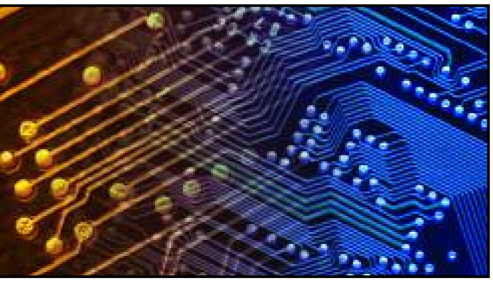
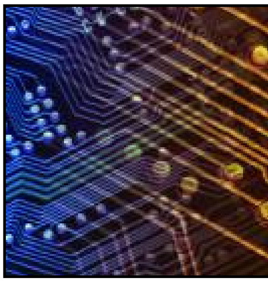
Stripline Performance in Hybrid Printed Circuit Boards



By James Broomall, Tamera Yost and Glen Walther

The hybrid construction of FR4 laminate and low loss prepreg improves signal transmission due to lower attenuation consistent with a lower effective dielectric loss tangent.



Design constraints for today's high data rate boards are forcing increased layer count when using conventional FR4 materials or the use of more expensive high performance dielectric materials to achieve lower signal attenuation and permit higher trace density. As illustrated in Figure 1, a hybrid construction uses a low-cost core such as FR4 with a higher performance prepreg to provide lower attenuation. There are some obvious performance questions, specifically near- and far-end crosstalk, frequency dependence of attenuation, and time delay in both single-ended and differential signaling. To address these concerns evaluation boards were fabricated to compare the hybrid construction to the industry standard all FR4 stripline construction. Results of time domain and frequency domain measurements are presented here.

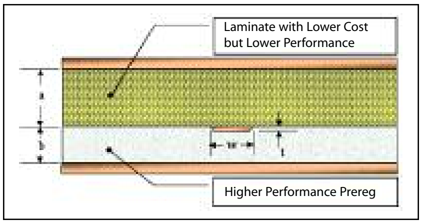


Figure 1. Hybrid Construction.

PERFORMANCE CONSIDERATIONS

The effects of near-end (NEXT) and far-end (FEXT) crosstalk between coupled transmission lines can be thought of in various ways. A straightforward approach is to consider two lines as a differential pair, then look at the even and odd modes of propagation. In this approach, a step stimulus of the aggressor line is seen as a combination of one half even and one half odd mode. This will result in a net zero input stimulus on the victim line. The response of the victim line is then the resulting superposition of the two modes' interaction with the transmission lines. For near-end crosstalk, the coupling impedance of the lines is a measure of the expected crosstalk. Far-end crosstalk will result if differences in attenuation and propagation velocity of the two modes result in incomplete cancellation of the two modes.

When the dielectric is not homogenous throughout the cross section, it has been recognized that additional modes of propagation can be stimulated. These have been studied in some depth theoretically [2,3], but there are few experimental results in the literature. A complete discussion of this phenomenon is very much beyond the scope of this presentation, but some general comments are appropriate.

There are two general classes of modes in addition to the expected modes that are "bound" to the striplines. One type results in leakage of the signal from the stripline into one or more parallel plate waveguide modes. These modes rob signal from the stripline, resulting in increased attenuation. The other very general type results in propagation in the direction of the stripline but typically having different propagation speed and attenuation than the bound mode. The generation of both of these additional modal types is dependent on transmission line geometry and dielectric homogeneity and consequently has propagation characteristics that are dependent on frequency.

EVALUATION BOARDS

A series of printed circuit boards were fabricated to explore the effects of asymmetry of placement of the stripline between the two ground planes and the use of homogeneous versus hybrid materials. Figure 1 shows schematically the stackup geometry and Table 1 lists the parameters as measured from cross-sections of the fabricated boards (Parameters as identified in Figure 1).

Table 1. Measured parameter values (mils) and Impedance Ohms)

Stackup	Description	a	b	w	t	Z_0
1	Balanced Homogeneous	9.3	11.2	7.55	0.36	59.2
2	Unbalanced Homogeneous	13.9	9.6	7.69	0.36	55.8
3	Balanced Hybrid	10.1	7.1	7.51	0.36	56.7
4	Unbalanced Hybrid	13.9	5.6	7.55	0.36	54.6

The stackups were chosen to demonstrate the effects of material homogeneity and unequal thickness layers of dielectric surrounding the stripline. Stackup 1 was a homogeneous design of all FR4 (Nelco 4000-6) and was used as an industry standard baseline construction. Stackup 2 was also a homogeneous design of all FR4 but with the stripline trace offset with respect to the top and bottom ground planes. Stackup 3 was a hybrid construction of FR4 and SBC intended to provide the same capacitance per unit length between the trace and each ground plane, therefore demonstrating a "balanced" configuration. And lastly, stackup 4 was intentionally designed to emphasize the effects of an offset in a hybrid construction of FR4 and SBC by promoting stronger coupling of the signal through the SBC.

Microphotographs of the 4 stackups are shown in Figure 2. The two on the left have core and prepreg of FR4, while the two on the right are FR4/SBC hybrids. The top two stackups are more balanced than those on the bottom. The trace thickness of 0.36 mils is less than was originally planned, causing the trace impedance to be higher than expected. This causes a somewhat higher trace resistance, but the higher impedance lowers the conductor loss while having little effect on the dielectric component of the loss.

Table 2. Percent Crosstalk Measurements

NEXT				
	Homogeneous		Hybrid	
Spacing	Unbalanced	Balanced	Unbalanced	Balanced
8	6.4	6.3	4.5	4.3
16	2.4	2.3	1.5	1.2
24	1.0	0.9	0.7	0.5
FEXT				
	Homogeneous		Hybrid	
Spacing	Unbalanced	Balanced	Unbalanced	Balanced
8	2.2	5.4	9.2	5.3
16	2.4	4.1	8.2	4.7
24	1.2	1.8	9.4	5.5

EXPERIMENTAL RESULTS AND DISCUSSION

Single-Ended Measurements. Measurements were taken for near-end (NEXT) and far-end (FEXT) crosstalk on lines at 8-, 16- and 24-mil spacings using four ports on a time domain sampling oscilloscope A TDR source of one of the scope heads was used to provide a step aggressor signal to one of the launch connectors. The aggressor step had an amplitude of 250 mV and a 10-90% risetime of 30 ps. The TDR step was chosen as an aggressor signal since it provided a clear response for NEXT and FEXT. The 30 ps risetime is appropriate for digital signals in the 10 Gbps range. Input impedance, NEXT, FEXT and transmitted signal amplitude could be viewed with a single configuration. Sample data is shown in Figure 3. The top signal trace is the NEXT response, showing the typical step-like form of transmission line NEXT. The second signal trace shows a typical FEXT blip on the victim line. The third signal trace is the input impedance, displayed in units of Ohms at 5 Ohms per division. The bottom trace is the signal exiting the aggressor line. All signal traces except for the impedance response are displayed at 10 mV per division. All of the tested boards showed typical NEXT step responses like that of the sample with varying amplitudes depending on stackup and trace separation as shown in Table 2. There is not much difference between the balanced and unbalanced stackups for a given material set, but there is a significant difference between the hybrid and homogeneous constructions. The hybrid boards show approximately a 30% improvement in NEXT over the homogeneous boards.

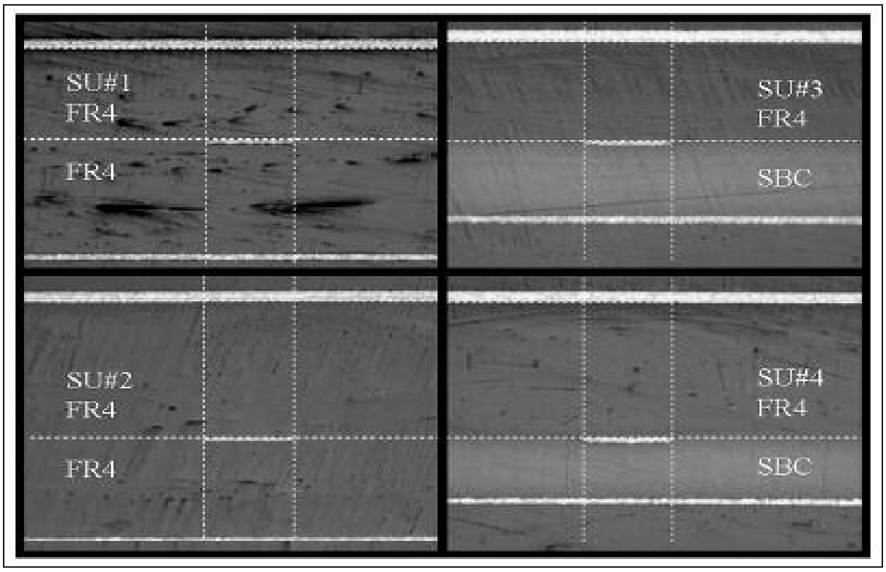


Figure 2. Microphotographs of Stackups.

The far-end crosstalk results are also shown in Table 2. The unbalanced Hybrid board shows substantially more crosstalk than the other stackups at all spacings. The balanced boards of both material sets showed very similar results at 8-mil and 16-mil spacings.

The homogeneous results are somewhat surprising at first glance. If the material is truly homogeneous, the even and odd modes should propagate at the same speed, producing very little FEXT. This should be true regardless of trace centering. Inspection of the material

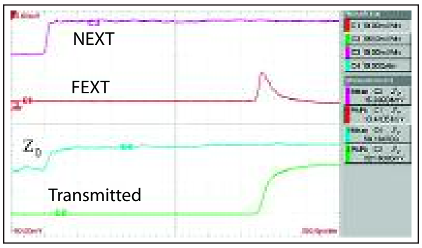


Figure 3. Sample data.

specifications for different thickness of core and prepreg [4] shows a fairly broad range of possible dielectric constants depending on thickness. This may be the root of the difference in these two examples.

There is no obvious way to isolate measurement of the additional modes caused by lack of homogeneity. There is however the ability to look at their effect in the frequency domain. The lines at 8-mil spacing were tested using a 4-port vector network analyzer. The phase data from the through path of one of the lines for each board was unwrapped to provide phase as a function of frequency. This data was inspected to be certain there were no regions where the phase data was not monotonically increasing due to frequency step size. The phase data was then divided by frequency at each point and converted to time delay. The estimated time delay of the launches was subtracted and the result scaled by length to time delay in ps/in. Figure 4 is a graph of these results plotted versus frequency for each board. Note that all responses show the typical delay increase at low frequency caused by an increase in the conductor inductance expected at low frequency.

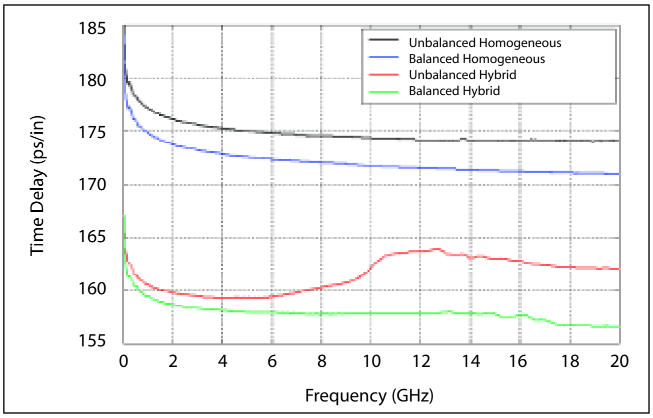


Figure 4. Time Delay (ps/in.) Vs. Frequency.

The time delay results show the expected difference in effective dielectric constant for the hybrid versus the homogeneous stackups. The homogeneous stackups have measurably different delays. The likely explanation is differences in dielectric constant of the FR4 cores and prepregs. This possibility is consistent with the FEXT results presented earlier. The unbalanced hybrid results are striking. Starting as low as 6 GHz there appears to be a transition to a different mode of propagation, or possibly combined modes. The balanced hybrid remains well behaved to above 12 GHz. Compare these results to the insertion loss plots in Figure 5. All but the balanced homogeneous construction show some evidence of irregularity at higher frequency. The dip in S21 of the unbalanced hybrid construction coincides with the delay anomaly seen in Figure 4.

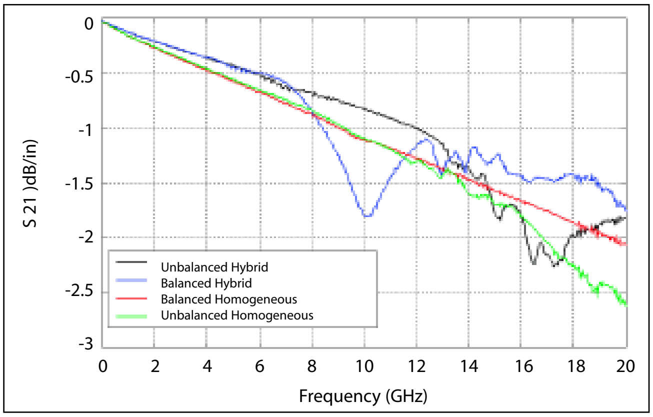
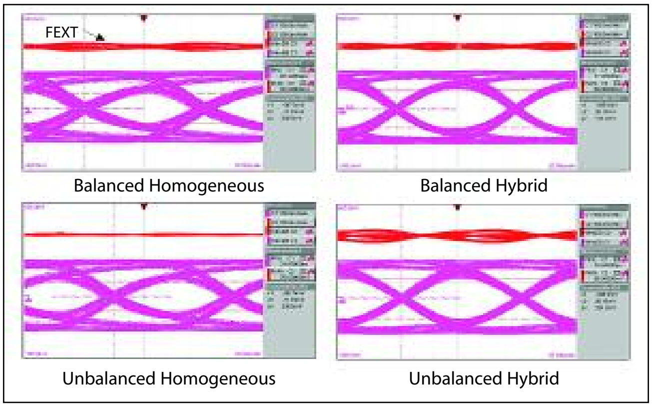


Figure 5. Insertion Loss Plots.

Eye diagrams for the single ended constructions at 10 Gbps are shown in Figure 6. The 500 mV source had a 25 pS (10-90%) edge with a 2^7-1 PRBS. The figures also show the FEXT observed on an adjacent line at 8-mil spacing. The Hybrid versions achieve eye height advantages of 30% with 25% or better reduction in jitter.



Balanced Homogeneous

Balanced Hybrid

Unbalanced Homogeneous

Unbalanced Hybrid

Figure 6. Eye Diagrams for Single-Ended Constructions.

DIFFERENTIAL MEASUREMENTS

In addition to the single-ended results, S-parameter and eye diagram measurements were taken on the differential paths created by the coupled traces at 8-mil spacing. The differential insertion loss is shown in Figure 7. The balanced constructions show very nice performance. Both unbalanced versions show some anomalies, but they are not as severe below 15 GHz. Eye diagram measurements were taken with a 1 Volt differential source at 10 Gbps using a 2^7-1 PRBS pattern. Figure 8 shows the results.

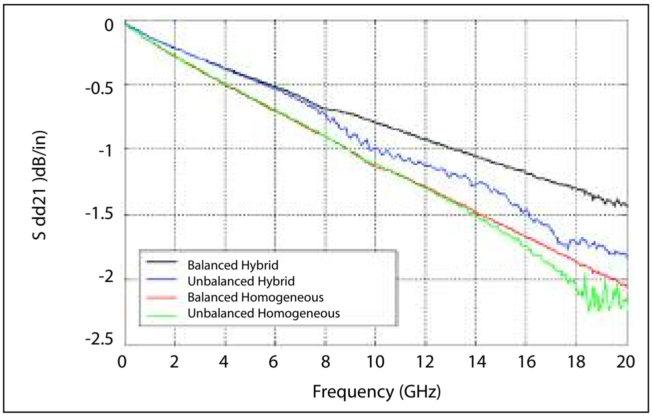
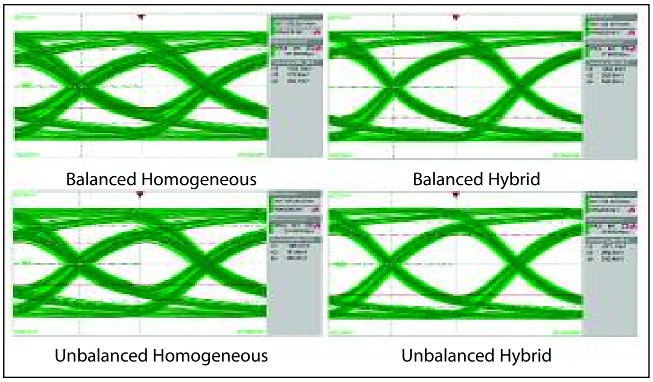


Figure 7. Differential Insertion Loss.

Table 3. Differential Eye measurements

Homogeneous Hybrid				
	Unbalanced	Balanced	Unbalanced	Balanced
Peak eye height (mv)	368	358	530	520
Peak to peak Jitter (ps)	24.8	27.6	18.8	17.6



Balanced Homogeneous

Balanced Hybrid

Unbalanced Homogeneous

Unbalanced Hybrid

Figure 8. Eye Diagram Measurements, 1V Differential Source.

The displayed eye diagrams were measured with 125 mV and 20 ps per division settings. The increased high frequency insertion loss of the all FR4 versus FR4/SBC construction is evident in the reduced eye opening height as shown in Figure 8. The associated increase in inter-symbol interference is the major contributor to deterministic jitter in passive components. Peak-to-peak jitter measurements of the eye diagrams using the oscilloscope are summarized in Table 3. The measurements include the contribution of 10.8 ps of peak-to-peak jitter from the pattern generator. The hybrid construction, regardless of stackup, shows a distinct jitter advantage versus an all FR4 construction as seen in the eye diagrams.

Although differential crosstalk was anticipated to be minimal, an additional set of boards were constructed using the balanced stickups. 8-mil wide differential lines with 10 mil spacing were spaced 15 mils from an adjacent differential pair and tested using the same (differential) TDR sources as were used for the single-ended tests. The results are presented in Table 4.

CONCLUSIONS

The study described here solidifies the notion that understanding the propagation characteristics of complex structures is difficult. Various modes of propagation exist in most cases that can cause signal degradation. This is true even for the all FR4 balanced stripline construction used widely in industry today.

As expected, the hybrid construction of FR4 laminate and low loss prepreg like GORE™ SPEEDBOARD® C Prepreg provides a benefit in signal transmission due to lower attenuation consistent with a lower effective dielectric loss tangent. For a given trace spacing, the near-end crosstalk for the hybrid construction is noticeably less due to weaker coupling between the traces and stronger coupling to the ground plane. For a balanced construction, the far-end crosstalk of the hybrid and homogeneous dielectric single ended stackups were comparable while differential signals showed less crosstalk in hybrid stackups than in the homogeneous cases.

While near-end crosstalk is dependent upon the impedance matrix values, far-end crosstalk is a function of the modes of propagation. The causes of far-end crosstalk are complex and are affected by the launch, trace length, and interaction with other planar features on the board such as grounding vias. Some initial investigations have shown that placing grounding vias close to the trace can minimize the generation of unwanted modes of propagation. The literature contains a variety of suggestions for inhibiting these modes [5,6,7].

Table 4. Percent Differential Crosstalk

	NEXT	FEXT
Homogeneous	0.9	0.9
Hybrid	0.6	0.3

When compared to an all FR4 construction, the anticipated board design benefits include the use of narrower lines, closer spacing, and reduced layer thickness. In addition, the performance of a hybrid construction is significantly better than all FR4 and comparable to a homogeneous mid-range performance dielectric material set. Various cost analyses have been conducted that repeatedly show cost savings of 20% using a high performance prepreg with a low-cost FR4 over a mid-range cost-performance material in a balanced stripline construction. The reduced cost originates from the material cost benefits of continuing to use low-cost FR4, reduced board layer count, and reduced manufacturing costs associated with lower layer count boards.

We have shown that hybrid stripline structures offer a variety of benefits. To understand the complex length-dependent modes of propagation a detailed model is needed to allow for optimization of the design parameters. Specifically, the literature suggests that scaling of layer thickness can shift the interaction of the unwanted modes to a frequency above our region of interest for 10 Gbps. If this is true, the use of hybrid structures for narrow traces in dense designs would be an obvious choice.

One of the promising aspects of this study seems to lie in the use of a hybrid stripline structure for differential signals where the effects of unwanted modes are greatly reduced. The data in this study showed a 25% reduction in insertion loss at 20 GHz for the hybrid stackup with the expected low crosstalk result. **CT**

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