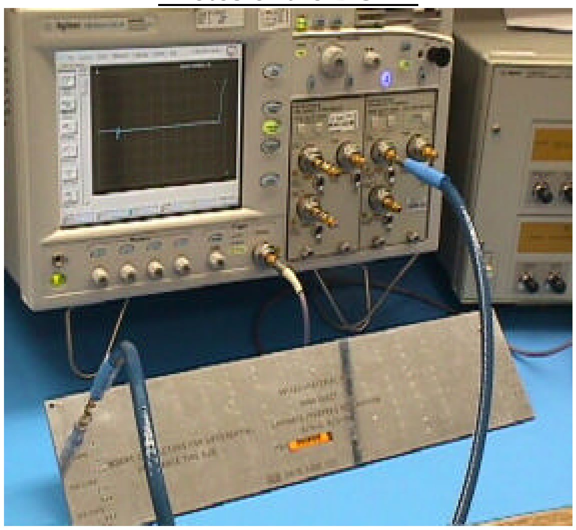

Figure 1 - Time domain (propagation delay)

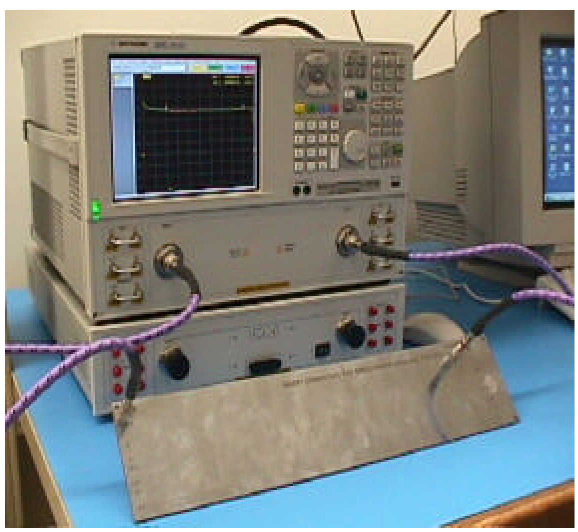

Figure 2 - Frequency Domain (Group or Phase delay)

Figure 3 illustrates the measured propagation delay using TDT. In TDT, the measured time, in ns, is not divided by two.

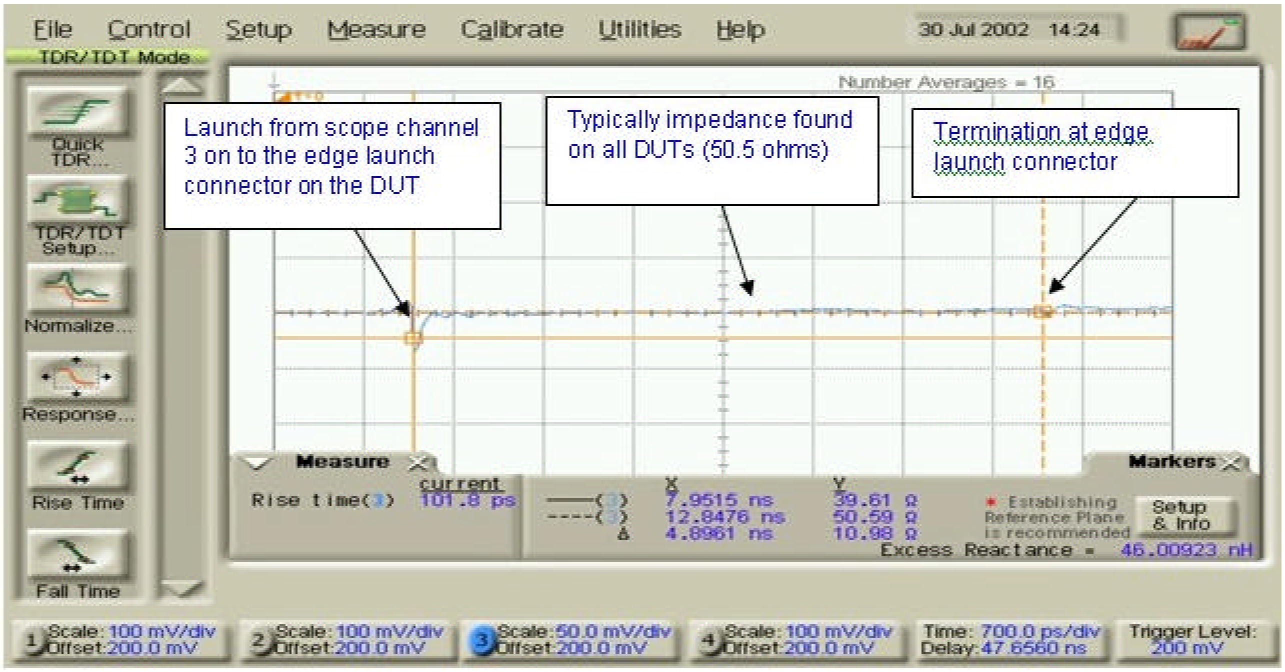

Figure 3 - Time Domain Transmission (TDT)

Figure 4 illustrates the measured propagation delay using TDR. In TDT, the measured time, in ns, is not divided by two.

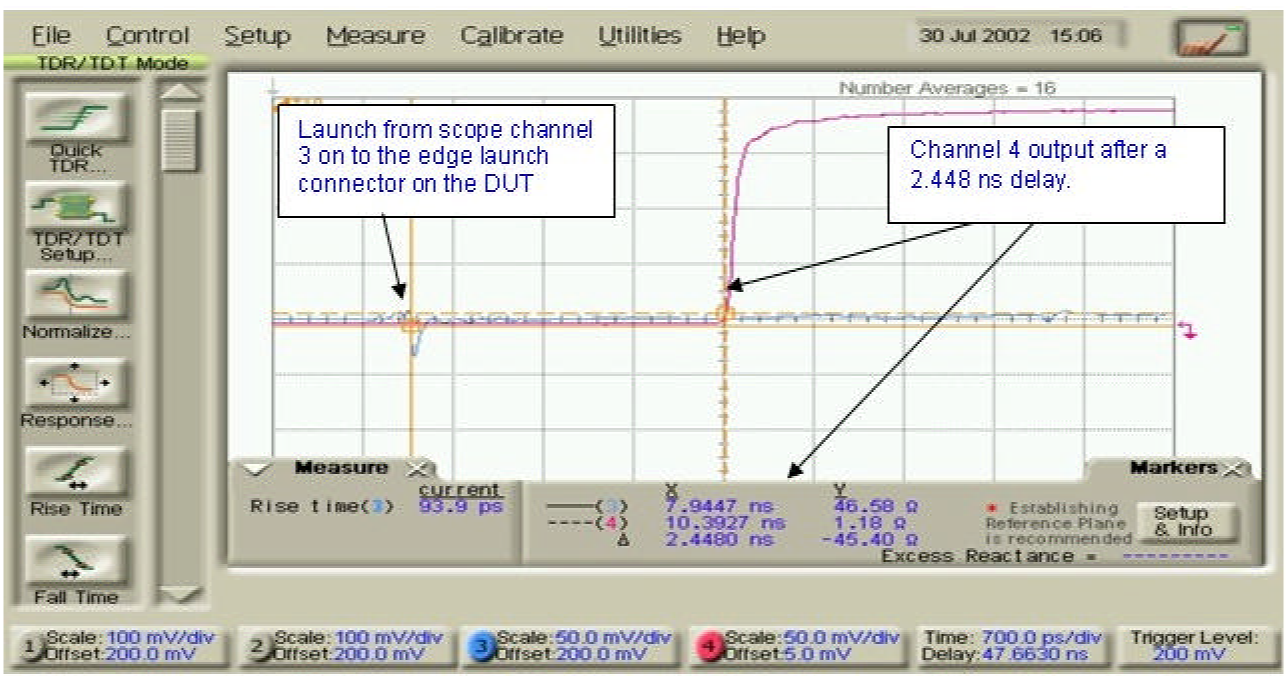

Figure 4 - Time Domain Reflection (TDR)

Figure 5 illustrates the measured group or phase delay of the transmission line using the network analyzer. Group or phase delays are measured in degrees or time.

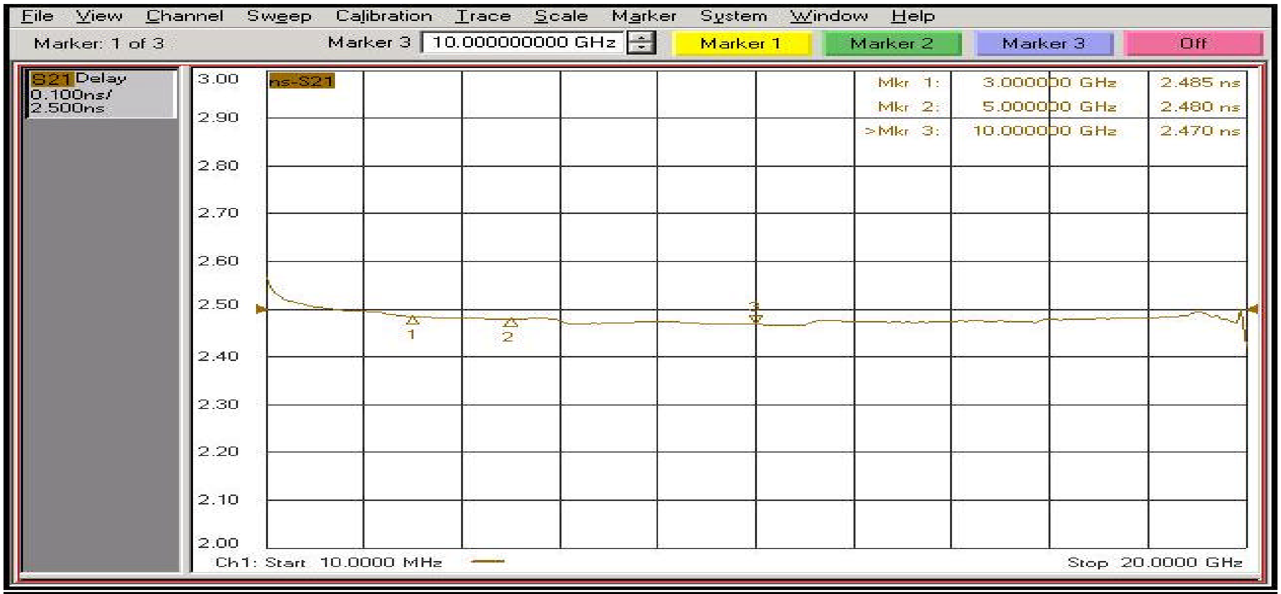

Figure 5 - Measured Group or Phase Delay of the Transmission Line

Measured Values and Calculation Method for Er'

To calculate the Er', propagation, phase or group delays are measured on the 16-inch transmission lines on each test coupon and logged. To ensure accurate test methods, fixturing lengths and data correlation, the propagation delay is measured in both the TDR, TDT and group/phase delay modes.

The Er' is then calculated using these delay values (measured in ns or degrees) applied to the equations 1 and 2 on page 5.

Fixturing will add additional delay to the test results. It is important to understand the effects of fixturing in addition to the process related variables and via effects. These variables are not included in these equations due to the lack of consistency in fixturing, via structures and processes between manufacturers. Interconnect Technologies recommends each manufacturer apply the appropriate offset for fixturing, via structures and processes to the equations.

Variables Used for Calculating Er'

- C = speed of light in meters/sec.
- τ_{pd} = propagation delay through the medium in ns.
- τ_{pd} = propagation delay through the medium in degrees or ns.
- Er'' = effective dielectric constant.
- L = transmission line length.

Equation 1 and 2 below are used to calculate the effective dielectric constant using the variables above. The calculated values of Er' using these variables can be found in Table 3 on page 9.

$$Er := \left[\frac{C}{\left(\frac{1}{\tau_{pd}} \right)} \right] \qquad (1)$$

$$Er := \left[\frac{C}{\left(\frac{1}{\tau_{phase}} \right)} \right] \qquad (2)$$

Figure 6 illustrates dielectric constant, Er', as a function of phase delay. Note the bond sheet (Teflon) materials uniform response.

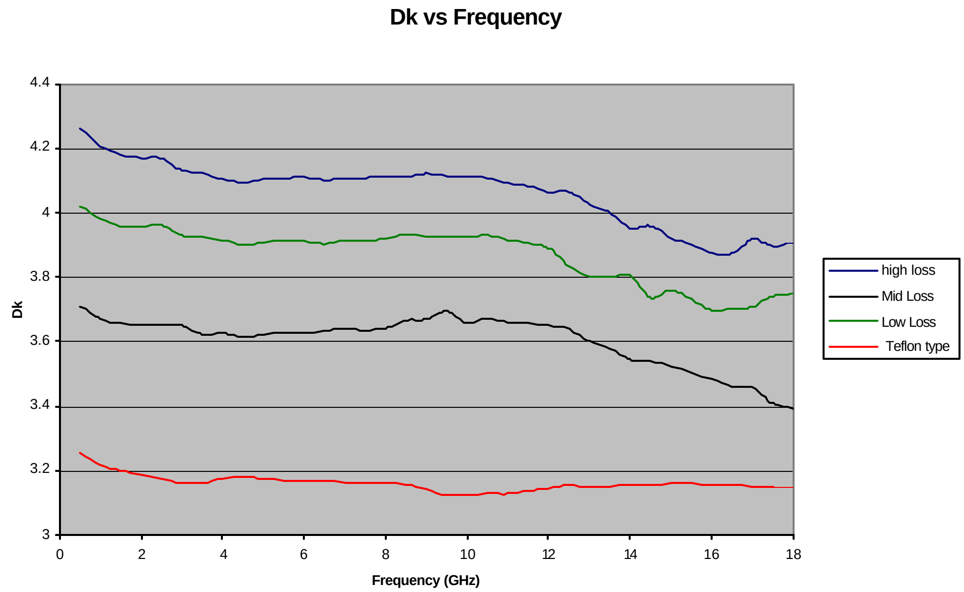

Figure 6 –As a Function of Phase Delay

The data in Table 2 is data derived from the propagation, phase or group delay and calculated using equations 1 and 2.

Table 2 - Dielectric Constant (Er') Derived from Delay

	Analog					**Digital**
	1 GHz	**3 GHz**	**5 GHz**	**10 GHz**	**Average**	**Dc to 10 Ghz**
Hi Loss	4.07	397	3.91	3.99	3.98	4.04
Mid Loss	3.84	3.77	3.72	3.81	3.78	3.93
Low Loss	3.53	3.45	3.40	3.51	3.47	3.46
Teflon Type	3.22	3.16	3.18	3.13	3.17	3.12

Dissipation Factor

The transmission line component primarily associated with a loss at high speed is the Dissipation Factor (Df). Df is a material electrical parameter that determines the losses assigned to the laminate surrounding the transmission line and related to frequency. For good dielectrics, the Df should approach zero as in air.

Refer to network analyzer setup shown in Figures 7 and 8.

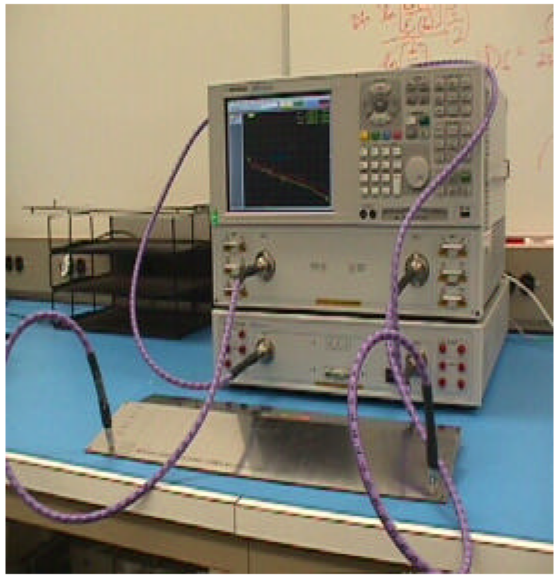

Figure 7 – Network Analyzer and DUT

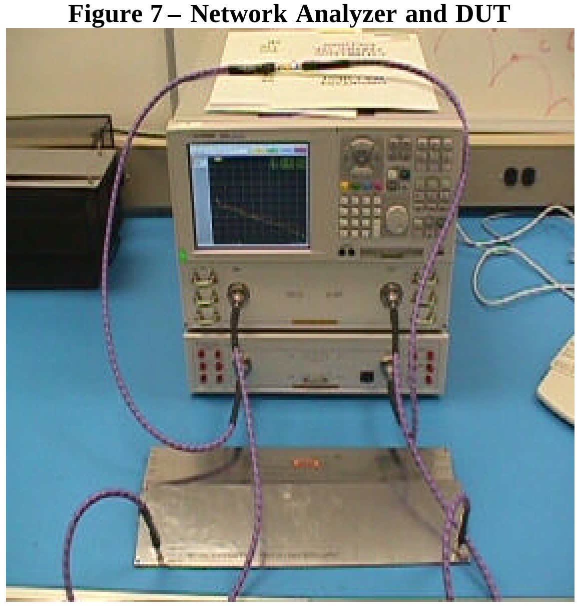

Figure 8 – Network Analyzer and DUT

There are several methods for calculating Df. I have listed four methods below. The second and third equations are derived from the first equations.

Method One

Equation 1: Loss tangent using conductance and capacitance.

The first equation uses the conductance, G, and the capacitance, C, to calculate the loss tangent. Dissipation factor is found at each frequency (f). Using the first equation, capacitance and conductance must be known for each frequency.

Df = G/(2pfC)

Method Two

The second method used to predict the Df is a textbook equation and derived from the first equation. However, this equation is limited in its use because the conductance (s) in the equation is static. For any equation to emulate test, conductance must vary with frequency.

s ? is the conductance in s^-1 (Typical variable name is G)
f = frequency applied to the test piece (typically a band width).
When calculating using MathCAD, frequency will be the variable.

df = dissipation factor (ratio assigned to loss in the material)
Er' = the effective dielectric constant (permittivity).

$\varepsilon_0 := 8.854187817 \cdot 10^{-12} \cdot \frac{\text{farad}}{\text{m}}$ permittivity of air

Static equation:

$$df := \frac{\sigma}{2 \cdot \pi \cdot f \cdot er \cdot \varepsilon_0}$$

Method 3

Equation 3: This equation, solving for db, is calculated from a known Df and at a specific frequency in GHz. The variables for this calculation are;

1. Frequency = (freq)
2. f = frequency converted to Ghz.
3. Dk is the Dielectric Constant
4. The constant provided in the original equation = 2.3 and is assigned to c1
5. db is the calculated loss per inch
6. df is the dissipation factor

The db variable in the following equation is given in loss/ inch

$freq := 3000000000$ $\quad Dk := 4.04$ $\quad db := .25$

$db := \left(2.3 \cdot . \ freq \cdot df \cdot \sqrt{Dk}\right)$ Equation provided by Eric Bogatin

loss in db equals .2 db

$f := freq \cdot .000000001$ Convert to Ghz

$f = 3$ Frequency in GHz

$c1 := 2.3$ Constant per equation

$db = z \cdot df \cdot f \cdot \sqrt{Dk}$

$$\frac{db}{\left(c1 \cdot f \cdot \sqrt{Dk}\right)}$$

$df := \frac{db}{\left(c1 \cdot f \cdot \sqrt{Dk}\right)}$ Derived df

$df = 0.018$

Although the equations and methods listed above are acceptable with certain known variables, the fourth method and the method adopted by Interconnect Technologies is a simple solution yet very accurate. This method considers the relationship between known lossy material and unknown lossy material. Normalizing to the known using measured data.

This solution is only acceptable if the test equipment and fixturing is in place to assure accurate measurements and if all variable components along the transmission line that are lossy but do not relate to material loss, can be removed. If this is true, Df's can be calculated to ±5 % or less. To achieve best accuracy, each transmission line component will need to be evaluated for loss content and that content removed.

Method 4
The Results of Method 4 are shown in Figure 9. Calculated Df from measured -db.

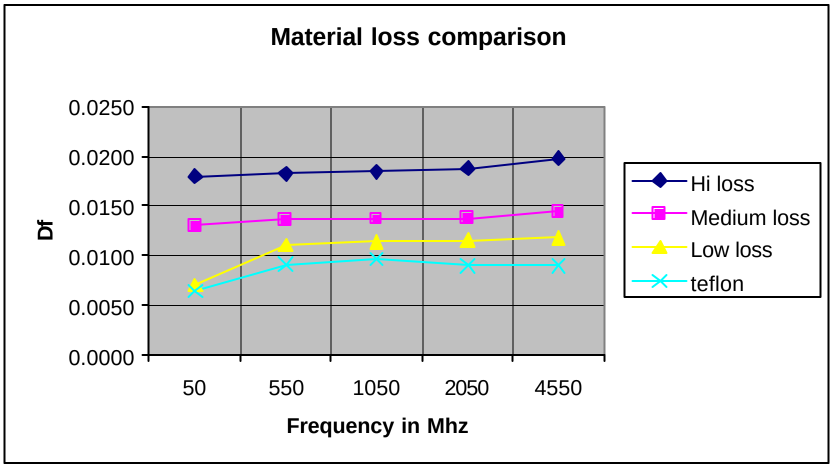

Figure 9 – Df as Calculated Using Method 4

Conclusion
A critical step in the printed circuit board process is to correlate electrical characteristics of materials to the models used to predict the finished process. To achieve correlation between measured and modeled data, Interconnect Technologies uses an RLGC modeler. Our control tolerance for this correlation is ±0.1 for Er' and ±0.001 for Df. If the separation between measured and modeled is =< ± 0.1 for Er' or ± 0.001 for df, we assume correlation.

Correlating measured data to the modeled data is an important final step. For modeling results, refer to page 9 of this report.

In addition to the propagation delay method of predicting Er', we also use the dimensions extracted from section analysis and a field solver (calculating RLGC) to predict the impedance and then compare that impedance to the measured impedance. Variables are entered as model data to achieve the desired impedance. In this case, the variable is the Er'. This method is shown in Figure 10, the stack-up, and the RLGC report.

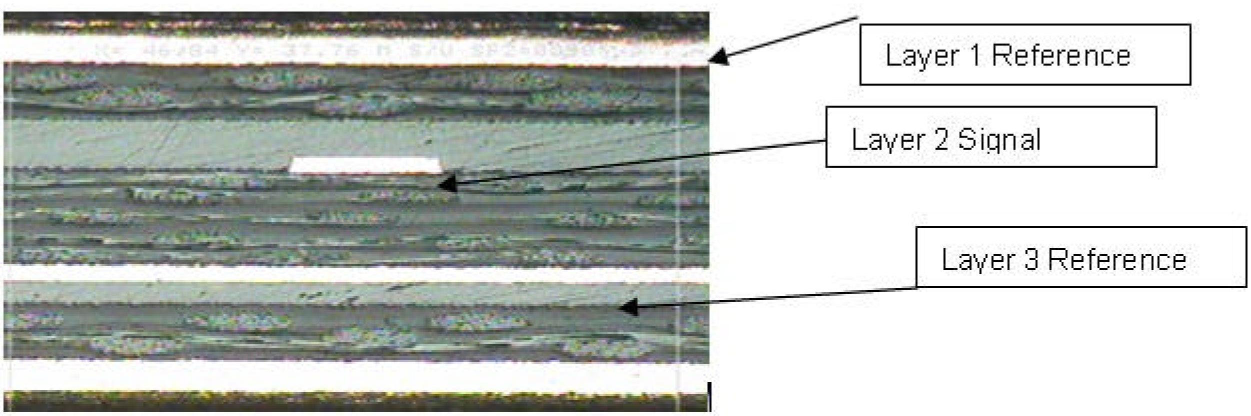

Figure 10 - Analysis of a Teflon Test Sample

The Model
The RLGC Field Solved model shown below illustrates the dimensional model developed from the section found on page 8. The data in the model is derived from the dimensions found in the section. The Er' is determined by adjusting the Dk value until the impedance of the model equals the measured impedance of the test sample.

The Teflon section used in this evaluation yielded an impedance of 50 ohms using an Er' of 3.1. Reference the modeled data in the RLGC matrix below.

The graph of the stack-up and RLGC matrix for Teflon material in described in Table 3 and shown in Figure 11. The matrix report has been abbreviated to reflect the essential data.

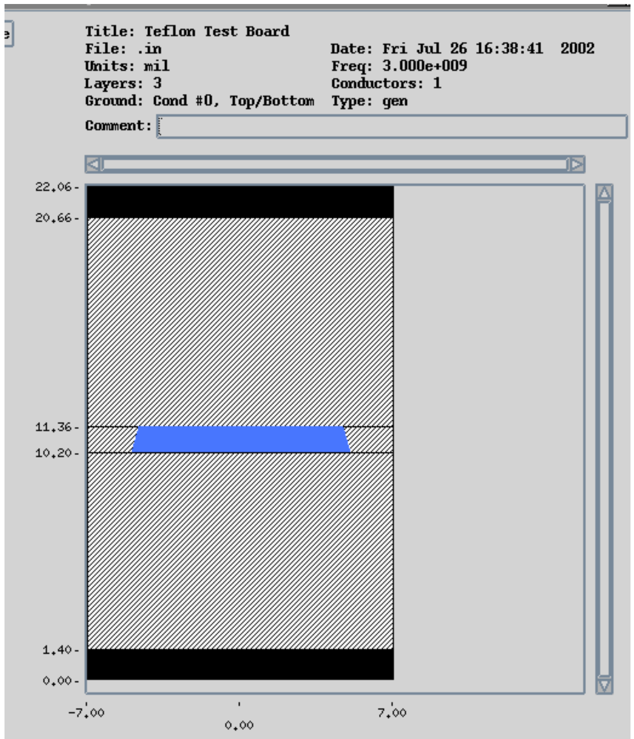

Figure 11 - Stack-up and RLGC Matrix for Teflon

Table 3 - Stack-up

RLGC MATRICES FOR GENERAL CONFIGURATION for a Teflon Test Coupon

Frequency = 12.5e+009 Units = mil

Stack-up data/Dimensions:

Er'1 = 3.100e+000 tand1 = 2.400e-003 height1 = 9.300e+000
Er'2 = 3.100e+000 tand2 = 6.000e-003 height2 = 1.160e+000
Er'3 = 3.100e+000 tand3 = 2.400e-003 height3 = 8.800e+000
Note: Er' are predicted until validated by test.

Conductor/Trace dimensions

Number of traces in conductor 1 = 1
layer1 = 2, widthBottom1 = 1.000e+001, widthTop1 = 9.300e+000,
xcord1 = 0.000e+000, sigma1 = 5.800e+007
Top ground plane thickness = 1.400e+000;
Conductivity of Top ground plane = 5.800e+007
Bottom ground plane thickness = 1.400e+000;
Conductivity of Bottom ground plane = 5.800e+007

CHARACTERISTICS OF VARIOUS MODES

Mode #	Z0 (Ohms)	Eff Rel Er'	Attenuation dB/mil
1	*50.42+j0.05*	*3.10*	*3.708e-005*

Delay (ns/mil) = 1.492e-004

Periodically, Er' and Df values are revised. These revisions are typically due to variable electrical characteristics of the raw materials or possibly PCB process variation. Whether these variations are caused by raw material or process, continual testing will detect any process driven changes and allow for electrical model correction.

Acknowledgments

1. Eric Bogatin of Bogatin Enterprises, Signal Integrity - Simplified, Prentice Hall, 2003. Neltec, Isola and Matsushita for providing materials for testing;
2. Dan Enos and Bill Jernigan at Northrop Grumman for their assistance.