A Study on Crosstalk Analysis in Aggregative Transmission Lines with Turning Vias

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Abstract

This paper presents measurement, modeling and simulation studies of high-speed signal propagation in multi-layered PCB with turning vias (immediate layer changing) in a mixed-referencing environment. The effects of turning vias, plane referencing, decoupling capacitor placement and, panel dimensions on high-speed signal propagation in an organic board are studied.

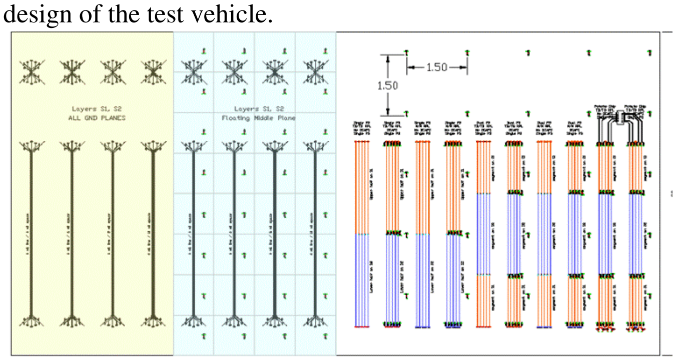
Introduction

In next-generation high-performance systems, power and signal integrity in high-speed signal channels is extremely important. Transmission lines and vias in multilayered Printed Circuit Boards (PCBs) are the most important components in signal integrity analysis of high-speed communication systems. Simultaneous switching noise (SSN) and signal traces changing layers through turning vias can be sources of high-frequency noise in the power distribution network (PDN) [1-4]. Noise can also be coupled into the signal traces passing through a power/ground plane from the existing noise on the PDN [5]. Signal traces which experience a change in the plane of reference can be subject to significant signal distortion.

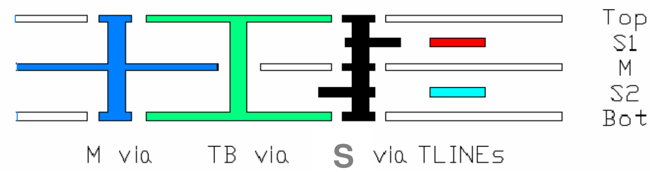
This paper presents detailed measurement and simulation studies on an organic test board with multiple power/ground planes, signal layers and different types of vias in order to investigate the effect of turning vias, plane referencing, decoupling capacitor placement and, panel dimensions on high-speed signal propagation.

Test Vehicle design

A comprehensive test vehicle with 5 metal layers using an organic substrate was designed, modeled, fabricated and, measured to have a complete electrical and physical parametric study of signal propagation through a high-speed system board with mixed-referencing. Figure 1 shows the design of the test vehicle.



(a)



(b)

Figure 1. Test Vehicle. (a) Design of the Test Vehicle. (b) Cross-section schematic of the Test Vehicle.

The PCB was comprised of 3 planes and 2 signal layers (S1 and S2). The 2 outer planes (Top and Bot) are designated as “ground” and the middle plane (M) is used as a “power” plane. Three different types of vias were used in this test board. The M via provided access to the power plane, the TB via connected the 2 ground planes together, and the S via was used either as the signal via or for connecting the 3 planes together.

The signal layers contained transmission lines (4 mil width) of different lengths arranged in bundles. The eight transmission line bundles on the left half of the test vehicle (shown in black color in Figure 1a) did not have any via transitions. There were seven transmission lines in each of these bundles. For the first four transmission line bundles (shaded yellow in Figure 1a) all the 3 planes were tied together with vias at the launch sites. The line spacing was 4, 6, 8 and 10 mils respectively for the four bundles from left-to-right. For the next four transmission line bundles (shaded blue in Figure 1a) the middle plane was floating while the 2 ground planes were tied together with TB vias at the launch sites. The line spacing was 4, 6, 8 and 10 mils respectively for the four bundles from left-to-right.

The eight transmission line bundles on the right half of the test vehicle had via transitions. The lines shown in red (in Figure 1a) were in the S1 layer while those in blue (in Figure 1a) were in S2 layer. Each of these bundles had 5 transmission lines each. Half of these transmission line bundles were referenced to the ground plane (i.e., signals were launched on these lines with the reference provided by the TB vias while the middle planes were floating) while the other half was referenced to the power plane (i.e., signals were launched on these lines with the reference provided by the M vias while the 2 outer planes were floating).

There were also some locations for placing surface-mount discrete decoupling capacitors on the board. The pads for capacitor placement were connected to the M and TB vias which provided access to the power and ground planes respectively. Some of the transmission line bundles with via transitions (i.e., the ones on the right half of the test vehicle) had these pads (for capacitor placement) next to the via transition points and the signal launch points. There were pads (for capacitor placement) close to the transmission line bundles shown shaded in blue (in Figure 1a). In addition, there were some capacitor placement locations on the top portion of the test vehicle.

Recessed Probe Launches (RPLs) [6] were used to launch signal into the transmission lines with minimal parasitic discontinuities. The transmission lines had 0, 1 or, 2 turning via transitions between the two RPL points at their ends.

Measurements

The test vehicle measurements were done using an Agilent E8364A 4-port Vector Network Analyzer. SOLT calibration was performed prior to measurements. Crosstalk was studied between the lines in every bundle, and the effects of line/via density, coupling approximation, referencing configuration, and decoupling capacitors were extracted.

1. Effect of Turning Vias

The effect of the turning via on the signal transmission losses in the transmission lines was studied. Figure 2 compares the insertion loss of three transmission lines with 0, 1 and 2 via transitions. The lines with 1 and 2 via transitions were referenced to the ground planes (Figures 8a and 10a). For the line with no via transitions, the middle plane was floating. The result shows that the insertion loss increases by about 4 dB at 40 GHz for every via transition in the signal path.

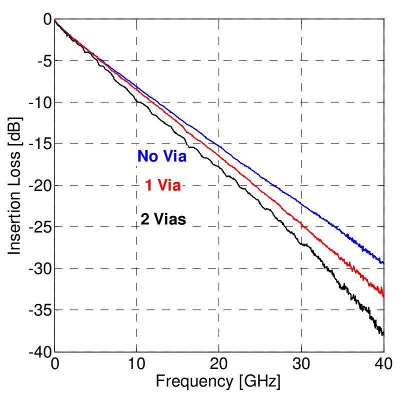


Figure 2. Measured insertion loss for transmission lines with 0, 1 and 2 via transitions.

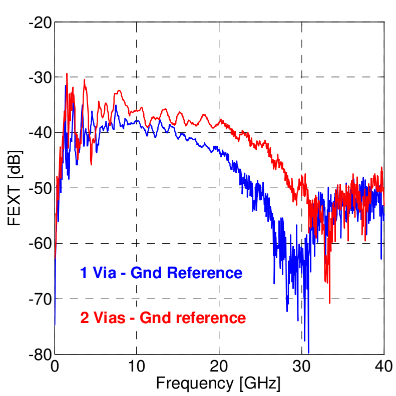


Figure 3. Far End Crosstalk (FEXT) measurement comparison for transmission lines with 1 and 2 via transitions.

Figure 3 compares the Far End Crosstalk (FEXT) between two transmission line pairs – one pair with 1 via transition and another pair with 2 via transitions. Both these transmission line pairs were referenced to the ground planes. The measurements show that the FEXT between transmission lines with 1 via transition is less than that between the lines with 2 via transitions.

2. Effect of Line Spacing

In order to study the effect of line spacing on the near-end and far-end crosstalk, two adjacent lines in the transmission line bundles were probed as shown in Figure 4.

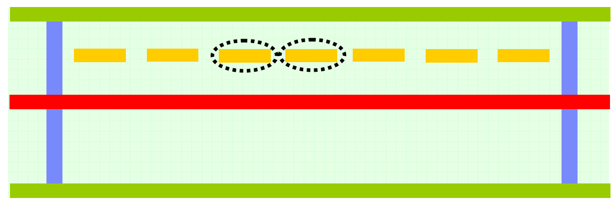
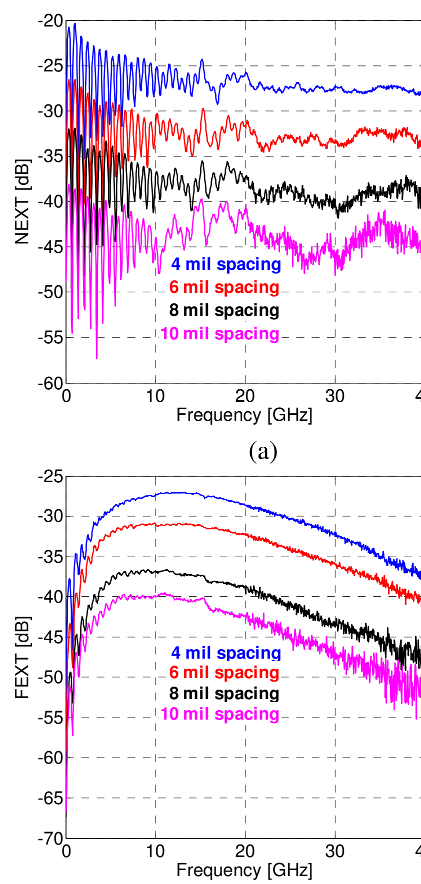


Figure 4. Cross-sectional schematic of transmission line bundle with no via transitions. All the 3 planes are connected together. The dotted circles mark the lines that were measured.



(a)

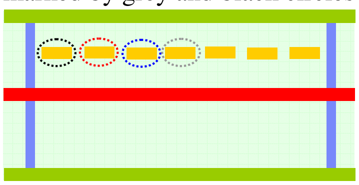
(b)

Figure 5. Crosstalk comparison for transmission lines with different line spacing. (a) Near-end Crosstalk (NEXT) measurements. (b) Far-end crosstalk (FEXT) measurements.

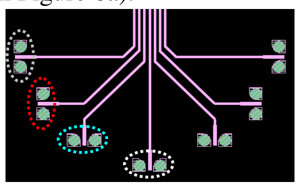
Figures 5a and 5b show the comparison in NEXT and FEXT for transmission line pairs without any via transition in the signal path. As expected, the crosstalk steadily increases as the line spacing is reduced.

3. Effect of neighboring lines

The effect of the neighboring lines on crosstalk was measured in the following manner. Crosstalk was measured between two adjacent transmission lines (1st neighboring lines) with no via transitions (all the 3 planes were connected together) as shown in Figure 6a (the lines marked by grey and blue circles). Crosstalk was then measured between the 2nd neighboring lines (lines marked by grey and red circles in Figure 6a) and, then between the 3rd neighboring lines (lines marked by grey and black circles in Figure 6a).

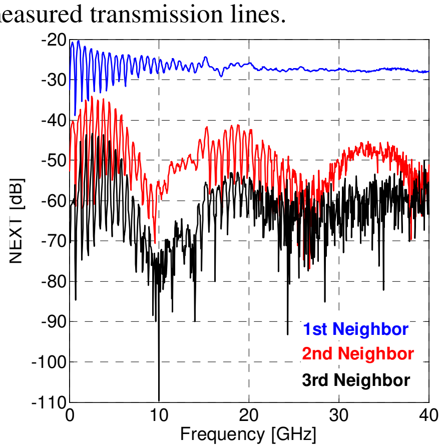


(a)

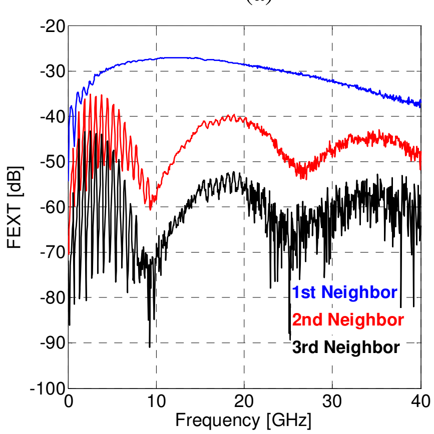


(b)

Figure 6. (a) Cross-sectional schematic view of transmission lines measured for crosstalk to study the effect of neighboring lines. (b) Top view of the signal launch points (probe points) of the measured transmission lines.



(a)



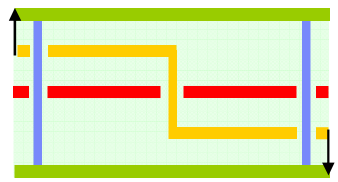
(b)

Figure 7. Crosstalk comparison for transmission lines without via transitions and all the 3 planes connected together. (a) Near-end Crosstalk (NEXT) measurements. (b) Far-end crosstalk (FEXT) measurements.

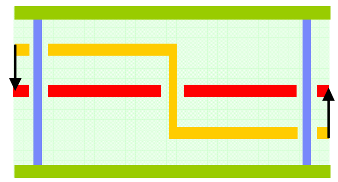
Figure 7a and 7b presents the measurement results for NEXT and FEXT. We can observe from these plots that the crosstalk reduces as we progress from the 1st neighboring lines to the 3rd neighboring lines.

4. Effect of Plane Referencing

The effect of different types of plane referencing on the signal propagation and crosstalk was also measured and studied. The following figure shows how the signals were launched on the lines with 1 via transition with reference to the ground plane (Figure 8a) and, on the lines with 1 via transition with reference to the power plane (Figure 8b).

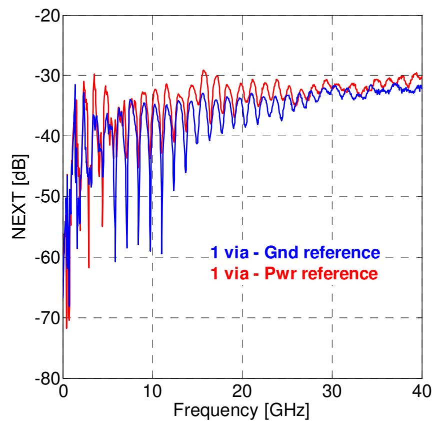


(a)

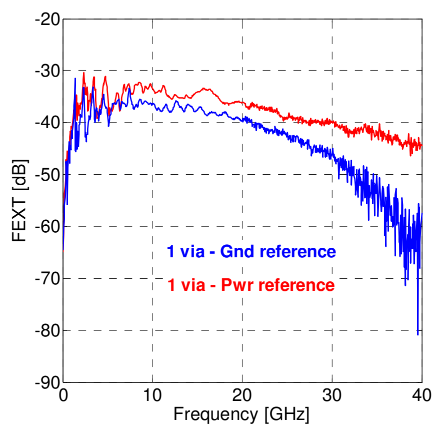


(b)

Figure 8. Cross-sectional schematic view of transmission lines with 1 via transition in signal path. (a) Lines referenced to the ground planes. (b) Lines referenced to the power plane.



(a)

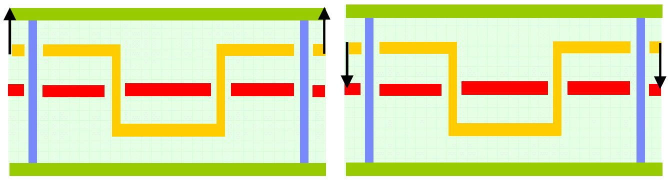


(b)

Figure 9. Crosstalk comparison for transmission lines with 1 via transition. (a) Near-end Crosstalk (NEXT) measurements. (b) Far-end crosstalk (FEXT) measurements.

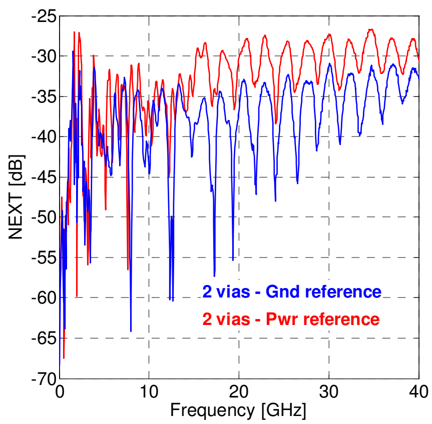
The measurement results are shown in Figures 9a and 9b. We observe that the crosstalk is less for the transmission line pair that was referenced to the ground planes as compared to the one referenced to the power plane.

The following figure shows how the signals were launched on the lines with 2 via transitions with reference to the ground plane (Figure 10a) and, on the lines with 2 via transitions with reference to the power plane (Figure 10b).

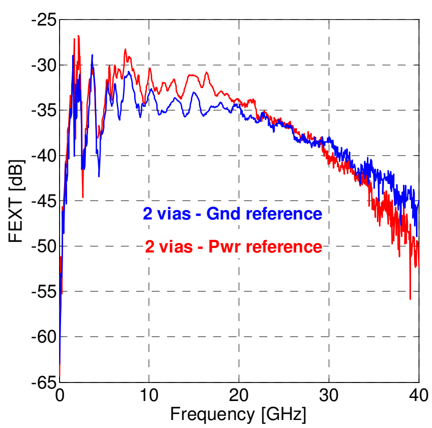


(a) (b)

Figure 10. Cross-sectional schematic view of transmission lines with 2 via transitions in signal path. (a) Lines referenced to the ground planes. (b) Lines referenced to the power plane.



(a)



(b)

Figure 11. Crosstalk comparison for transmission lines with 2 via transitions. (a) Near-end Crosstalk (NEXT) measurements. (b) Far-end crosstalk (FEXT) measurements.

The measurement results are shown in Figures 11a and 11b. We observe that over most of the frequency range, the crosstalk is less for the transmission line pair that was referenced to the ground planes as compared to the one referenced to the power plane.

5. Effect of Decoupling capacitors and cutting the PCB

The effect of placing discrete decoupling capacitors on the crosstalk between transmission line pairs was measured. Transmission line pairs in the bundle marked by the arrows in Figure 12 were measured first without placing any capacitors. Measurements were repeated after populating decoupling capacitors in the far-away locations (marked by red circles in Figure 12). In the next step, capacitors were placed close to the signal lines (marked by blue circles in Figure 12) and the lines were measured again. Finally the effect of cutting the PCB into small sections was studied. A small section of the test board (marked by the dotted rectangle in Figure 12) was cut out (the capacitors still being in place) and the measurements were repeated.

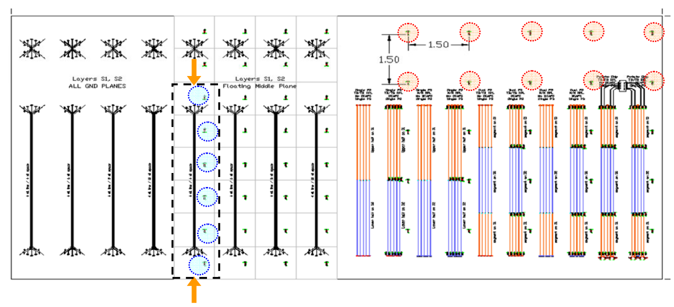
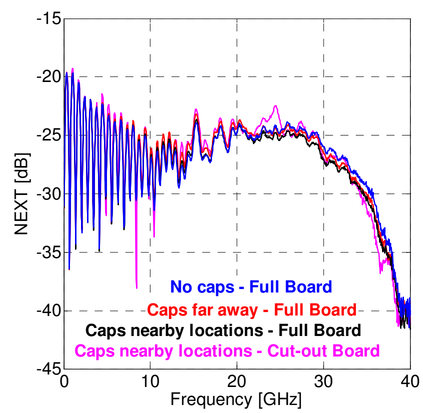
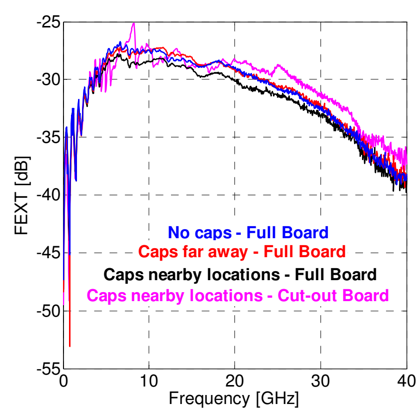


Figure 12. Schematic view of the test vehicle. The capacitor locations that were sequentially populated are marked by circles while the arrows point to the transmission line bundle that was measured.



(a)



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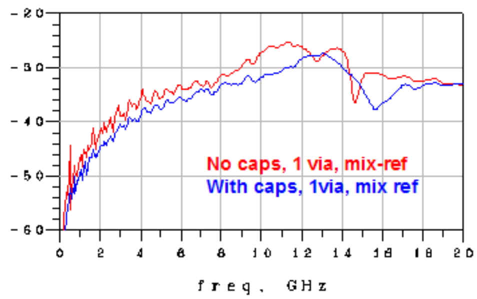


(c)

Figure 13. Crosstalk comparison for transmission lines with no via transitions – effect of decoupling capacitors and cutting the test board. (a) Near-end Crosstalk (NEXT) measurements. (b) Far-end crosstalk (FEXT) measurements. (c) FEXT of 1 via case with and without decoupling capacitors.

Figure 13 shows the measurement results for crosstalk between two adjacent lines without via transitions, the power plane floating. From these plots, we observe that placing decoupling capacitors far away from the signal lines had little effect on the crosstalk. However, the capacitors which were placed 5mm away from the transmission lines helped reduce the FEXT by ~1dB in the frequency range from 6GHz up to 30GHz. The measurements performed after cutting the test board showed an increase in FEXT by ~2dB up to 40GHz. The effects on NEXT are relatively small. In the case mix-referenced turning vias, decoupling capacitors at 2mm away from the turning vias help reduce FEXT by 2~3dB in a wide frequency range.

6. Effect of Cavity

The effect of the cavities (created on the top plane to provide access to the capacitor pad on the middle plane) on the signal propagation in transmission lines was also investigated. The transmission lines were measured in the transmission line bundles 13 and 14. The lines in both these bundles had 1 via transition in the signal path, and were excited with reference to the power plane. Bundle 14 had capacitor pads (for placing the decoupling capacitors) close to the signal launch points and the via transition point but bundle 13 did not have these capacitor pads. Figure 14 shows the top view of the test board near the signal launch points for bundles 13 and 14.

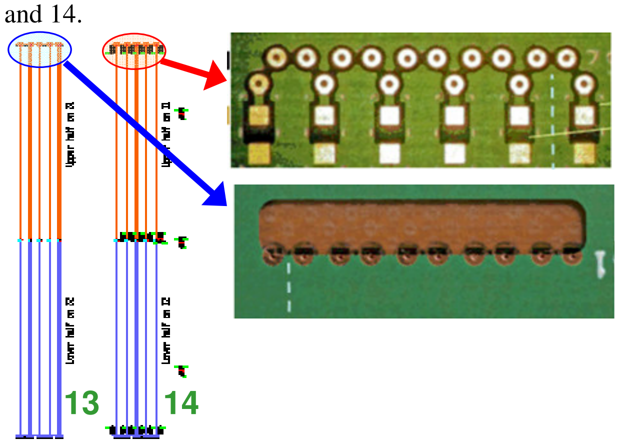
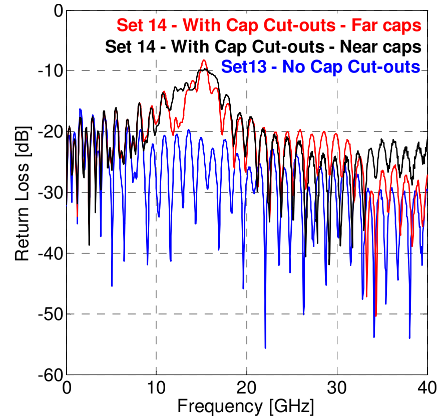
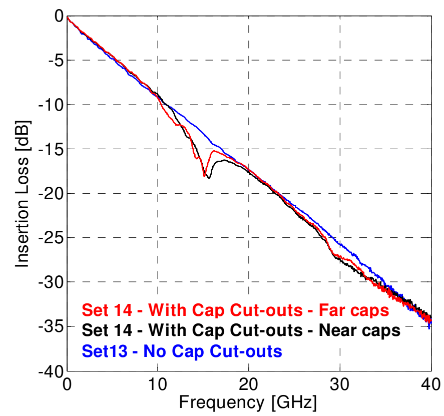


Figure 14. Schematic and top view of the test board for transmission line bundles 13 and 14.



(a)



(b)

Figure 15. S-parameter measurement plots for transmission lines in bundle 13 and 14. (a) Return loss. (b) Insertion loss.

Figures 15a and 15b shows the measurement results for the transmission lines in bundles 13 and 14. We observe that there are distinct notches in the insertion loss plot for the line in bundle 14 near 15 GHz and 30 GHz frequencies. But these notches are absent in the measurement plot for the transmission line in bundle 13. The notches are observed in both the measurements – with and without the decoupling capacitors. Thus, these notches are not due to the placement of the capacitors. Even in the return loss plots, there is a marked difference between the graphs for lines in bundle 13 and 14 near 15 GHz and 30 GHz.

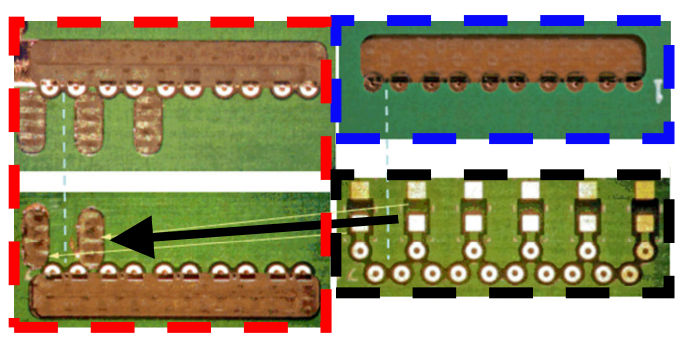
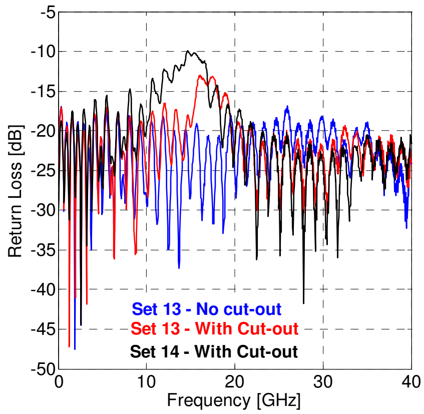
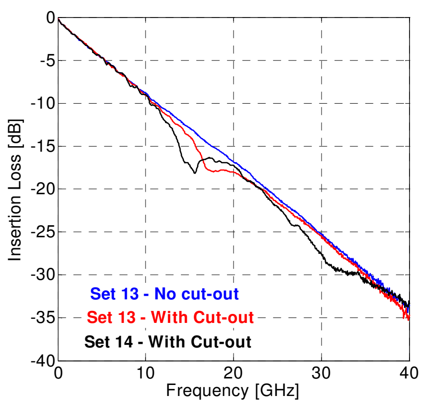


Figure 16. Top view of the test board (near the RPL points) for transmission line bundles 13 (blue dotted rectangle), bundle 14 (black dotted rectangle), and bundle 13 with milled out cavity (red dotted rectangle).

In order to investigate the reason for this difference, the transmission line bundle 13 in another (identical) test board was measured after milling out the cavities (similar to the cavities present near the line bundle 14) near the signal launch points as shown in Figure 16.



(a)



(b)

Figure 17. S-parameter measurement plots for transmission lines in bundle 13 (without cavities), 13 (with milled out cavities) and, 14. (a) Return loss. (b) Insertion loss.

Figure 17a and 17b shows the S-parameter plots for transmission lines in bundle 14, bundle 13 and, bundle 13 with the cutouts. We observe a similar notch in the insertion loss plot of transmission line in bundle 13 with the cutouts as observed for the line in bundle 14. There is also a similar shift in the return loss pattern for these two cases. This confirms our initial guess that the difference between the two plots is actually due to the cavities present near the signal lines in bundle 14 for capacitor placement.

However, there is a shift in the frequency for the notch at 15 GHz and the notch at 30 GHz seems to move to a higher frequency beyond 40GHz. This is because in the new test board, cavities were not milled near the via transition point and, the milled cavity near the signal launch point was not exactly of the same shape and size as that near the signal launch point of bundle 14. Similar phenomena were observed by Shan et al. in their study of plane perforation effects. [7]

Modeling and Simulation

A couple of transmission lines pairs were designed and fabricated in the test vehicle for extracting the dielectric properties of the organic substrate material (Figure 18). These lines were measured in a VNA to obtain the scattering parameters.

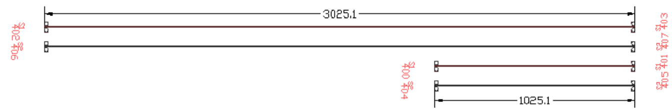


Figure 18. Schematic view of the transmission lines used for extracting the dielectric properties of the organic substrate.

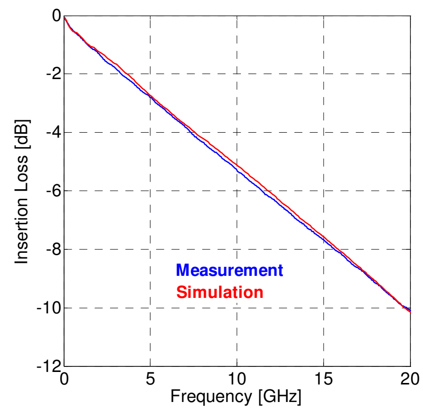
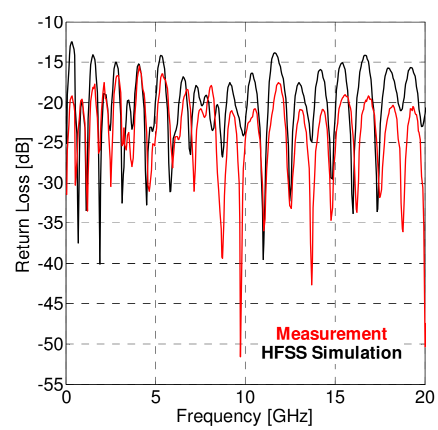
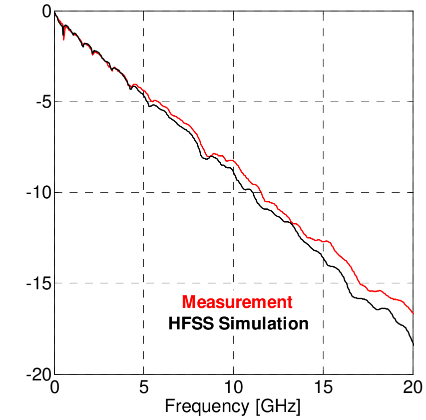


Figure 19. Comparison between measurement and simulation results for the transmission lines used for dielectric property extraction.

A cross-section study was performed on these lines to obtain the exact layer stack-up. Using these dimensions, the lines were then simulated iteratively in a 2D solver (it was also separately simulated in Ansoft HFSS) with frequency dependent dielectric constant and loss tangent values in order to get an exact fit with the measured values (Figure 19). The extracted values of the frequency dependent dielectric properties were used in all further simulations.



(a)



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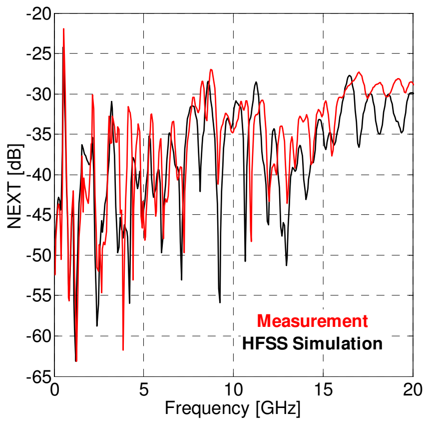
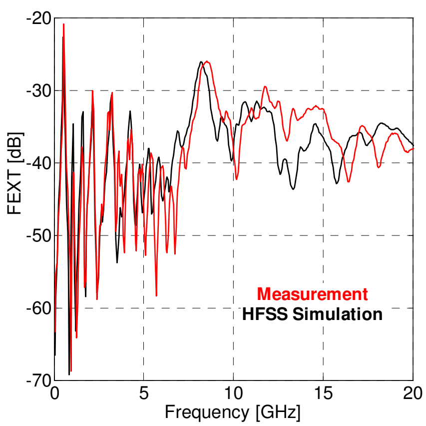


(c)



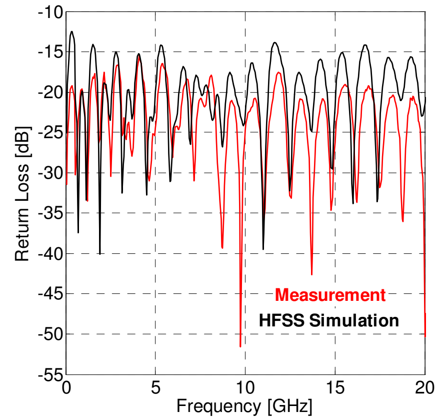
(d)

Figure 20. Comparison between measurement and HFSS simulation results for transmission lines without via transitions, the power plane floating. (a) Return loss. (b) Insertion loss. (c) Near end crosstalk. (d) Far end crosstalk.

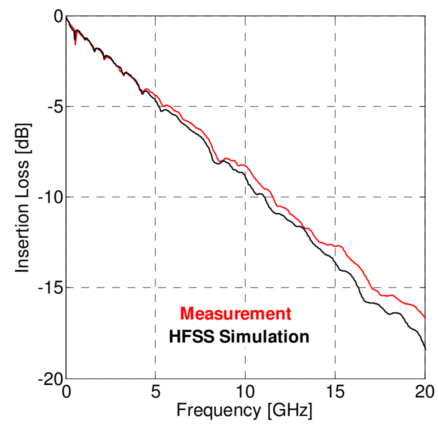
Ansoft HFSS was used as a 3D full-wave EM solver for modeling and simulation. Figures 20a, b, c and d show the comparison between measurement and HFSS simulation results for transmission lines without via transitions, the power plane floating.

The following figures (Figures 21a, b, c and d) show the comparison between measurement and HFSS simulation results for transmission lines with 1 via transition, excited with reference to the power plane (Figure 8b).

In all cases, reasonable model-to-hardware correlations were found. The discrepancies (especially on return loss) could be mostly from the dielectric constant variations when a transmission line is over a glass fiber vs. filling resins. [8]



(a)



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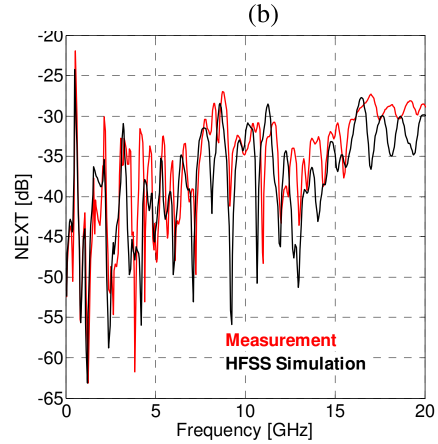

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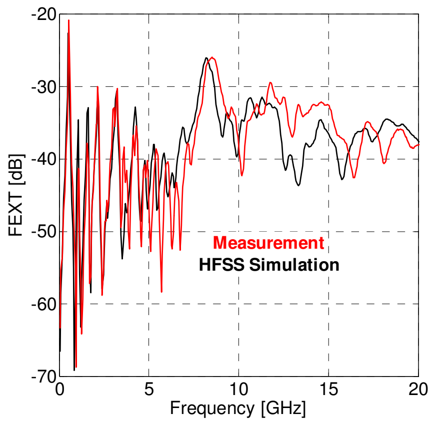

(d)

Figure 21. Comparison between measurement and HFSS simulation results for transmission lines with 1 via transition, excited with reference to the power plane. (a) Return loss. (b) Insertion loss. (c) Near end crosstalk. (d) Far end crosstalk.

Results and Conclusion

The crosstalk between the adjacent transmission lines in a bundle decreased progressively by almost 15dB between the 1st, 2nd and, 3rd neighboring lines. The crosstalk between two adjacent lines increased by about 5 dB as the line spacing was decreased by 4 mils. The transmission lines with ground referencing had lower crosstalk as compared to the ones with mixed-referencing (both power and ground).

Each addition of a turning via in the transmission lines increased the insertion loss by 1dB at 20GHz and crosstalk between adjacent lines by 6dB at 20GHz. The effects on NEXT almost doubled when two turning vias were involved. Mixed-referencing introduces an additional 3~5dB FEXT compared to the pure ground referenced turning via. These results show the potential impact of turning vias and referencing on crosstalk, which may not be obvious at all by simple through-loss measurements or simulation.

Decoupling capacitors had little effect on the signal propagation and crosstalk unless they were located close to the signal launch points and via transition locations. In the case of mix-referenced transmission lines, decoupling capacitors 5mm from the launch points help reduce FEXT by 1dB in the range from 6GHz up to 30GHz. In the case mix-referenced turning vias, decoupling capacitors at 2mm away from the turning vias help reduce FEXT by 2~3dB in a wide frequency range. It may not be possible to locate decoupling capacitors this close in dense layouts with many turning vias.

The dimensions of the reference planes also had effects on line-to-line crosstalk. In case of mixed-referencing with nearby decoupling capacitor, the measurements performed after cutting the test board (from 16”x8” to 1”x5”) showed an increase in FEXT by ~2dB up to 40GHz. The effects on NEXT are relatively small. This underscores the long-distances that energy can travel between planes once radiated from a discontinuity.

The cavities which were cut into the top plane and the upper dielectric layer in order to place the capacitors had a significant effect on the signal propagation and crosstalk. The crosstalk between the lines was observed to increase when measured after cutting the test board into much smaller dimensions, again showing the impact of boundary conditions on energy coupled to parallel plane modes.

The HFSS simulation results were correlated with measurements and a close match was observed. However, such simulations of large-area structures stretch the limits of present tools, and call for more efficient methods to model long-range crosstalk effects like those studied here.

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