

Introduction

As more designs move toward high-speed serial links with picosecond edge rates, any impedance discontinuity in the channel can adversely affect signal quality. Channel discontinuities come from several sources and each source must be carefully considered. One commonly overlooked source of channel discontinuity is the signal via. Vias can add jitter and reduce eye openings that can cause data misinterpretation by the receiver.

This application note discusses the effects of via discontinuities in the transmission line and the ways to mitigate their effects. A time-domain reflectometer (TDR) and full-wave 3D field simulator are used to explain impedance signatures, and insertion and return losses of typical standard vias and their effect in the signal path. Also, tuning methods to make the vias more transparent to faster edge rates are evaluated. Via-tuning trade-offs are also examined because of manufacturability concerns of higher oven temperatures associated with the recent switch to restriction of hazardous substances (RoHS) processes. Finally, general guidelines and recommendations show how to design an optimized via for better high edge-rate signal transmission.

Standard Differential Via

Figure 1 shows the construction of a typical differential via in a high-speed serial link. Vias consist of the capture pads where signal traces enter or exit the vias, the drill barrel for layer transitioning, the non-functional pads (NFP or unused pads), and the via anti-pad clearance. In this via, 100- Ω differential traces enter the vias on layer 1 and exit on layer 6, while leaving a via stub from layer 6 to the bottom of the board, as well as two NFPs on layers 3 and 8, respectively.

Table 1 shows the dimensions used in the construction of this differential via. The via with this construction is referred to as a standard via. Simulation results shown in this application note compare against this standard via to show any improvement gains.

Via Parameter	Size (mils)
Drill diameter	10
Capture pad diameter	20
Anti-pad diameter	30

Figure 3 shows the detailed stackup of the test board. Table 2 shows the required trace geometries to meet a nominal differential impedance target of $100\ \Omega$ with $\pm 10\%$ tolerances. Given these design specifications, lab measurements of this standard differential via are correlated with HFSS simulation results to first calibrate the simulation setup. When calibrated, additional simulations explore and evaluate techniques for optimizing the via design.

Figure 3. Test Board Stackup

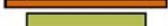
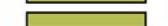
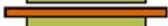
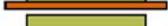
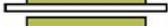
Lamination Stackup:			Thickness and Tolerances:	
L#/Type		Description:	Cu+:	Laminate/PrePreg:
1 Sig		Core 0.0060 H/1	.00060	.0060
2 Pln			.00120	
		Pre-Preg (1 x 2116)		.0125 +/- 0.0013
		Pre-Preg (1 x 2113)		
		Pre-Preg (1 x 2116)		
3 Sig		Core 0.0060 1/1	.00120	.0060
4 Pln			.00120	
		Pre-Preg (1 x 2113)		.0036 +/- 0.0004
		Filler Core 0.0210 0/0		.0210
				
		Pre-Preg (1 x 2113)		.0036 +/- 0.0004
5 Pln			.00120	.0060
6 Sig		Core 0.0060 1/1	.00120	
				
		Pre-Preg (1 x 1080)		.0120 +/- 0.0012
		Pre-Preg (1 x 7628)		
		Pre-Preg (1 x 1080)		
7 Pln			.00120	.0066
8 Sig		Core 0.0066 1/H	.00120	.00060

Table 2. Test Board Controlled Impedances by Layer

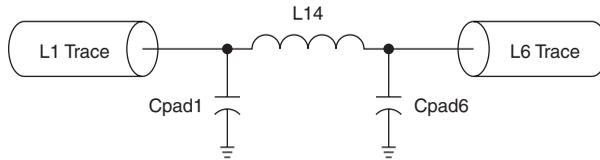
Impedance Requirements		Fin. Line	Ref Pin	2nd Ref Pin	Targeted Desired Impedance	Impedance Tolerance	Actual Calculator Impedance	Diff Line Centers	Diff Line Space
L#	Impedance Type								
1	SE-Coated Microstrip	.00950	2	—	53.00 Ω	+/- 10%	53.59 Ω	—	—
1	DIF-Coated Microstrip Edg	.00950	2	—	100.00 Ω	+/- 10%	99.55 Ω	.02400	.01450
1	SE-Coated Microstrip	.01075	2	—	50.00 Ω	+/- 10%	50.27 Ω	—	—
3	SE-Stripline	.00750	4	2	51.00 Ω	+/- 10%	50.87 Ω	—	—
3	DIF-Stripline Edg Cpld	.00750	4	2	100.00 Ω	+/- 10%	100.10 Ω	.02600	.01850
6	SE-Stripline	.00700	5	7	51.00 Ω	+/- 10%	50.84 Ω	—	—
6	DIF-Stripline Edg Cpld	.00700	5	7	100.00 Ω	+/- 10%	100.27 Ω	.02600	.01900
8	SE-Coated Microstrip	.01050	7	—	55.00 Ω	+/- 10%	55.18 Ω	—	—
8	DIF-Coated Microstrip Edg Cpld	.01050	7	—	100.00 Ω	+/- 10%	100.69 Ω	.02400	.01350
8	SE-Coated Microstrip	.01250	7	—	50.00 Ω	+/- 10%	50.36 Ω	—	—

Lumped pi Model

Vias can appear as capacitive and/or inductive discontinuities. These capacitive and inductive parasitics contribute to the degradation of the signal as it passes through the via. Figure 4 shows a simple lumped LC pi model to illustrate via capacitance and inductance effects. Although this

model is only applicable if the delay of the via is less than $1/10^{\text{th}}$ of the signal rise time, it is still useful for understanding the capacitance and inductance effects.

Figure 4. Lumped pi Model of a Via



Equation 1 shows the empirical formula for the capacitance of the via. Equation 2 shows the empirical formula for the inductance of the via when vias are modeled as a lumped LC pi model.

$$(1) \quad C_{via} \approx \frac{1.41 \epsilon_r D_1 T}{D_2 - D_1} \text{pF}$$

$$(2) \quad L_{via} \approx 5.08h \left[\ln\left(\frac{4h}{d}\right) + 1 \right] \text{nH}$$

ϵ_r is the relative dielectric constant, D_1 is the diameter of the via pad, D_2 is the diameter of the anti-pad, T is the thickness of the PCB, h is the via length, and d is the via barrel diameter.

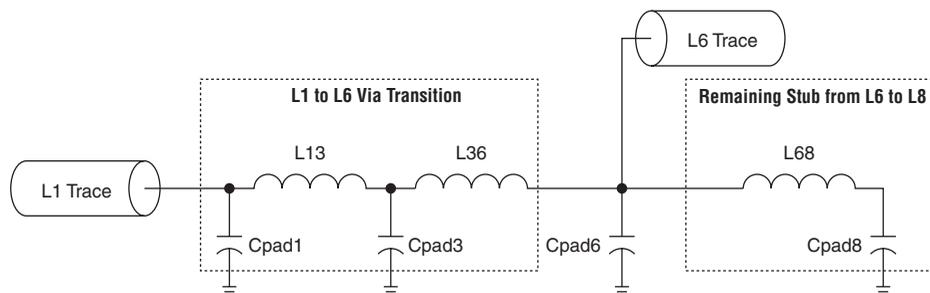
To minimize the capacitive effects of the via in Equation 1, make the diameter of the via pad small while increasing the diameter of the anti-pad. Similarly, minimize the length of the via barrel in Equation 2 to reduce the inductance of the via.

Cascaded Model

A representative equivalent circuit model for the standard via in [Figure 1 on page 2](#) is shown in [Figure 5](#). L1 is the microstrip trace on layer 1 entering the via and L6 is the stripline trace exiting the via on layer 6. As a signal travels through the via, each via pad it encounters contributes some capacitance, while each section of the via barrel adds inductance. In this case, Cpad1, Cpad3, Cpad6, and Cpad8 each represent the capacitive contribution from the via pads on layers 1, 3, 6, and 8, respectively. Similarly, L13, L36, and L68 model the inductive contribution from the portion of the via barrel transitioning from layer 1 to 3, layer 3 to 6, and layer 6 to 8, respectively. The series combination of L68 and Cpad8

represent the via stub below layer 6. These capacitive, inductive, and stub parasitics contribute to the degradation of the signal as it passes through the via.

Figure 5. Cascaded Via Equivalent Circuit



Although Equations 1 and 2 cannot be directly applied to this equivalent model, the techniques to minimize the via capacitance and inductance still apply. To further understand these individual contributions, a HFSS full-wave 3D field simulator is used to evaluate the impedance and s-parameter profiles of vias with selected optimizations applied. These optimizations are a direct result for understanding the C_{via} and L_{via} described in Equations 1 and 2, and include the following:

- Minimize C_{via} by
 - Reducing capture pads
 - Eliminating NFPs
 - Increasing anti-pads
- Minimize L_{via} by
 - Eliminating and/or reducing stubs
 - Minimizing via barrel length by routing outer layers near surface layers and applying backdrilling

The results from HFSS simulations, as well as TDR and VNA measurements taken from the Altera® test board, are discussed in:

- [“Effects of the Standard Via”](#)
- [“Via Optimization Techniques”](#) on page 10
- [“Addition of GND Return Vias”](#) on page 13
- [“Use of Via Backdrilling”](#) on page 16
- [“Reliability Trade-Offs”](#) on page 18
- [“Recommendations”](#) on page 18
- [“Via Tuning Guidelines”](#) on page 18

Effects of the Standard Via

The following compares the simulated TDR and s-parameter profiles for the standard via in [Figure 1 on page 2](#) for three different cases:

- Layer 1 to layer 3 (long stub)
- Layer 1 to layer 6 (short stub)
- Layer 1 to layer 8 (no stub)

[Figure 6](#) shows the TDR measurements for the test board layer 1 to layer 6 via discontinuity for calibration purposes. The measurement shows the odd-mode impedance of the test board discontinuity as $42.5\ \Omega$ at the via. Because the differential impedance for symmetrical lines is equal to twice the odd-mode impedance, this measurement translates to an equivalent differential impedance of $85\ \Omega$. This is in line with the simulated result of $83\ \Omega$ for the differential impedance at the via, as shown in [Figure 7](#) (layer 1 to layer 6 standard via). With the simulation calibrated, you can confidently explore different via optimizations through additional HFSS simulation.

Figure 6. Measured TDR for Standard Via

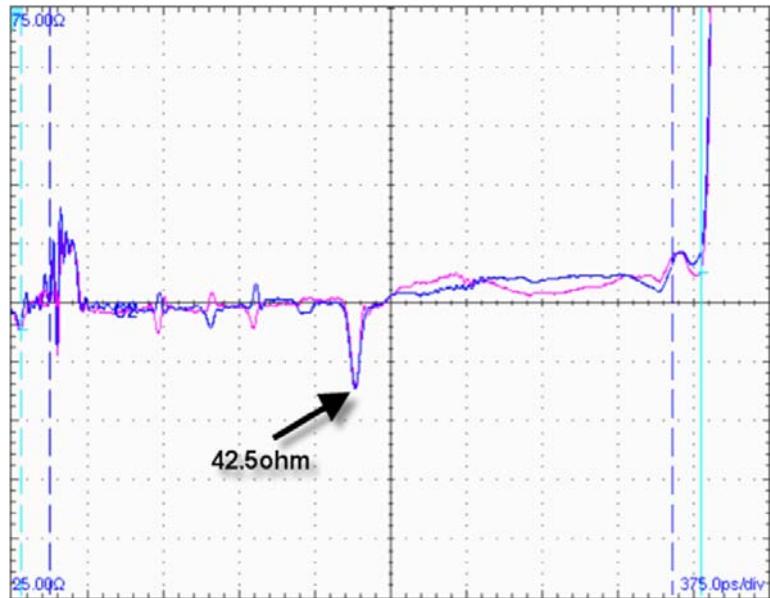
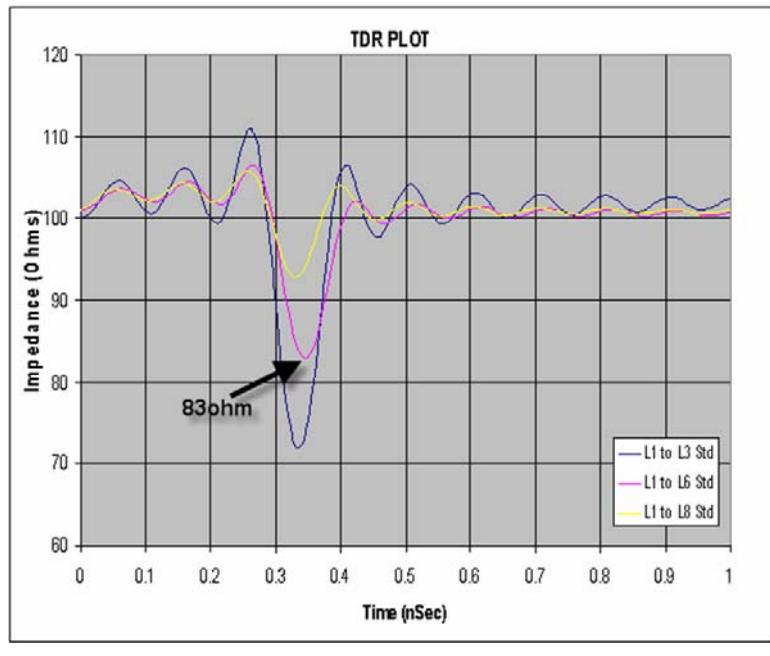
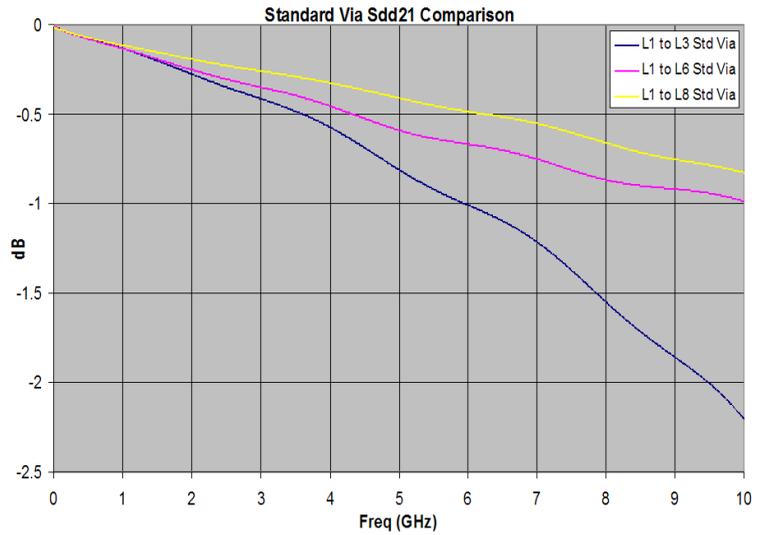
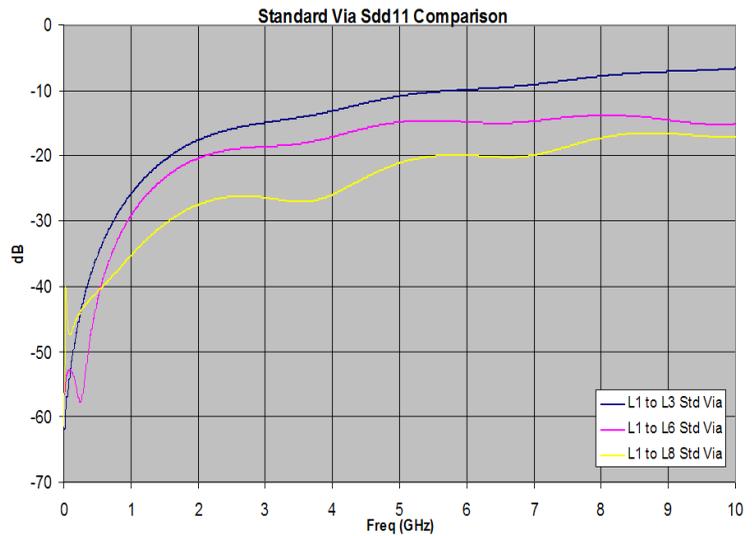


Figure 7. Simulated TDR Comparison for Standard Via

For completeness, [Figures 8](#) and [9](#) compare the insertion and return losses (Sdd21 and Sdd11) for the same three via cases (long stub, short stub, and no stub) with HFSS simulation.



The test board measurements are not compared because these measurements would include more losses as a result of additional end-to-end loss contributions from the SMA connectors and 10 inches of trace routing. Conversely, simulated results model the isolated via by itself.

Figure 8. Simulated Sdd21 Comparison of Standard Via**Figure 9. Simulated Sdd11 Comparison of Standard Via**

Figures 7 through 10 show that longer via stub lengths cause larger impedance discontinuity and present more loss to the signal path. You can eliminate the via stub by routing only microstrip traces on the top and bottom layers of the board. However, this might not be possible because of layout constraints, electromagnetic interference (EMI) related concerns, or other board design considerations with microstrip traces. Therefore, you must consider other ways to optimize the via for internal routing layers.

Via Optimization Techniques

You must minimize C_{via} and L_{via} parasitics to mitigate the effects of the via, as shown in Equations 1 and 2. Typically, via capture pads are already designed using the minimum diameter in order to maximize routing space. Therefore, perform the following optimizations to minimize C_{via} and L_{via} :

- Eliminate NFPs
- Increase via anti-pad diameter
- Eliminate and/or reduce via stubs

Figures 10 through 12 compare the simulation results for the TDR profile, and insertion and return losses for the standard (non-optimized layer 1 to layer 6) via with the same via that has the aforementioned optimizations successively applied. In the figures:

- “L1 to L6” indicate a layer 1 to layer 6 signal transition
- “No NFP” indicates removal of all non-functional pads
- “40AP” and “50AP” indicate increases in the via anti-pad to 40 mils/50 mils from the standard 30 mils.

Applying all of these optimizations improves the design of the via as illustrated by the simulation results.

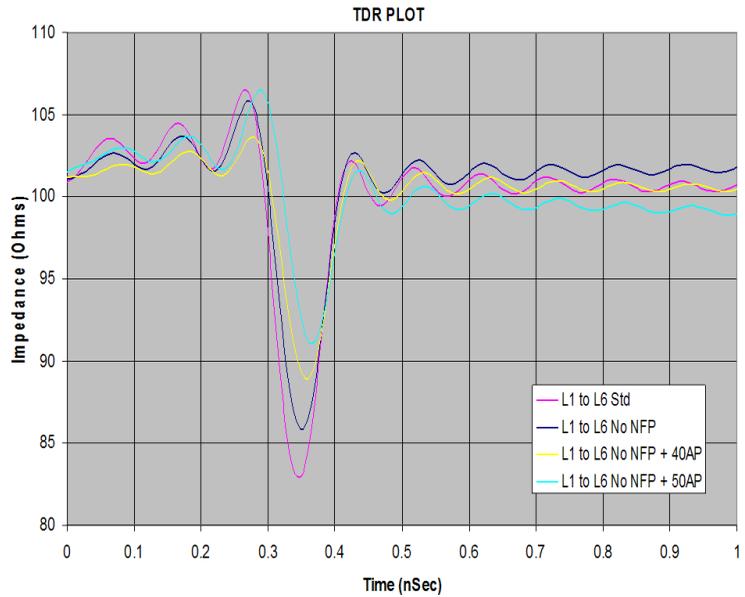
Figure 10. TDR of Standard Via versus Via with Various Optimizations

Figure 11. Insertion Loss of Standard Via versus Various Optimizations

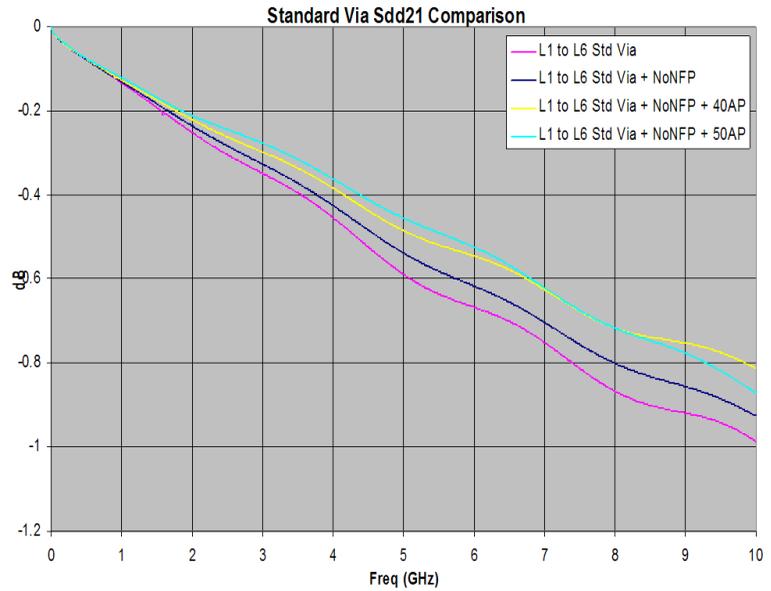
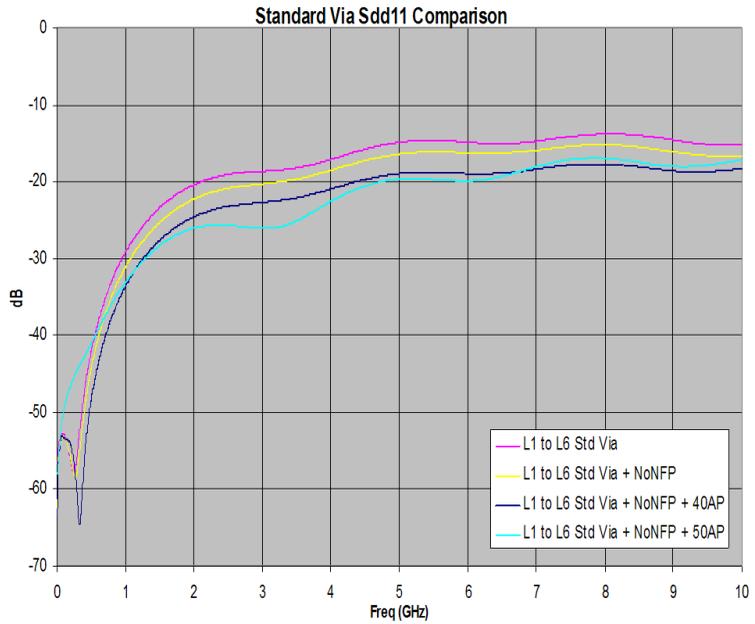


Figure 12. Return Loss of Standard Via versus Various Optimizations

Addition of GND Return Vias

Another improvement involves providing a better AC return path by adding adjacent ground vias next to each signal via, as shown in [Figures 13 through 16](#).

[Figures 13 through 16](#) show the effect on the TDR, and insertion and return loss plots of adding ground vias 35 mils on either side of each signal via for the optimized 50-mil anti-pad via case. Adding ground vias provide added improvements to the impedance and insertion and return losses of the optimized via under consideration.

Figure 13. Optimization with GND Return Vias

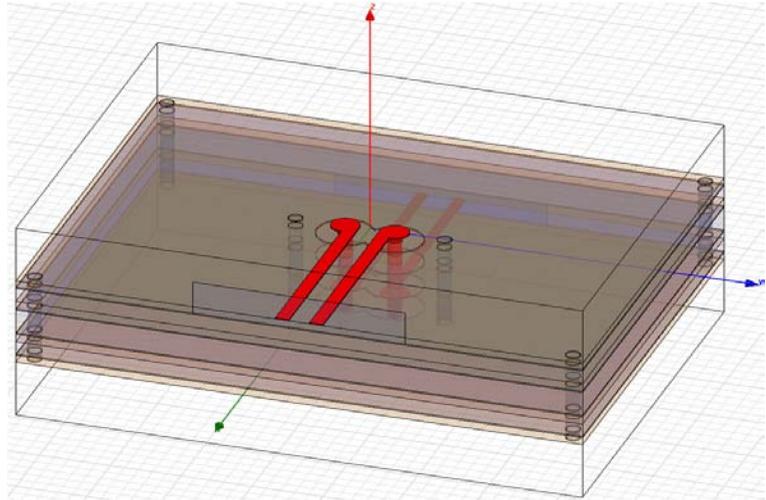


Figure 14. TDR Plot with GND Return Vias

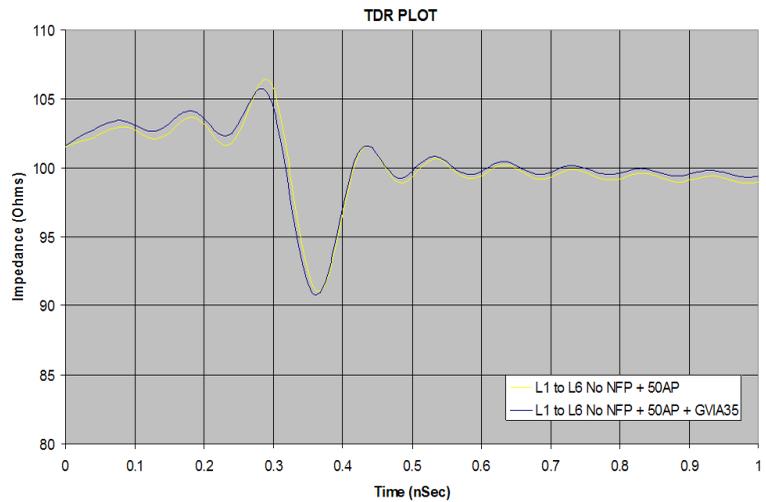


Figure 15. Insertion Loss with GND Return Vias

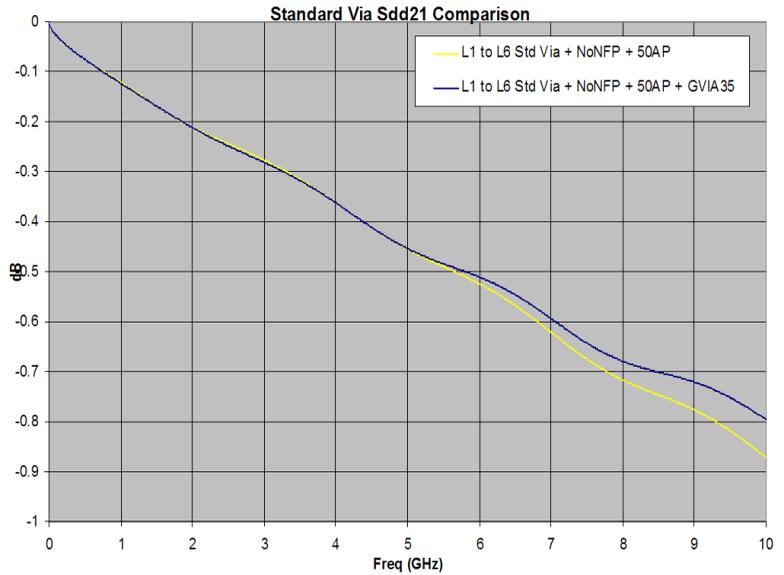
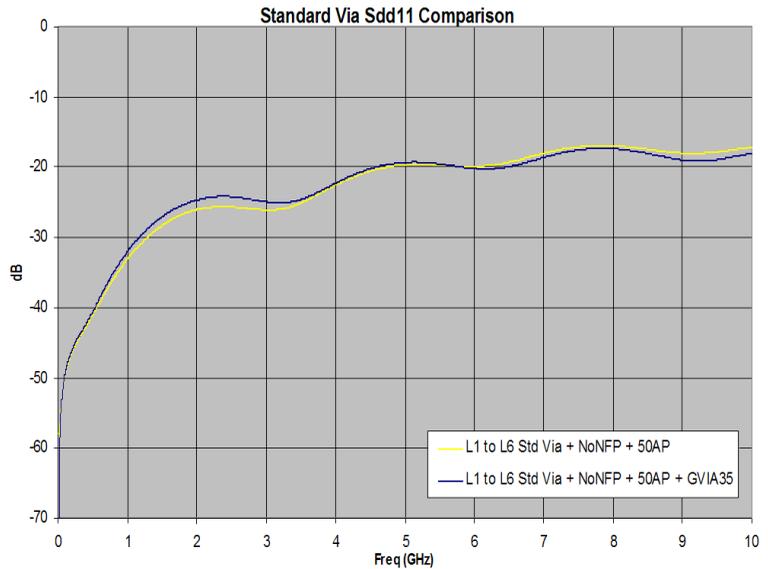


Figure 16. Return Loss with GND Return Vias



Use of Via Backdrilling

For another method to optimize the via, remove the via stub by backdrilling or counter-boring the backside of the PCB with a slightly oversized drill bit to remove the parasitic stub. This method demands a cost premium over using standard vias because it requires an additional step in manufacturing the PCB. The simulated TDR and insertion and return loss plots in Figures 17 through 19 show the benefits of backdrilling by comparing a standard layer 1 to layer 3 via, versus the same via with backdrilling applied. In this case, the signal is routed from Layer 1 to Layer 3 (instead of Layer 6 as in the previous cases) to show the effect of backdrilling to remove the long stub. If shorter stubs are backdrilled, the improvements are not significant. Backdrilling can provide significant improvements, especially if the via stub is long.

Figure 17. TDR Plot of Standard L1-L3 Via versus Backdrilled L1-L3 Via

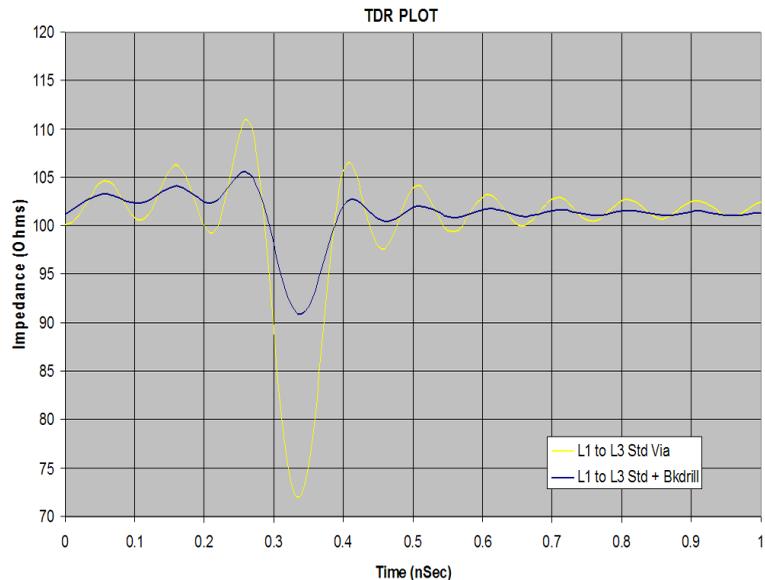


Figure 18. Insertion Loss of Standard L1-L3 Via versus Backdrilled L1-L3 Via

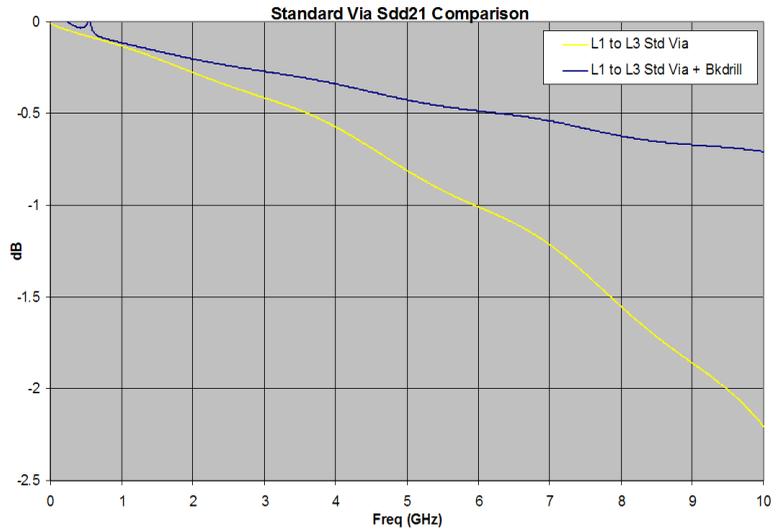
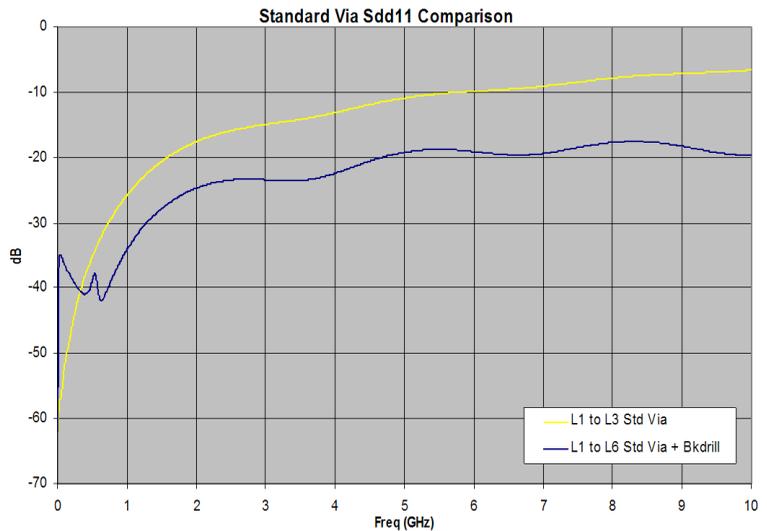


Figure 19. Return Loss of Standard L1-L3 Via versus Backdrilled L1-L3 Via



Reliability Trade-Offs

With the recent transition to RoHS manufacturing processes where printed circuit boards are exposed to multiple oven cycles at a much higher temperature, removing a via's NFPs can cause more stress on the vias as the material expands and contracts. Various studies have shown that when the via aspect ratio is high (as in the case of typical modern high-density, high-layer count PCBs), the inclusion of via NFPs can cause a reduction in long term reliability. Conversely, with low aspect ratios (larger via holes), the inclusion of NFPs can increase long-term reliability. As a result, you must be aware of and understand the reliability trade-offs that are made and tune vias according to the specific via aspect ratios used in the design.

Recommendations

Because FPGA boards with transceivers tend to have high via aspect ratios (10:1 or more), Altera recommends that you optimize vias used in high-speed serial channel designs to mitigate their effect on the channel. The following summarizes guidelines that you can use to tune vias so that they are more transparent in the transmission line. Altera recommends you perform simulations to validate the design whenever possible.

Via Tuning Guidelines

Minimize C_{via} by:

- Minimizing capture pads



Altera's boards regularly use 18-mil to 20-mil capture pads on 9-mil to 10-mil drill diameters, respectively.

- Removing all non-functional pads



Altera recommends removing all NFPs for designs with high aspect ratio vias. Altera regularly uses 9-mil and 10-mil drills on 90-mil and 100-mil thick PCBs, respectively (an aspect ratio of 10:1).

- Increasing anti-pad diameter



Altera recommends using 40-mil to 50-mil anti-pad clearances. Altera boards have achieved good performance results with 40-mil and 50-mil anti-pad via designs.

Minimize L_{via} by:

- Minimizing via stubs



Altera recommends using stripline routing on layers near the opposite surface of where the signal enters the via to minimize stub lengths.

- Adding AC return vias adjacent to each signal via:
 -  Altera recommends adding ground vias placed within 35 mils center-to-center adjacent to each signal via for providing better AC return path.
- Using backdrilling to remove stubs when appropriate.

Conclusion

Vias add impedance discontinuity to the signal path. With gigabits-per-second serial channels pushing rise and fall times below 50 ps, any degradation to the transmission line can add to the problem of eye closure at the receiver. Via tuning methods discussed in this application note help minimize the impact of signal vias in the transmission line and improve channel performance.

References

The following references were used in this application note:

- *Stephen W. Hall, Garrett W. Hall, James A. McCall, High-Speed Digital Systems Design, A Handbook of Interconnect Theory and Design Practices. New York, John Wiley & Sons, Inc., 2000*
- *Howard Johnson and Martin Graham, High-Speed Digital Design, A Handbook of Black Magic, New Jersey, Prentice Hall, 1993*
- *Bill Birch, "Discussions on Non Functional Pad Removal / Backdrilling and PCB Reliability", PWB Interconnect Solutions Inc., 103-235 Stafford Road West, Nepean, Ontario, Canada.*

Document Revision History

[Table 3](#) shows the revision history of this application note.

<i>Table 3. Document Revision History</i>		
Date and Version	Changes Made	Summary of Changes
May 2008 v1.0	Initial release.	—