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

Insertion Loss, Eye Pattern and Crosstalk Analysis of Mixed Dielectric Striplines (Simulation and Measurement)

Noel Hudson, Tammy Yost and Gregg Wildes, Ph.D.
W.L. Gore & Associates
Elkton, MD

Abstract
As digital data rates reach 5Gb/s, 10Gb/s and beyond, digital designers are finding it increasingly difficult to meet their design constraints using FR4. While there are a host of alternative materials available, cost constraints often prohibit the use of these materials as their increased performance brings a proportional increase in price. An often overlooked compromise solution is available which gives substantial improvements to the loss characteristics of high speed layers by using a mixed stripline construction which pairs FR4 with a high performance material such as those available from Nelco, Rogers, and W.L. Gore. This paper addresses the question of the potential benefits of mixed dielectric stripline construction by comparing the crosstalk and insertion loss performance of hybrid (mixed dielectric) stripline constructions to industry standard, homogeneous PCB stackups. Data is obtained both via direct measurement of test traces and via simulated results. Finished PCB cost-performance considerations are also presented for the constructions evaluated in this study.

FR4's Days are Numbered
As digital data rates reach 5Gb/s, 10Gb/s and beyond, digital designers are finding it increasingly difficult to meet their design constraints using FR4. While there are a host of alternative materials available, cost constraints often prohibit the use of these materials as their increased performance brings a proportional increase in price. However, it is clear that with ever-increasing data rates the time when standard FR4 will simply not work any longer is not far away. As an example, let us take the simple case of a chip-to-chip signal line on an FR4 microstrip plane. Figure 1 shows the measured loss of 8-inch long 8mil wide 50ohm lines of Speedboard C (SBC) and FR4 microstrip through 10GHz:

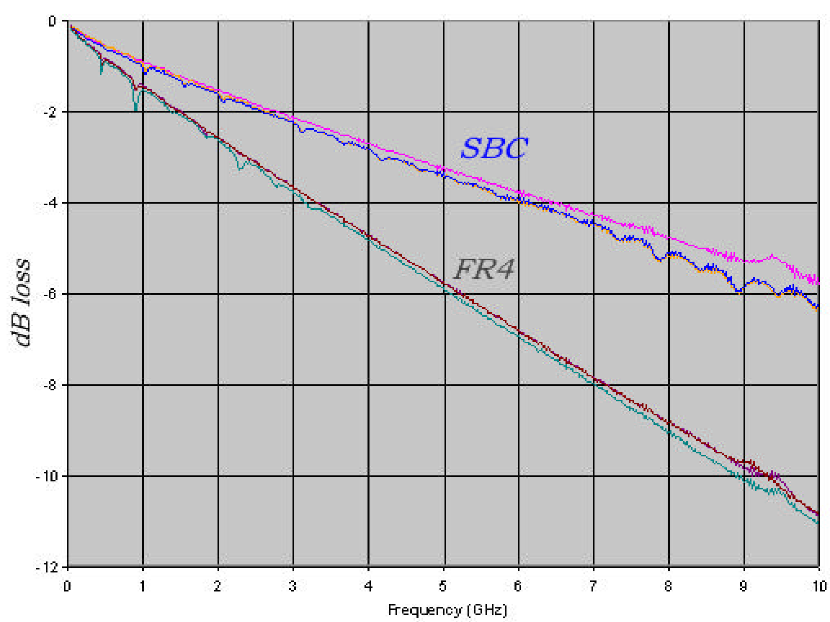

Figure 1 - Measured Loss of Several Microstrip Constructions

At 10Gb/s the fundamental frequency of the alternating 0 1 bit pattern in the data stream is 5GHz. The loss at 5GHz of the standard FR4 used in this study is about 6dB. This means that at 10Gb/s eight inches of FR4 can cut the voltage amplitude of a digital signal in half, and of course this doesn't take into account the effects of connectors, crosstalk etc. At this rate it doesn't take very long trace lengths for the attenuation to reach a point where there is simply no signal left for the receiver to sense.

The digital designer who must make the design work at this data rate is faced with a difficult dilemma: if FR4 simply will no longer work and budget constraints preclude substituting an exotic low loss material, what is one to do? An often-overlooked compromise solution is available which gives substantial improvements to the loss characteristics of high speed layers by using a mixed stripline construction which pairs FR4 with a high performance material such as those available from Nelco, Rogers, and W.L. Gore. Perhaps the primary reason that this solution is often not considered is because many digital designers are unsure of the properties of mixed dielectric stripline.

In an effort to bring further understanding to the question of the differences between mixed dielectric stripline and standard single-dielectric stripline constructions a number of experiments have been performed using both simulated and measured data.

Taking the Field

An intuitive understanding of the potential benefits of hybrid stripline can be gained by understanding what is physically happening inside the stripline construction. This may be done by examining the field distributions of a few different stripline constructions. Consider the following 50ohm +/- 10% stack-ups for 5mil wide signal lines:

1. All FR4 (dk = 4.0 loss tan= 0.022) 6mil laminate/ 6mil prepreg (5.3mils from top of signal trace to groundplane), half oz copper
2. FR4/Speedboard C (SBC dk= 2.6 loss tan= 0.004) FR4 laminate= 6mil, SBC prepreg= 4.4mil (3.7mils from top of signal copper to groundplane)

For the all FR4 case the only imbalance introduced in the stripline is that resulting from the prepreg flowing around the signal trace such that the signal is 0.7mils closer to one groundplane than to the other. A look at the electrical field magnitude as solved by the 3D solver HFSS shows a nearly even field distribution between the two groundplanes. (See Figure 2)

For the imbalanced hybrid stripline construction, however, there is a clear predominance of the electric field on the SBC side of the board. (See Figure 3)

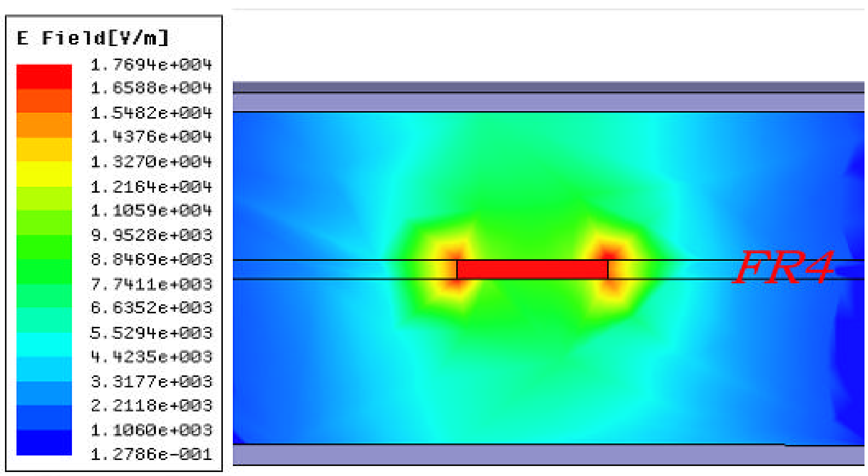

Figure2 - Magnitude of the Electric Field for an all FR4 Construction

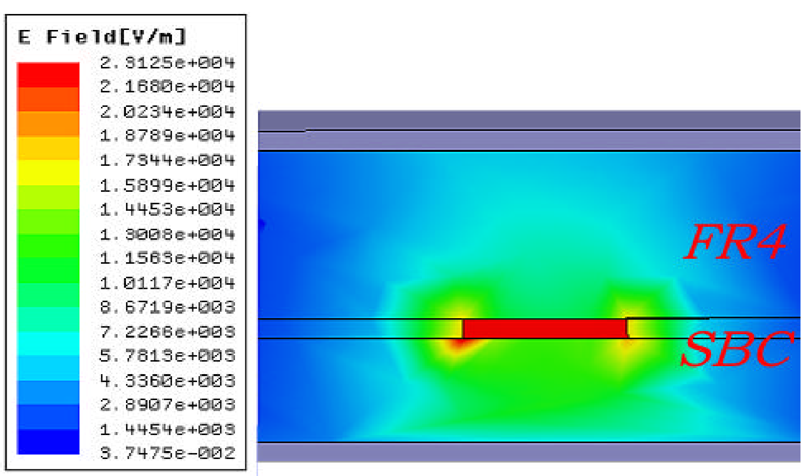

Figure3 - Magnitude of the Electric Field for a Hybrid FR4 –SBC Construction

This imbalanced situation is desirable from an attenuation standpoint, for if more field density is located in the low loss material then the overall loss of the stripline trace will be lower.

Quiet Neighbors

Another important benefit conferred by hybrid stripline is the potential ability to reach greater signal line densities while maintaining the same crosstalk level as in an all FR4 construction.

Figure 4 shows the port set-up for the crosstalk simulations using Agilent's ADS circuit simulator. The following charts show the results of a series of frequency domain crosstalk simulations comparing all FR4 stripline constructions to hybrid FR4-SBC. All traces were 50ohms +/- 5% unless noted otherwise.

Crosstalk was measured as S31 (near-end crosstalk). The following graph illustrates the difference in crosstalk between the 6mil all FR4 construction (red) and the 6mil FR4/3.4mil SBC (blue). It may be seen in Figure 5 that from zero to ten GHz the FR4/SBC construction has about 8dB lower crosstalk than the all FR4 board for a one-inch trace.

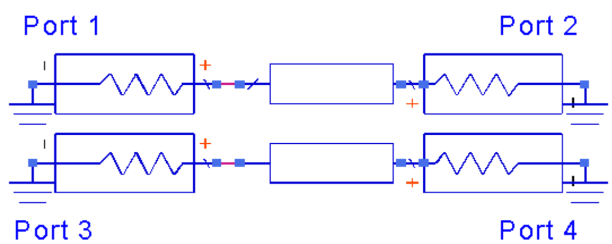

Figure 4 - Port Arrangement for Crosstalk Measurements

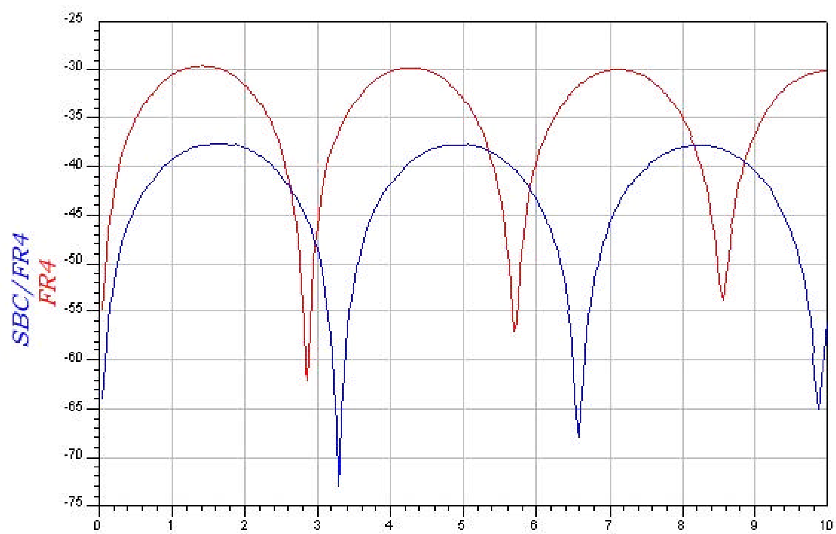

Figure 5 - NEXT of 6mil/6mil FR4 Stripline (red) vs. 3.4mil SBC/6mil FR4 Stripline (blue). Both Examples used a 10mil-space/4mil-trace Architecture

In order to further investigate the crosstalk improvement noted above several other experiments were simulated in ADS as noted in Table 1 below. All constructions were 50ohms +/- 10%.

It may be seen from the above results that for all cases examined hybrid stripline with a low dk material had superior crosstalk performance to all FR4. It was found that for a given construction similar crosstalk performance on the hybrid board could be obtained at 17% greater line density.

Table 1 - Other Experiments Simulated in ADS

laminate	prepreg	trace spacing	trace width	improvement over FR4
6mil FR4	6milFR4	4mils	5mils	n/a
6mil FR4	3.4mil SBC	4mils	5mils	5dB
6mil FR4	6milFR4	10mils	5mils	n/a
6mil FR4	3.4mil SBC	10mils	5mils	8dB
60milFR4	4.02milFR4	4mils	5mils	n/a
60milFR4	3.05milSBC	4mils	5mils	2dB
60milFR4	3.99milFR4	10mils	5mils	n/a
60milFR4	3.06milSBC	10mils	5mils	2dB
5.7mil FR4	5.7mil FR4	10mils	5mils	n/a
5.7mil FR4	3.85mil SBC	8.25mils	5mils	0dB

No Big Loss

While hybrid striplines of the type examined clearly exhibit better crosstalk performance, another reason for using hybrid stripline is for the improved loss performance. So just how much better can the loss performance be? The question is actually a bit more complex to answer than it would first seem. Stripline composed of materials with different dielectric constants cannot easily be compared directly, for the same line width will give different characteristic impedance which affects loss, and different line widths also have different conductor loss characteristics. To better examine the question a series of simulations were run in ADS in which either line width or characteristic impedance was held constant. All constructions were held to 50ohms +/-5%. The various stack-ups are presented in a table and the insertion loss is graphed in units of loss per inch from 0 to 10GHz. The materials simulated are Nelco 4000-6FC(FR4), Speedboard C, and Rogers 4350.

It may be seen that the balanced SBC/FR4 had slightly better IL than the unbalanced SBC/FR4, but it also had a much wider trace. Significantly, both SBC/FR4 constructions had much lower insertion loss than the all FR4.

The next simulation was done by maintaining the same trace width for all constructions and varying dielectric thickness:

Dielectric thickness	Width
6mil FR4 6mil FR4	5mil
6mil FR4 6mil SBC	6mil
4mil SBC 6mil FR4	4.5mil
6mil Rogers 6mil SBC	7mil

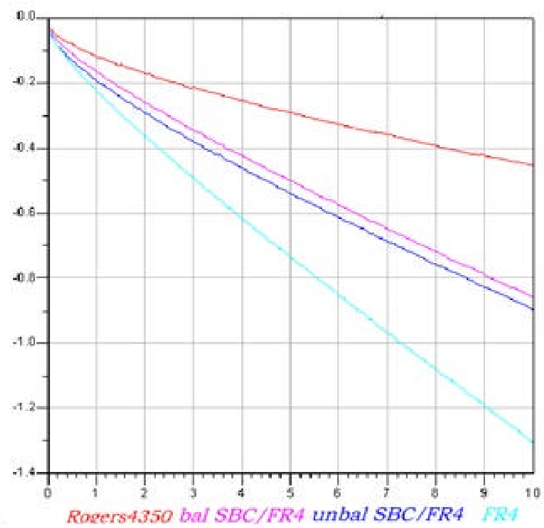

Figure6 - HybridStripline of Varying Trace Width

Dielectric thickness	Width
6mil FR4 6mil FR4	5mils
5mil FR4 5mil SBC	5mils
4milSBC 7mil FR4	5mils
4.5mil Rogers 4.5mil SBC	5mils

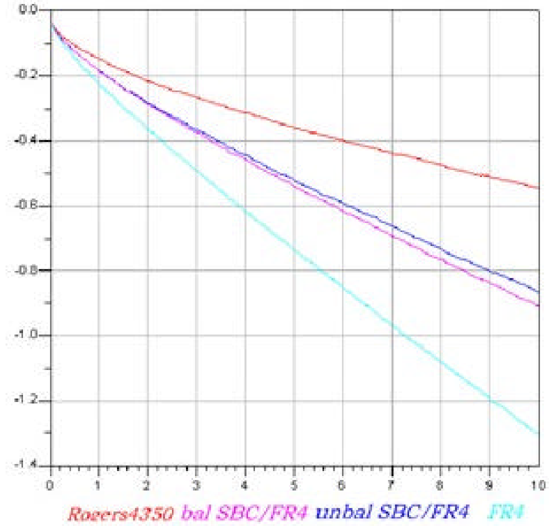

Figure7 - Hybrid Stripline of Varying Materials and Thickness

With all the same trace widths it may be seen that the mixed SBC/FR4 constructions have much better insertion loss than the all FR4 with the imbalanced SBC/FR4 performing a bit better than the balanced. (See Figure 8.)

The next simulation examined the thickness ratio of FR4 to SBC at a ratio of 2 vs. 3:

The ratio of three shows a definite improvement over the ratio of two. From the above data we may conclude that hybrid stripline which couples a high-performance material with FR4 can yield large improvements in insertion loss performance. We also see that the more the electric fields are driven to couple in the high performance material the better the insertion loss performance will be.

dielectric thickness	width
4mil SBC 8mil FR4	5.5mils
4mil SBC 12mil FR4	5.5mils
3mil SBC 6mil FR4	3.5mils
3mil SBC 9mil FR4	3.5mils

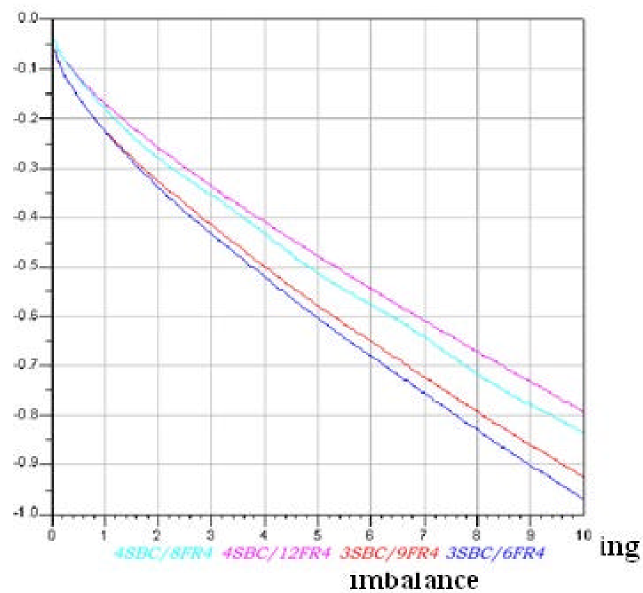

Figure8 - Hybrid Stripline of Varying Imbalance

Living in the Real World

Simulations can yield a great deal of information in a short time, but those who actually build and test boards know that the measured data rarely behaves exactly like the simulated data. In fabricated boards there are always issues to deal with such as launching onto the signal trace, maintaining signal integrity through connectors, discontinuities at pads and so on. In order to make a comparison more pertinent to real life applications, stripline boards were designed and fabricated and their behavior tested in both the frequency and time domains. Table 2 details the construction of each board:

Table 2 – Details of the Construction of Each Board

Prepreg	thickness	Laminate	thickness	trace width	trace length	Impedance
Speedboard C	4mils	Nelco4000-6FC	6mils	5.5mils	13in	51ohms
Nelco4000-13	5mils	Nelco4000-13	5mils	5.5mils	13in	52 ohms

* Boards fabricated by R&D Circuits in New Jersey.

The boards were designed with goal of 50ohms nominal impedance. They achieved this goal within 5%. The above materials were chosen to illustrate the midrange of the simulation data shown above. Nelco N4000-13 is one of a number of circuit materials, such at Getek, Megtron, Isola IS620, etc., with dielectric loss tangent (dissipation factor) in the range of 0.006 to 0.01 depending on frequency and resin content. Figures 9 and 10 below show cross sections of the fabricated boards.

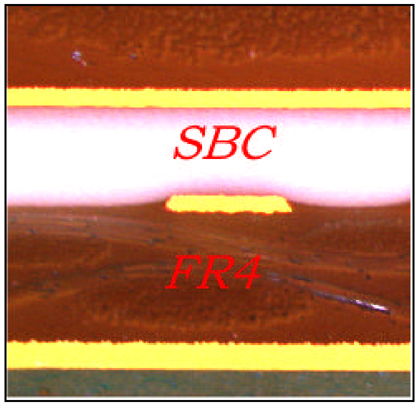

Figure 9 - Cross Section SBC/FR4 Stripl ine

Figure 10 - Cross Section N4000-13 Stripline

Upon measurement using TDR it was found that the launches on to the boards contribute to a less than ideal impedance match through the connector resulting in an impedance discontinuity of between 10 to 20ohms (depending on the board measured). This discontinuity is similar to certain edge mount and vertical mount connectors used in circuit board applications that contribute to signal integrity problems. (See Figure 11.)

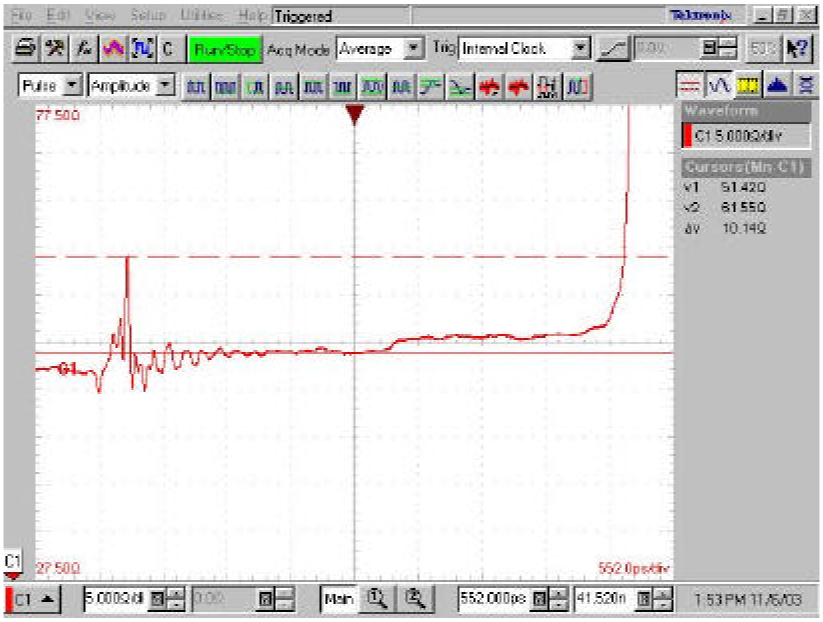

Figure 11 - TDR of a Board Launch with Greater than 10 ohm Discontinuity

The S-parameters were measured on an Agilent 8753 Network Analyzer for the boards with signal launches similar to the one shown in Figure 12. It was found that insertion loss performance through 6GHz was affected by the poor return loss of the connector (note the roll-off of the traces as they approach 6GHz in Figure 12).

The data pictured in Figure 12 does not correspond as well as expected to simulated data. While deviation is expected it is clear that an improved board launch would result in data more closely approaching simulated data.

In an attempt to obtain cleaner data the launches to the boards were manipulated and their improved performance verified via TDR (see Figure 13). The data was retaken as above and the results plotted in Figure 14.

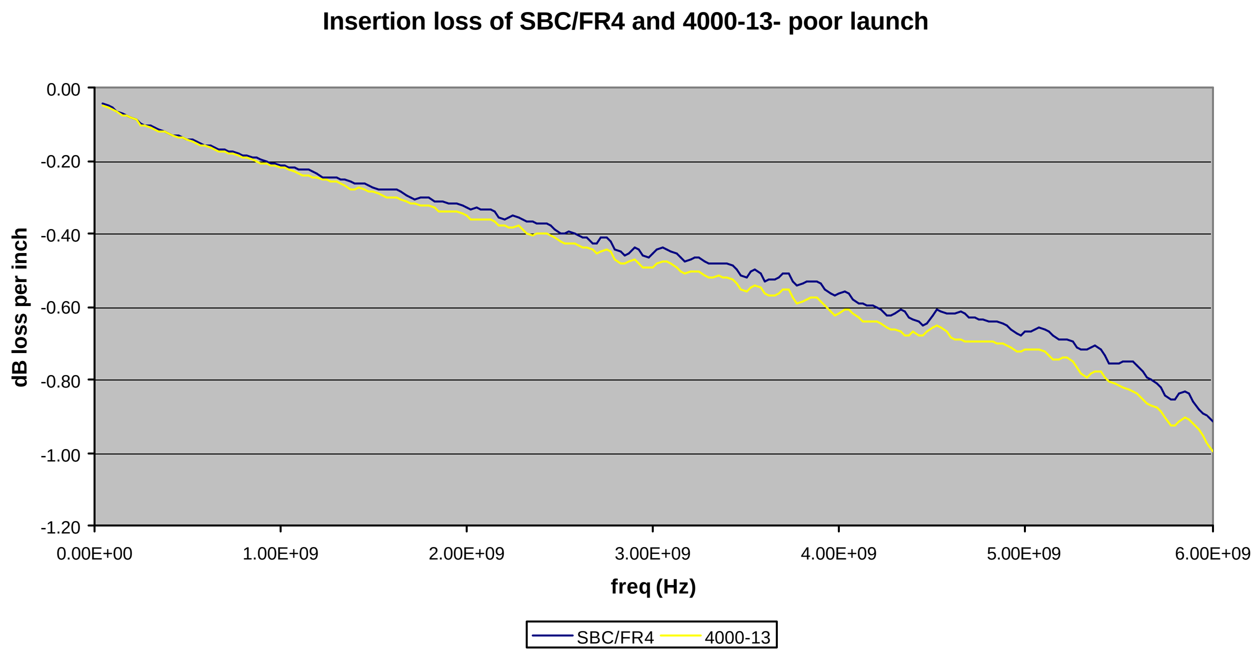

Figure12 - Stripline with Board Launches of 10-20 ohm Discontinuities

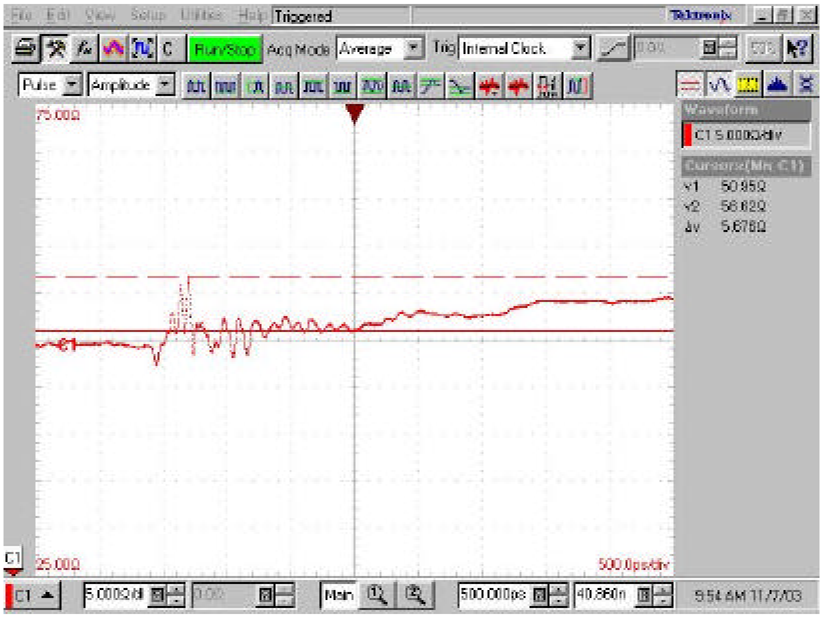

Figure13 - TDR of a Board Launch with a 5.6 ohm Discontinuity

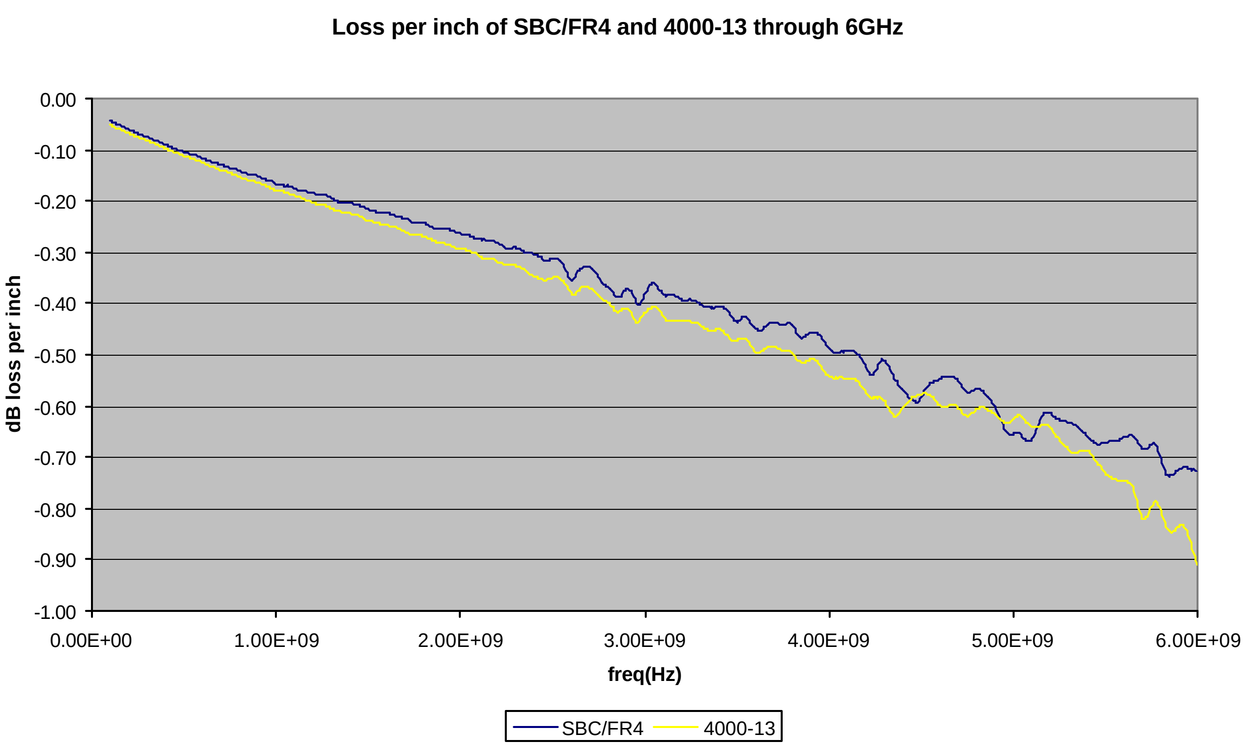

Figure14- Stripline with Board Launches of 5-10 ohm Discontinuities

The improved launch did decrease the roll-off noted in Figure 12, however the traces are still a bit jagged due to the imperfect launch. The S11 performance of all the traces was examined to see how much the reflections in the boards, especially at the launch (return loss) affect the insertion loss plot in Figure 14. The Figure 15 shows return loss through 6GHz.

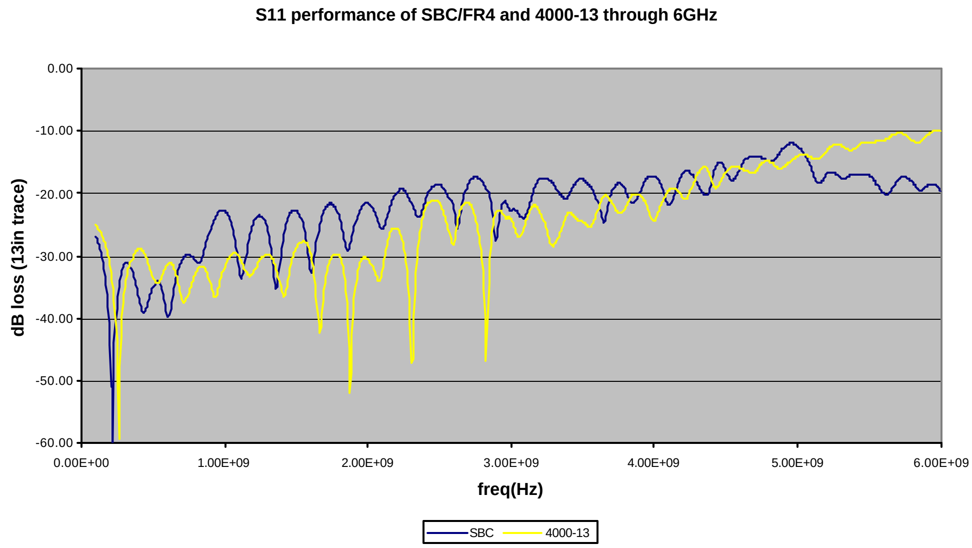

Figure15- Return loss of 2 materials through 6GHz

The return loss for these boards was fair through about 4.5GHz at which point it begins to have a greater effect on the insertion loss performance, especially in the N4000-13 material.

The next question to answer is how closely do these results correlate with the simulated data? Figure 16 shows a comparison of simulated and measured data.

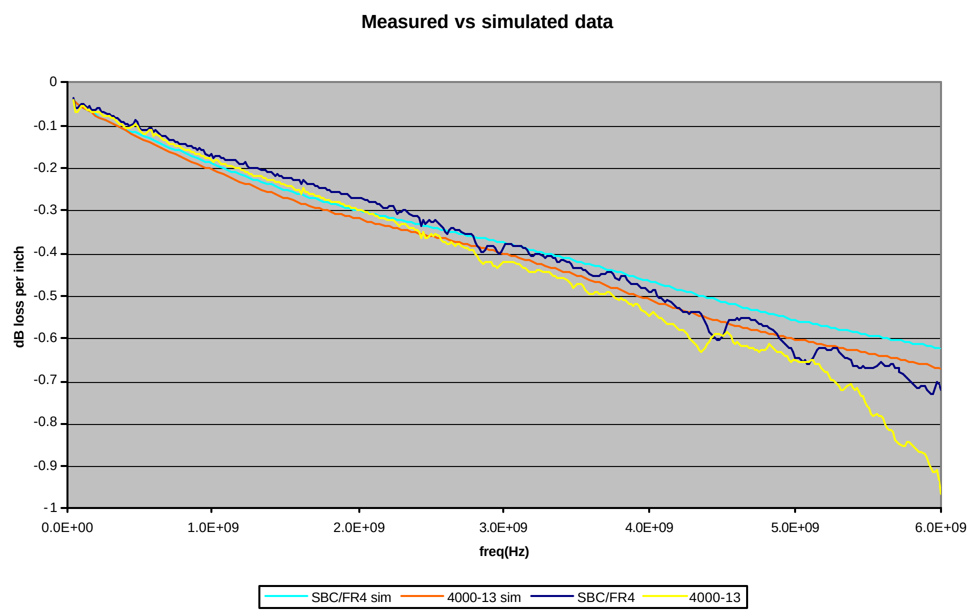

Figure16- comparison of simulated vs. measured data through 6GHz

It may be seen in Figure 16 that there is reasonably good agreement between the model and the measured data. The most obvious sources of error are the effects of return loss from the connectors on the measured data and discrepancies in impedance between the measured and simulated data.

The Eyes Don't Lie

While the frequency domain data contains a lot of important and useful information, it is also a good idea to keep an eye on the performance in the time domain. In order to compare the differences between FR4 and the materials of interest a 13in length of stripline from the above boards was compared to 13in of FR4 stripline when injected with an approximately 500mV signal at 10Gbps 2^7-1 PRBS. The input eye pattern is shown in Figure 17. The FR4 result is shown in Figure 18 and the SBC/FR4 and 4000-13 results are shown in Figures 19 and 20 respectively.

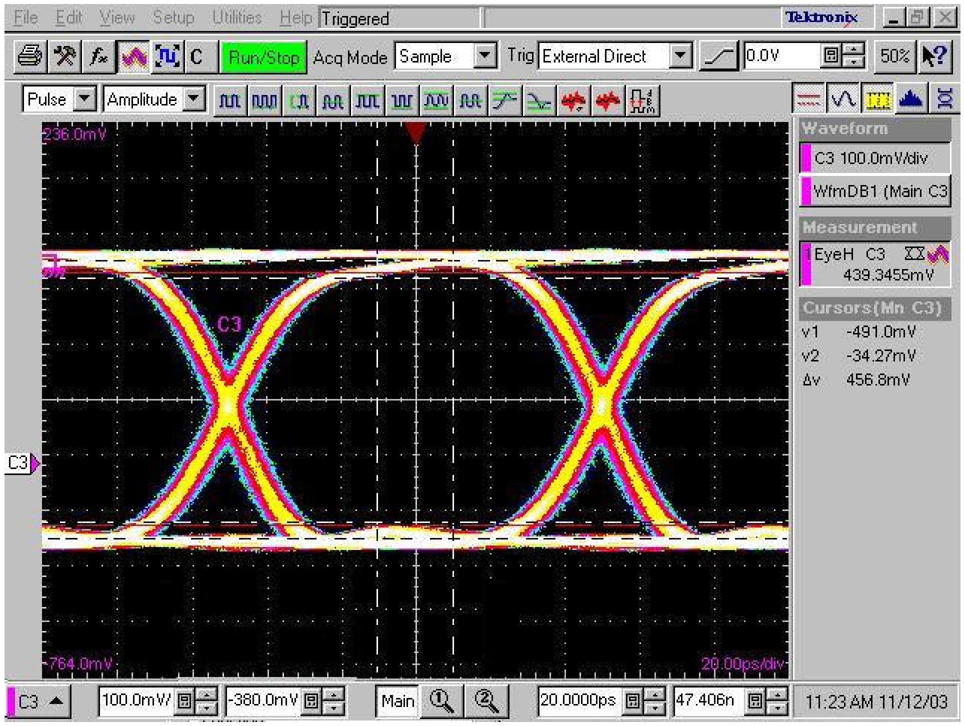

Figure17- Input Eye pattern 500mV 10Gbps

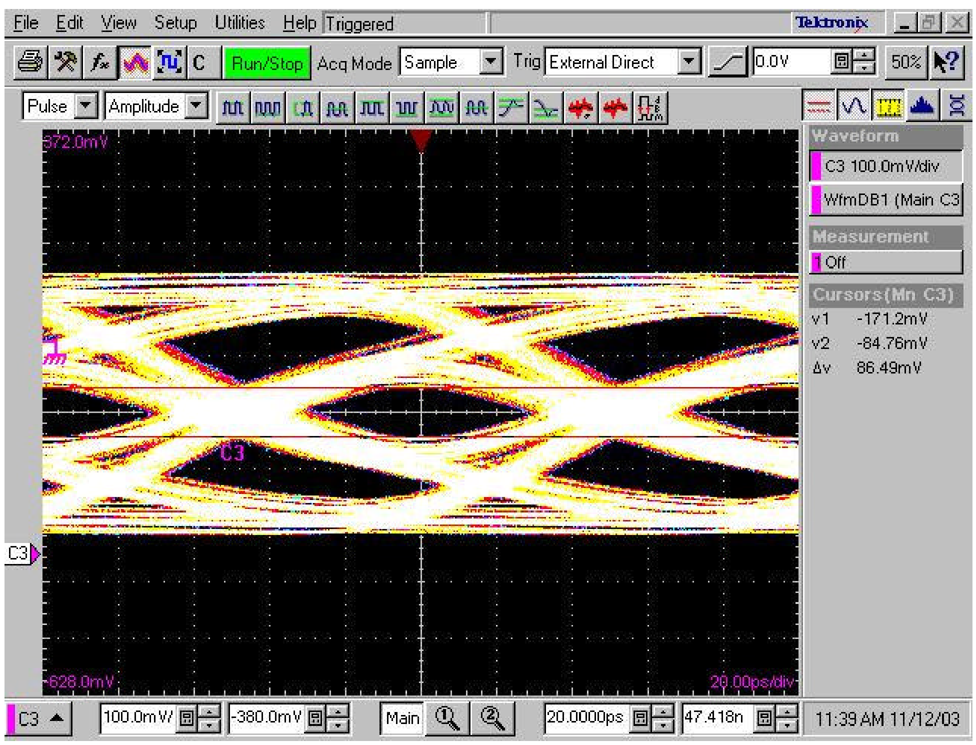

Figure18- FR4 Eye pattern 500mV 10Gbps

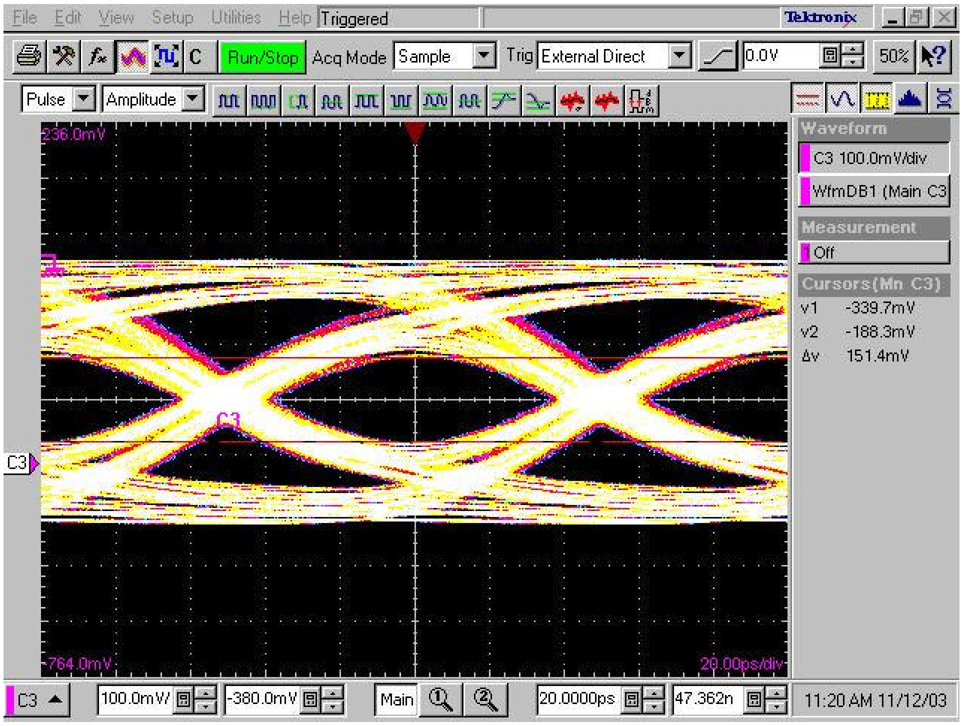

Figure19- SBC/FR4 Eye pattern 500mV 10Gbps

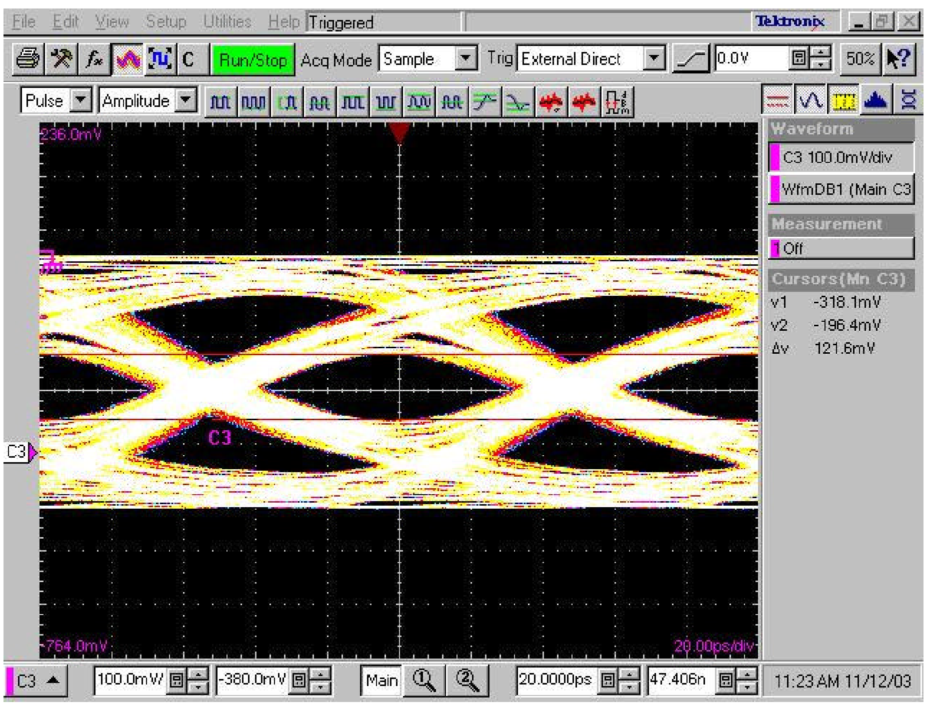

Figure20- 4000-13 Eye pattern 500mV 10Gbps

The Table 3 summarizes the results with respect to eye height for the figures above:

Table 3 – Results with Respsect to Eye Height for Figures 17 through 20

	eye height
Input	456.8mV
FR4	86.5mV
SBC/FR4	151.4mV
4000-13	121.4mV

As may be seen from the above table, The measured eye height for 4000-13 is nearly 50% greater than that of the FR4 stripline while the SBC/FR4 eye height is about 75% greater than that of the FR4 stripline.

The Need for Speed

For some applications the velocity of propagation down a signal line can be very important. This material property is determined by the dielectric constant of the material used. A rough measurement of the velocity of propagation was made and used to determine the effective dielectric constant of these two materials via electrical length measurement using TDR. The results of this measurement are shown in the Table 4.

Table 4 – Results of the Measurement

	delay 13in line	velocity of propagation	effective dielectric constant
FR4	2.25ns	1.47E^10 cm/sec	4.16
SBC/FR4	2.08ns	1.58E^10 cm/sec	3.59
4000-13	2.23ns	1.48E^10 cm/sec	4.10

The effective dielectric constants measured using this method are a bit higher than published values, likely due to the rough nature of the measurement. However, we may still draw conclusions about the relative performance of the materials. In this case we see that, as is intuitively clear, a hybrid stripline of FR4 coupled with a low dielectric material yields an effective dielectric constant which is lower than FR4 alone and hence has a higher velocity of propagation.

Counting the Cost

The fact that coupling a high performance material with FR4 gives better performance will come as no great shock to anyone. Just how much better may be impressive, but the real motivation for moving to a hybrid stripline construction is all about the bottom line. Designs today must balance both cost and performance.

Of course the final cost of a hybrid board as compared to all FR4 will depend a great deal on the stack-up of the board. As a simple example let us take a twenty-layer board of which six layers are high-speed signal layers. Obviously there is no need to use high performance materials on any layers other than the high speed layers, so using Speedboard C/FR4 on only the high speed layers would yield a board costing about 1.3 times the cost of an all FR4 stack-up.

For most applications in which FR4 will simply not meet the design specifications, an increased materials cost on the order of that associated with using hybrid stripline would be a very attractive solution, especially when one considers the alternative of creating a multilayer board using all high-performance material.

Conclusions

The electrical performance of simulated PCB transmission lines examined in this study correlated well with measured data. Based on the results of the simulations and experimental measurements performed in this study, there are a number of important points to consider when designing digital PCB solutions for use at multiple gigabit data rates:

- It is advantageous to design hybrid striplines with an imbalance which favors coupling through the higher performance material (Figure 7).
- Hybrid stripline may yield significant advantages over all FR4 or other material constructions in crosstalk, insertion loss and eye pattern (Figures 5,6,7,19,20).
- It is vital that the designer ensures good signal integrity of the entire signal path as even relatively small impedance discontinuities, such as launch and connectors, may nullify some of the improved loss performance obtained by using higher performance materials (Figure 12).