Minimizing Signal Degradation in Flexible PCB Microstrip and Stripline Transmission Lines That Use Cross-Hatched Return Planes

Franz Gisin
Multek
Milpitas, CA

Abstract
In restricted-space applications, flexible PCBs must be able to fold with especially small bend radii. This in turn requires the return planes associated with microstrip and stripline transmission lines be cross-hatched. But the process of cross-hatching the return planes can significantly degrade the performance of these transmission lines.

This paper shows examples of how the cross-hatching the ground plane introduces signal distortion and how changing the size, shape and orientation of the cross-hatch pattern can reduce some of the distortion.

Introduction
Transmission lines are a class of guided wave structures where the modulated electromagnetic wave that contains the signal's information is shaped and guided by the conductors that form the transmission line. The extent to which the modulated electromagnetic wave stays concentrated in the vicinity of the signal and return conductors is dependent on the size and shape of the conductors, with electromagnetic fields staying close to the signal and return conductors being preferred. Transmission lines that produce the least amount of distortion have signal and return currents that flow parallel to the transmission line and as a result, develop electromagnetic fields that are transverse (perpendicular) to the signal currents and the direction of signal propagation. Transmission lines that possess these characteristics are called TEM (Transverse Electro-Magnetic) transmission lines. [Another example of a transverse wave is the Mexican wave popular at sporting events, where the up-down motion of the spectator's hands is perpendicular to the direction of the wave.]

Flexible (and also non-flexible) interconnects that are configured as TEM transmission lines create less signal distortion than interconnects that are not.

A variety of transmission line geometries can be used in flexible PCB interconnects. Some examples of microstrip-based (top row) and stripline-based (bottom row) cross-sections are shown in Figure 1.

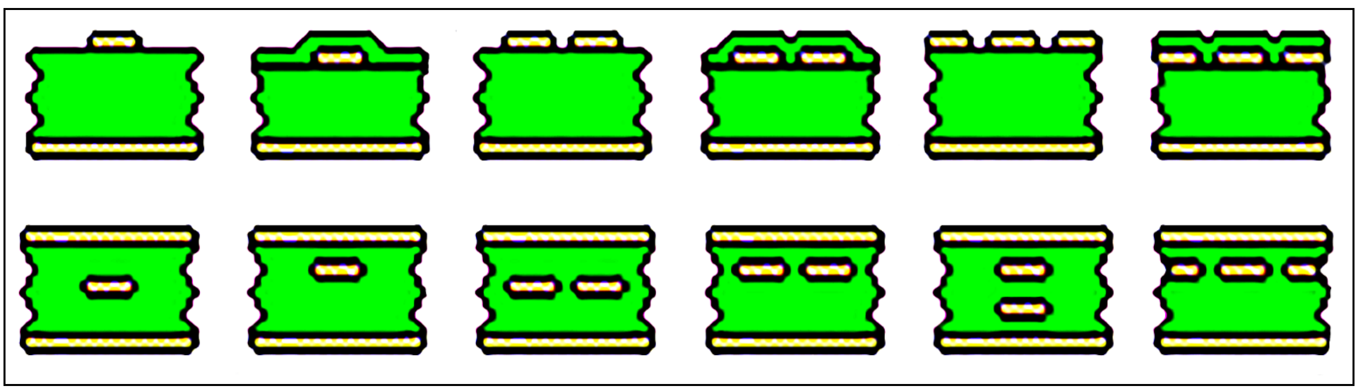


Figure 1: Examples of Micro-Strip-Based (Top Row) and Stripline-Based (Bottom Row) Transmission Line Geometries

Notice that in each case, the return plane below the microstrip traces and above/below the stripline traces are solid and continuous. These solid planes ensure that the return currents associated with the signal traces flow directly adjacent to the signal traces and flow parallel (albeit in the opposite direction) to the currents in the traces and direction of signal propagation. This ensures the transmission line behaves in a TEM manner.

Implicit in the cross sections noted in Figure 1 is that the cross-sectional dimensionsdo not change along the length of the transmission line. If any of the dimensions change along its length, a portion of the return currents no longer flow parallel to the direction of propagation and their associated electromagnetic field components are no longer perpendicular to the direction of propagation. This non-TEM behavior increases signal distortion.

Because cross-hatching the return planes results in an interconnect that is no longer uniform along its length, it introduces non-TEM currents and electromagnetic field components that in turn increase signal distortion. Depending on the size, shape and orientation of the cross-hatch pattern, the non-TEM behavior of a cross-hatched configurationcan be severe enough that technically it can no longer be called a transmission line.In this context, the goal of designing a functional cross-hatched interconnect is not to treat is as a "drag and drop" replacement for a transmission line employing a solid return plane - something that theoretically is not possible since interconnects based on cross-hatched return planes can never perform as well as those employing solid return planes. Instead, the goal is to minimize the amount of non-TEM electromagnetic fields that are introduced by the cross-hatching to an acceptably low level.

One example of this non-TEM behavior is graphically shown in Figure 2, where a top view of the return current paths of two adjacent microstrip transmission lines without gridding (left) and with gridding (right) are drawn.

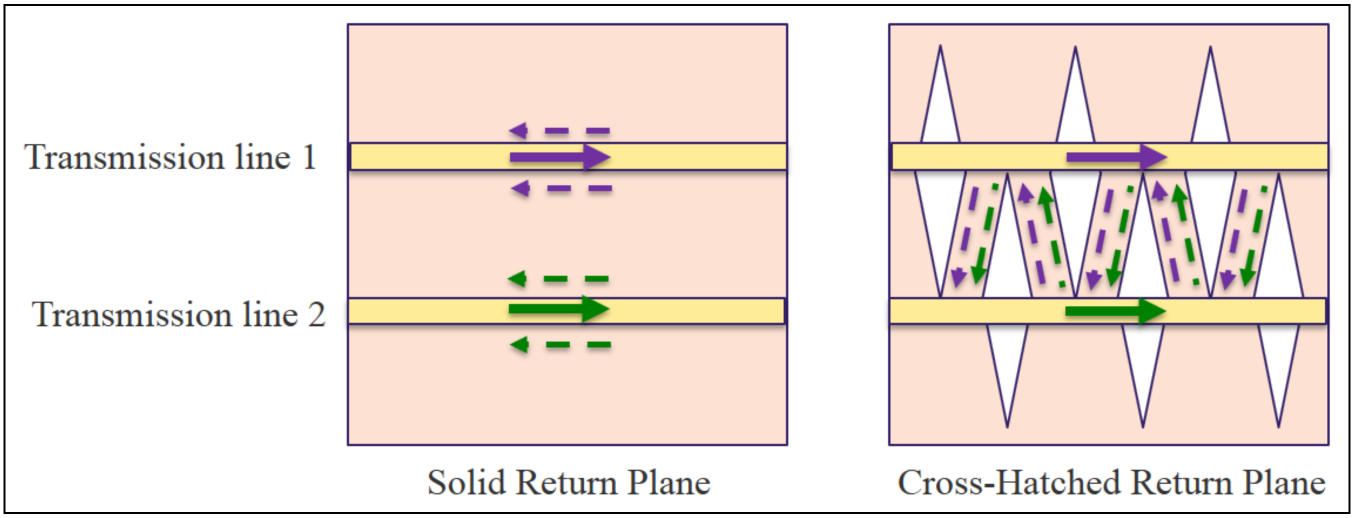


Figure 2: Comparison of Solid Return Plane and Cross-Hatched Return Plane Current Flow

Referring to Figure 2, one can see that for the solid return plane case, the return currents for each transmission line flow adjacent to the signal trace in the opposite direction. As a result, the return currents do not mix even though the return plane for both transmission lines is a solid conductor. However, if the return plane is cross-hatched, the signal return currents in the return plane can no longer flow adjacent to and parallel to the signal traces. These non-parallel current paths create electric and magnetic fields that are no longer perpendicular to the direction of the signal, creating a non-TEM interconnect. And in extreme cases, as shown in this figure, the return currents for these two transmission lines mix, introducing crosstalk.

Cross-Hatching Factors that Increase Signal Distortion

Some of the distortion-producing properties of an interconnect that employs cross-hatched return planes are outlined below.

- **Periodic Structures**: The repetitive nature of the cross-hatching creates a periodic structure. Periodic structures have their specialized application in, for example, linear particle accelerators, traveling-wave tubes and microwave filter networks. [1] But in flexible PCB applications, they introduce shunt resonances that reduce the effective bandwidth of the interconnect. If the reduction in bandwidth occurs within the signal's bandwidth, significant distortions can occur. For example, if the first resonance occurs at 5 GHz, and the required signal bandwidth is 10 GHz, then unacceptable distortion will occur. This phenomenon is identical to the periodic resonances that can occur with dielectric materials that incorporate anisotropic glass weave reinforcement. [2][3]

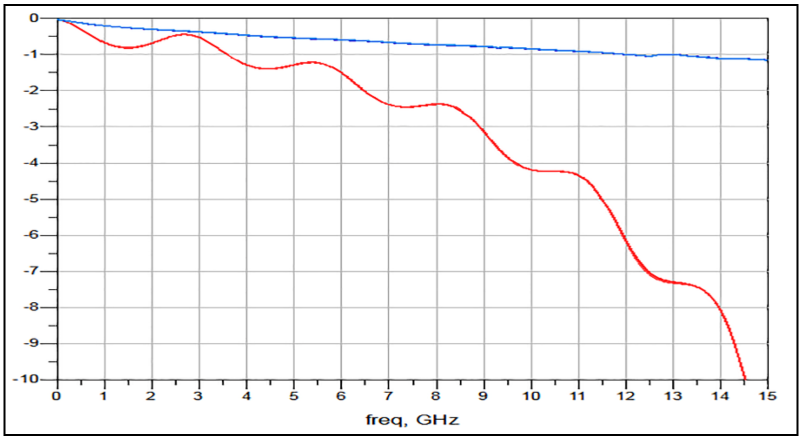


Figure 3: Impact of a Cross-Hatching on Interconnect Loss (dB/inch)

The resonant frequency is inversely proportional to the size of the cross-hatch holes. The larger the holes, the lower the resonant frequency and the larger the signal distortion. Figure 3 shows the results of a set of production computer simulations that compares interconnect losses (dB per inch) introduced by an improperly constructed cross-hatch pattern (red curves) to a solid return plane (blue curves).

- **Differential Pair Asymmetries:** Because the signal traces and cross-hatched return planes are on different layers, it is not possible to perfectly register (align) the signal traces with the cross-hatch pattern each time. For differential pair interconnects, this misregistration introduces impedance asymmetry and skew between the two signal traces.

  Referring to Figure 4, if the differential pair traces perfectly straddle the cross-hatch return plane pattern, then mirror-image symmetry is preserved and the single ended impedance and propagation delay are the same for both traces. However, if the registration is off, then one of the traces will have more cross-hatch ground underneath it as compared to the other trace. The ratio of return plane ground to signal trace impacts the effective dielectric constant associated with that trace, which in turn alters the trace's characteristic impedance and propagation delay. This in turn alters the differential pair characteristic impedance and introduces skew between the two traces.

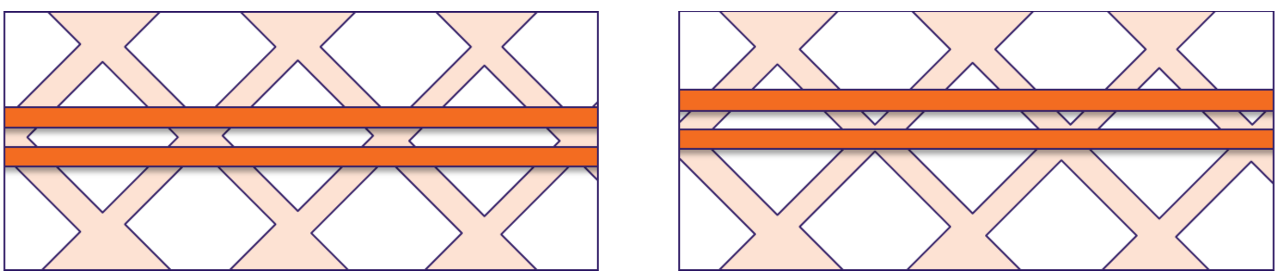


Figure 4: Examples of Ideal Registration (Left) and Poor Registration (Right)

A production computer simulation that shows how misregistration can significantly degrade the eye diagram is shown in Figure 5. Referring to Figure 5, the left eye diagram is for the ideal (perfect) registration, while the right eye diagram is for the poor registration example shown in Figure 4.

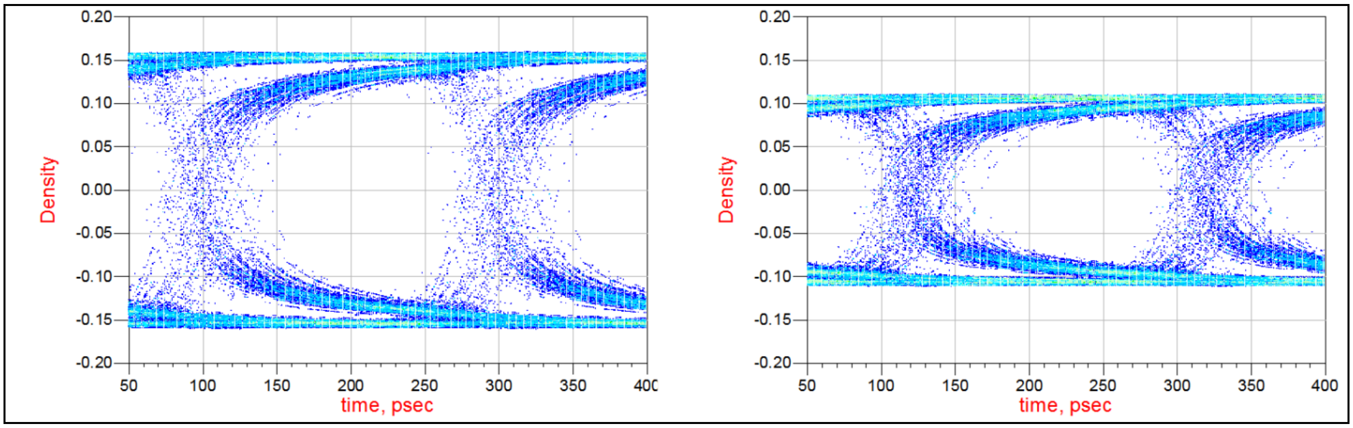


Figure 5: Signal Degradation Due to Trace-to-Cross-hatch Misregistration.

- **Interconnect Length:** It is important to note that in almost all cases, signal degradation increases with increasing interconnect length. While this also includes TEM transmission lines, it is especially true for non-TEM interconnects that use cross-hatched return planes. An example is shown in the two eye diagram simulations in Figure 6, where the length of a cross-hatched interconnect is increased from 25 cm (approximately 1 inch) to 100 cm (approximately 4 inches). In this context, shorter length cross-hatched flex interconnects introduce less distortion than longer length interconnects. A given length cross-hatched interconnect typically does not perform as well as the equivalent length solid return plane interconnect.

- **Combination Signal Return/Power (Ground) Planes:** It is common to also use ground planes that are part of a power distribution network for a signal return plane. Cross-hatching this "dual purpose" plane can significantly degrade the performance of the power distribution network.

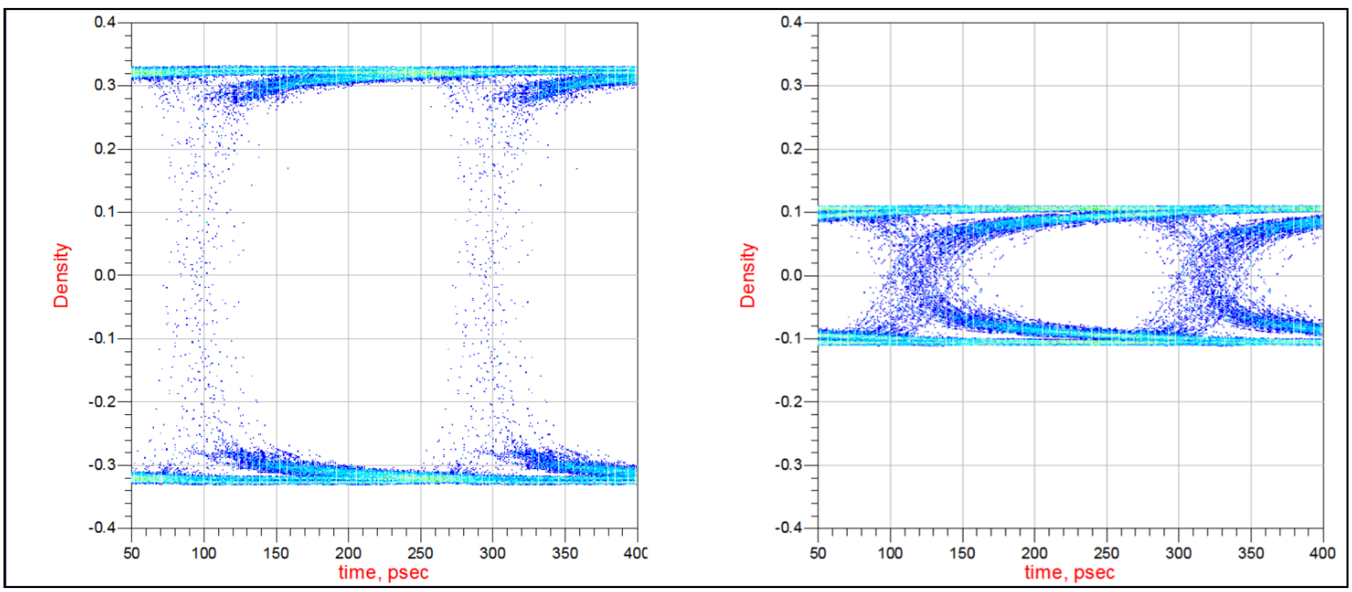


Figure 6: Impact of Interconnect Length on Signal Integrity Eye Diagram

Increased Crosstalk: As shown in Figure 1, crosshatching the return plane causes the return currents associated with two adjacent interconnects to co-mingle, creating a crosstalk situation. In many parallel data bus applications there are three or more interconnects, in which case inner traces that are sandwiched between two traces will experience increased level of crosstalk. [4]Besides increasing crosstalk between transmission lines on the same layer, the non-solid (and therefore the non-shielding) nature of cross-hatched return planes can also increase the crosstalk between transmission lines located on opposite sides of the return plane.

An example of how simply changing the size and orientation of the cross-hatch pattern to reduce the amount of current mixing in the return planes is shown in Figure 7.

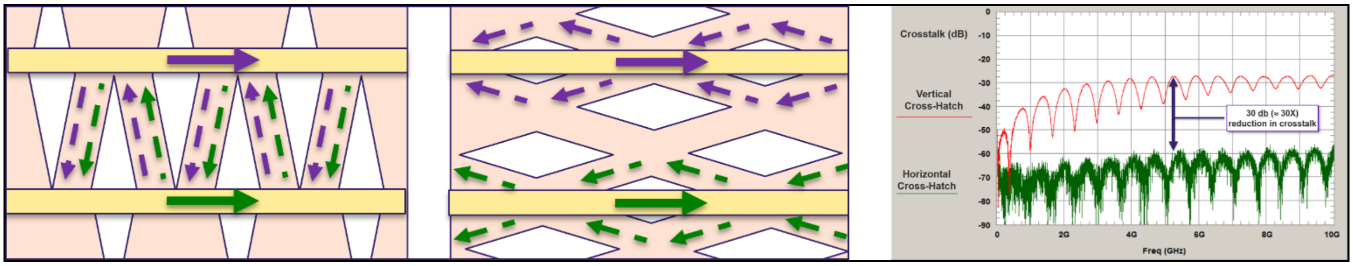


Figure 7: Example of How Changing the Orientation of the Cross-Hatch Pattern Can Significantly Reduce Crosstalk

Referring to Figure 7, by orienting the cross-hatch pattern so it is parallel to the direction of signal propagation, the return current no longer mix, thereby effectively reducing crosstalk to an acceptable level. Measurements of the significant reduction in crosstalk that such a simple re-orientation of the cross-hatch pattern can make is shown in the right plot in Figure 5, where a 30 dB reduction was realized. It should also be noted that with the improved orientation, the return currents now flow "more parallel" to the signal path, thereby making the interconnect behave more like a TEM transmission line. As an added benefit, the signal degradation caused by trace to cross-hatching misregistration is also reduced.

- **Characteristic Impedance**: Increased distortion due to structure periodicity, trace to cross-hatching registration and crosstalk are typically not quantified in commercially available characteristic impedance field solvers. For large cross-hatched geometries that typically produce non-TEM behavior, characteristic impedance is not even defined, even though one can calculate a "faux" characteristic impedance based on replacing the traditional R'L'G'C' per unit length values with quasi-static finite-length lumped element models. The assumption that two transmission lines have "equivalent" performance because the true characteristic impedance values of the solid return plane configuration and the "faux" characteristic values of the cross-hatched configuration are made the same can produce unexpected results that are not always positive.

Altering the Cross-Hatch Pattern to Reduce Signal Distortions

While the performance of a cross-hatched return plane transmission line can theoretically never be made as good as the solid return plane equivalent, it is possible to reduce distortions to an acceptable level by changing the size, shape and orientation of the cross-hatch pattern with respect to the signal traces. Referring to Figure 8, the following design guidelines can be used to minimize signal distortion.

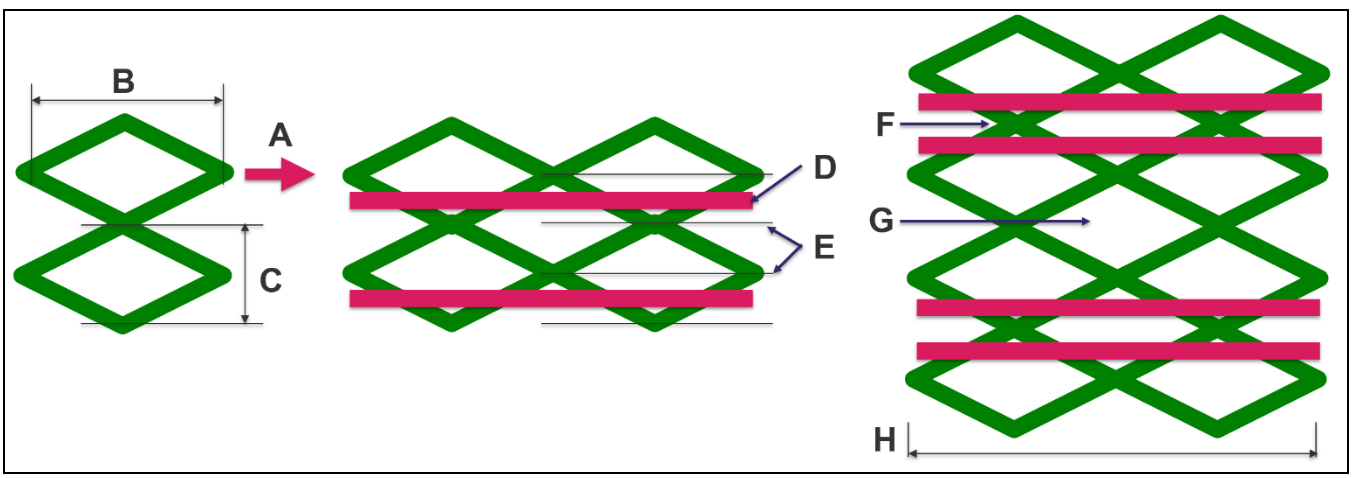


Figure 8: Cross-Hatching Design Guidelines

A: Diamond shaped cross-hatch patterns work better than square cross-hatch patterns. The longest length of the pattern should be parallel to the signal traces.

B: The longest length of the cross hatch pattern should be less than or equal to approximately 1.27 mm (50 mils).

C: The shortest length of the cross hatch pattern should be less than ½ of the longest length.

D: Single-ended traces should be centered between cross hatch intersections.

E: Two or more cross hatch intersections between each single ended trace will help reduce crosstalk.

F: Differential traces should straddle cross hatch intersections.

G: One or more empty crosshatch diamonds between differential pairs will help reduce crosstalk.

H: Total transmission line lengths less than approximately 2.5 cm (1 inch) exhibit much less distortion than those greater than 8 to 12 cm (approximately 3 to 5 inches).

Summary and Conclusions

By properly selecting the cross-hatch pattern, size and orientation, it is often possible to reduce signal distortions to an acceptable level provided the overall length is kept short and that the plane containing the cross-hatch pattern is not simultaneously used for some other application such as part of a power distribution network.

References

[1] "Field Theory of Guided Waves", Second Edition, Robert E.Collin. The IEEE/OUP Series on Electromagnetic Wave Theory, IEEE Press, 1991, Chapter 9.

[2] "Additional Trace Losses due to Glass-Weave Periodic Loading", Jason R. Miller et al. Signal Integrity Journal, April, 2017.

[3] "Numerical Investigation of Glass-Weave Effects on High-Speed Interconnects in Printed Circuit Boards, Xinxin Tian, et al. 2014 IEEE International Symposium on Electromagnetic Compatibility (EMC).

[4] "Crosstalk Effects on Eye-Diagram and BER for High-Bandwidth Memory Channel", Sumin Choi, et al. DesignCon 2017.

Minimizing Signal Degradation in Flexible PCB Microstrip and Stripline Transmission Lines That Use Cross Hatched Return Planes

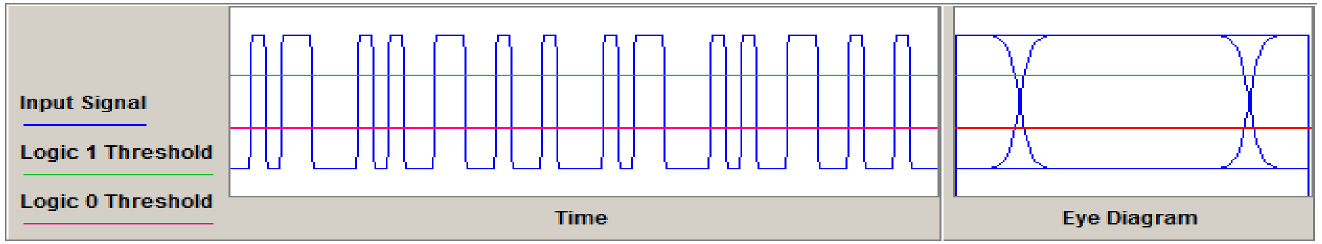
Vijay Moghe
Multek
Milpitas, CA

Overview

- **Signal Integrity – Managing PCB Interconnect Performance**
- **Causes of Signal Distortion and Degradation in a PCB Interconnect**
- **Cross Hatching Requirements for Good Signal Fidelity in Flexible Circuits**
- **Types of PCB Transmission Line Geometries**
- **Solid Return Plane vs Cross Hatched Return Plane**
- **Cross-Hatching Factors that Increase Signal Distortion**
  1. Periodic Structures
  2. Differential Pair Asymmetries
  3. Interconnect Length
  4. Increased Crosstalk
- **Altering the Cross Hatch Patterns to Reduce Signal Distortions**
- **Summary**

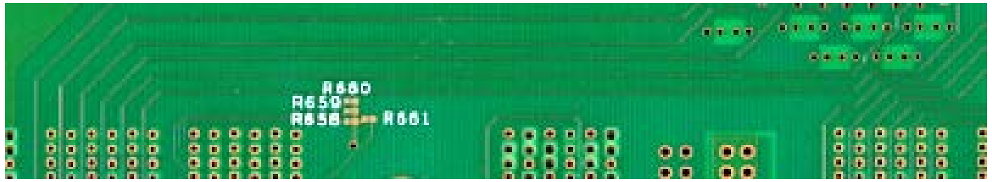
Signal Integrity – Managing PCB Interconnect Performance

- "Signal Integrity" is the discipline of Electrical Engineering that involves minimizing PCB interconnect distortions to an acceptable level.



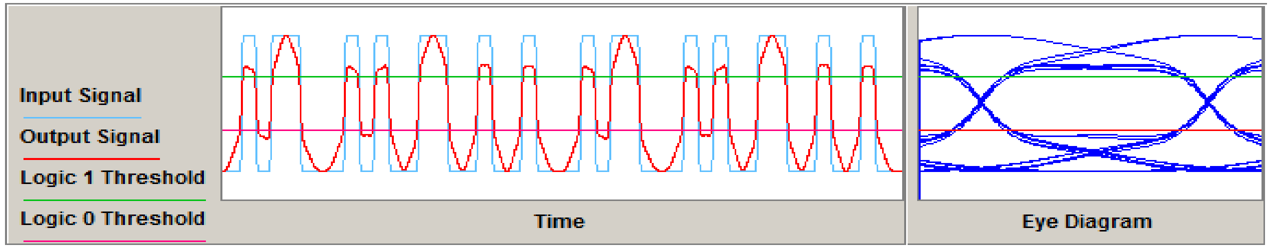
Input Data Stream

PCB Interconnect



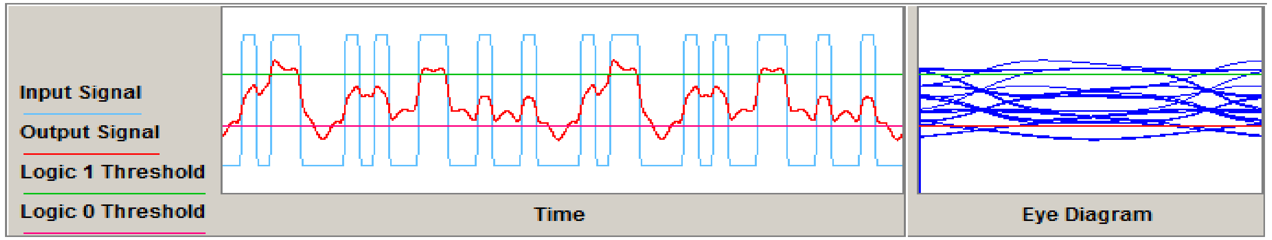
Distorted Output Data Stream

Acceptable Amounts of Distortion



Some distortion is acceptable. The interconnect does not need to be "perfect"

Unacceptable Amounts of Distortion



Causes of Signal Distortion and Degradation in a PCB Interconnect

Red –means problem area for cross-hatched return plane interconnect

- **Signal Reflection** due to
  1. Non-Uniform Trace Impedance (Return Loss due to impedance mismatch)
  2. Via Stubs
  3. Modal Resonances
  4. **Non-uniform (Non- TEM) Transmission Lines**
- **Heat Dissipation** due to
  1. Ohmic Conductor Loss
  2. Conductor Skin Depth Loss
  3. Surface Roughness Loss
  4. Current Crowding
  5. Dielectric Loss Tangent
- **Radiation Loss** – PCB traces behave like an antenna at quarter wave-length (λ /4) [Far-Field]
- **Crosstalk** between adjacent interconnects [Near-Field]
- **Signal Distortion is frequency/data rate dependent** – High Frequency Losses

Cross Hatching Requirements for Good Signal Fidelity in Flexible Circuits

- Flexible Circuits must be able to fold with very small bend radii
  1. This requires that the return planes of the board should be cross-hatched
  2. Proper shape, size and orientation of the ground plane cross-hatching pattern

- Ideal Transmission Lines have TEM Fields

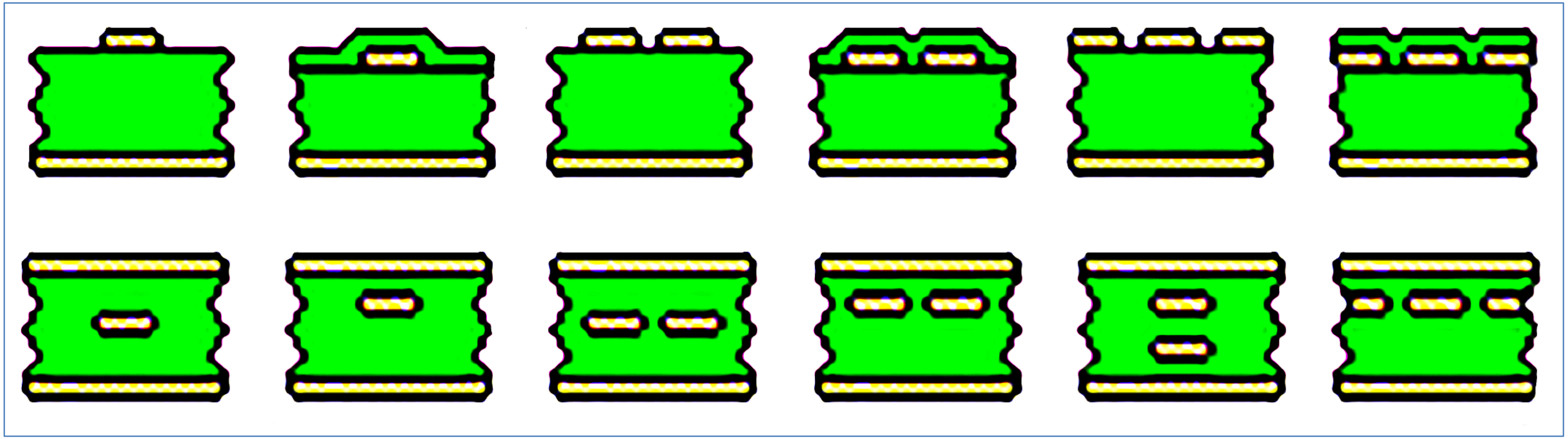
- The electric and magnetic field components are mutually perpendicular to the direction of signal propagation

- Cross hatching return planes introduces non-TEM electromagnetic fields, which need to minimized.

Types of PCB Transmission Line Geometries

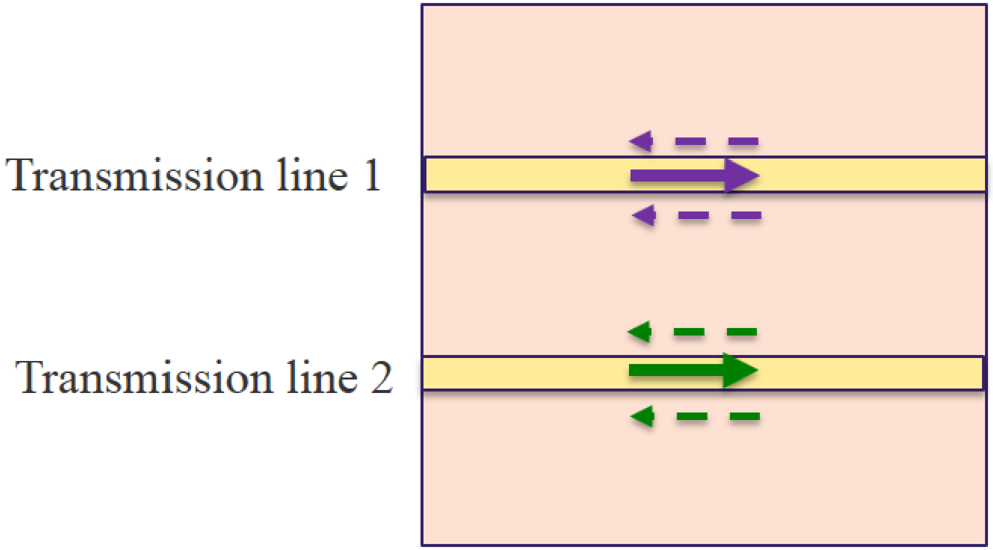
Micro-strip Geometries

Strip-line Geometries

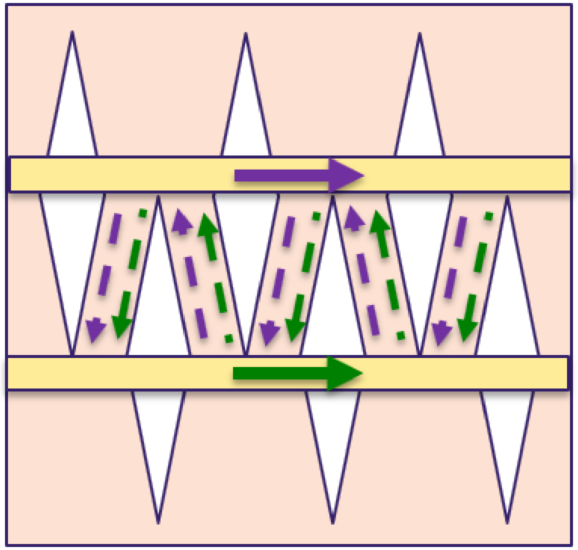


- Microstrip PCBs are cheaper to manufacture than Strip-line PCBs but are more lossy at higher frequencies
- Strip-line PCBs are less lossy at higher frequencies, but the manufacturing cost goes up as the number of interconnect layers increases
- For Flexible PCBs, the geometry constraints become tighter for optimum performances, thereby increasing the challenges in the design

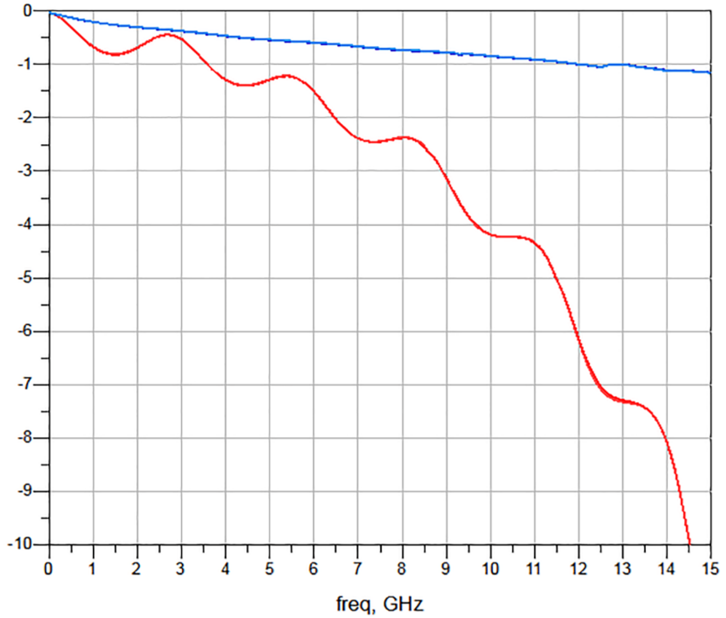
Solid Return Plane vs Cross Hatched Return Plane



Solid Return Plane



Cross-Hatched Return Plane



- For the solid return plane, the return currents for each transmission line flow adjacent to the signal in opposite direction, and therefore do not interfere with each other
- If a return plane is cross-hatched, the currents follow a non-parallel return paths and therefore the electric and magnetic fields are not perpendicular to each other (they are non-TEM). This causes signal distortion.

Cross-Hatching Factors that Increase Signal Distortion

■ Periodic Structures

The repetitive nature of cross hatching creates a periodic structure.

- **Pros** – They can be used in specialized applications like linear particle accelerators, traveling-wave-tubes, and microwave filter networks.
- **Cons**- In Flexible Circuits, they introduce shunt resonances which drop the signal level to an unacceptable value and reduces the effective usable bandwidth of the PCB.

Structures with periodically varying properties like cross hatches have **modal resonances** (i.e. frequency bands for which the wave propagates free along the interconnect separated by frequency bands for which the wave is highly attenuated.

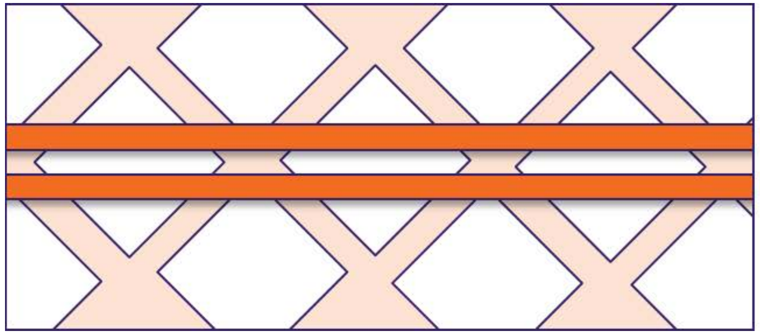
Most Field Solvers that are used to calculate Characteristic Impedance do **not** tell you what frequency these resonances occur at, thereby making it uncertain about the “signal integrity mischief” between those resonances.

Periodic structures like cross-hatch patterns can degrade the signal quality for high speed digital applications.

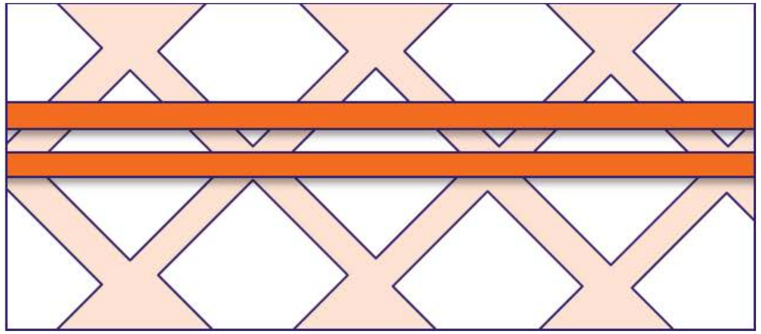
Cross-Hatching Factors that Increase Signal Distortion…

- **Differential Pair Asymmetries**

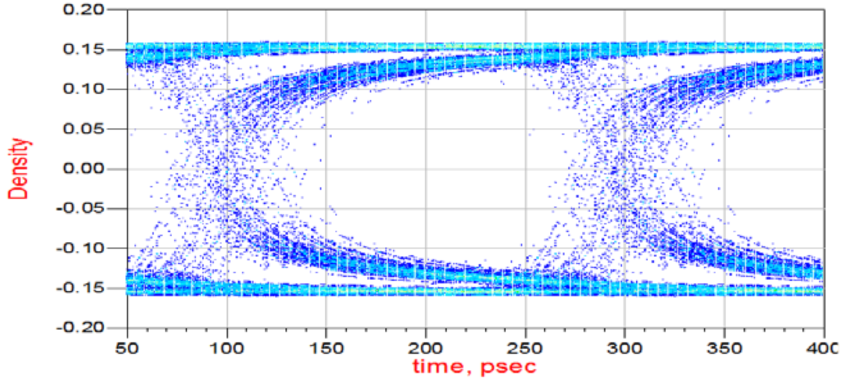
For differential pair interconnects, misalignment of the signal traces and cross-hatched pattern layers introduces impedance asymmetries and skew between the two signal traces. ("Mis-registration")

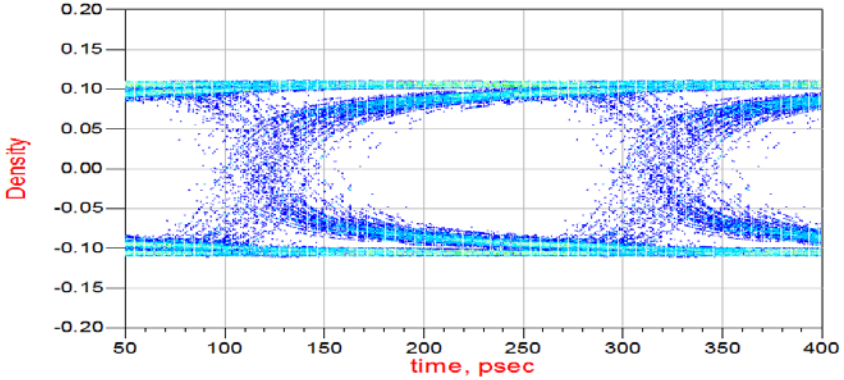


Properly Aligned Traces with Cross Hatch



Misaligned Traces with Cross Hatch



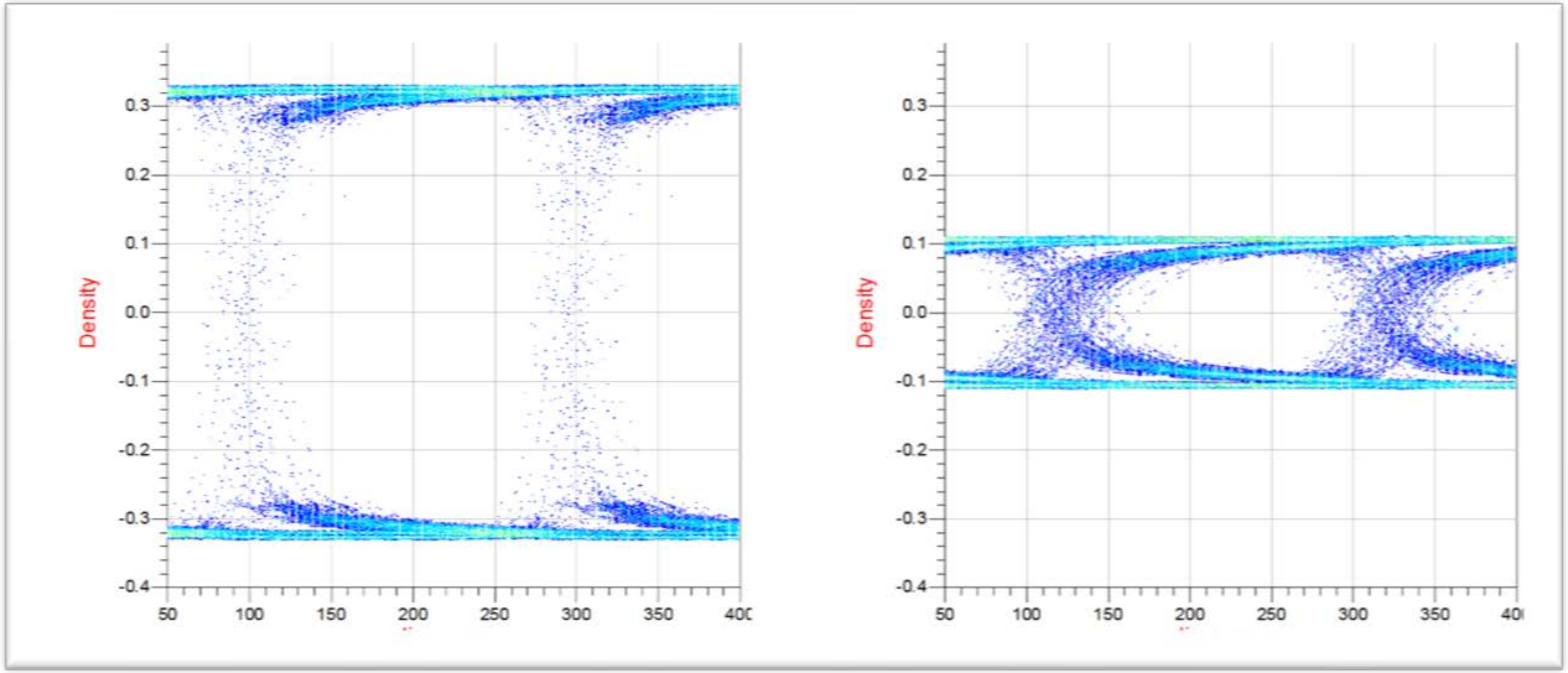


From the eye diagrams, we can see that the properly aligned traces have much better signal quality.

Cross-Hatching Factors that Increase Signal Distortion…

■ Interconnect Length

- Signal degradation is **directly proportional** to the **Length** of the PCB interconnect
- The length of the interconnects becomes a more serious issue in non-TEM interconnects that use cross-hatched planes (as compared to TEM interconnects)



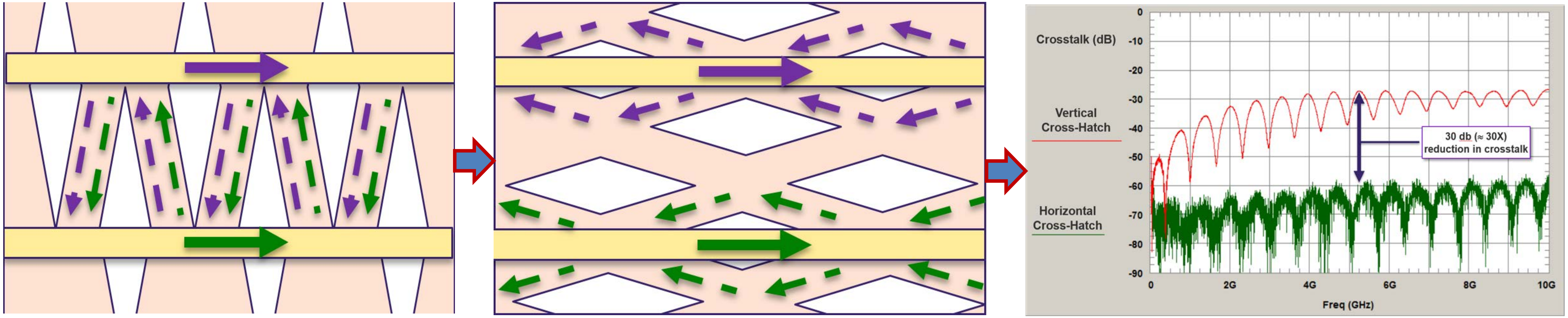
Short Length Interconnect vs Long Length Interconnect Impact on Signal Integrity

Cross-Hatching Factors that Increase Signal Distortion…

■ **Increased Crosstalk**

Cross-hatching a return plane causes the return currents associated with the two adjacent interconnects to interfere with each other, thereby introducing crosstalk.

Cross-talk becomes a more serious issue when one or more traces are “sandwiched” between two traces on the same layer for cross-hatched boards. This can degrade the signal quality significantly.



The above images show an example of how changing the orientation of the cross-hatched pattern from Vertical Cross-Hatch to Horizontal Cross-Hatch can significantly reduce crosstalk (In this case there was a 30 dB reduction in crosstalk)

Altering the Cross Hatch Patterns to Reduce Signal Distortions

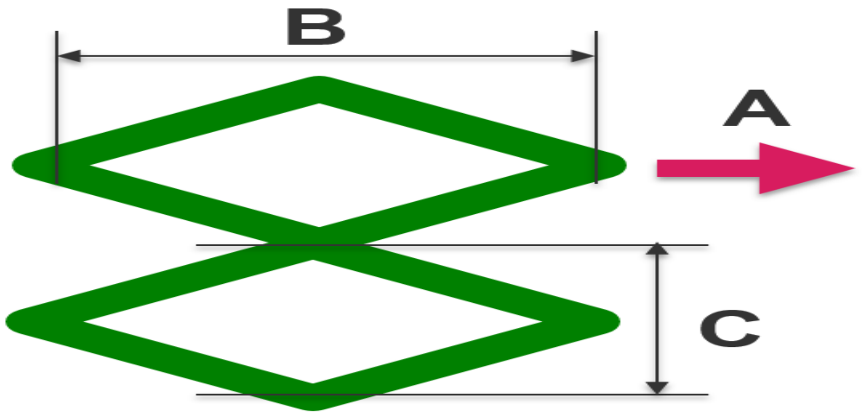
While it is theoretically impossible to make the performance of a cross-hatched return plane interconnect as good as a solid return plane equivalent, it is possible to change the signal distortions to an acceptable level by changing the size, shape, and orientation of a cross-hatched pattern with respect to the signal traces

Referring to the figure below, here are some design guidelines to minimize signal distortions

A: Diamond shaped cross-hatch patterns work better than square cross-hatch patterns. The longest length of the pattern should be parallel the signal traces.

B: The longest length of the cross hatch pattern should be less than or equal to approximately 1.27 mm (50 mils).

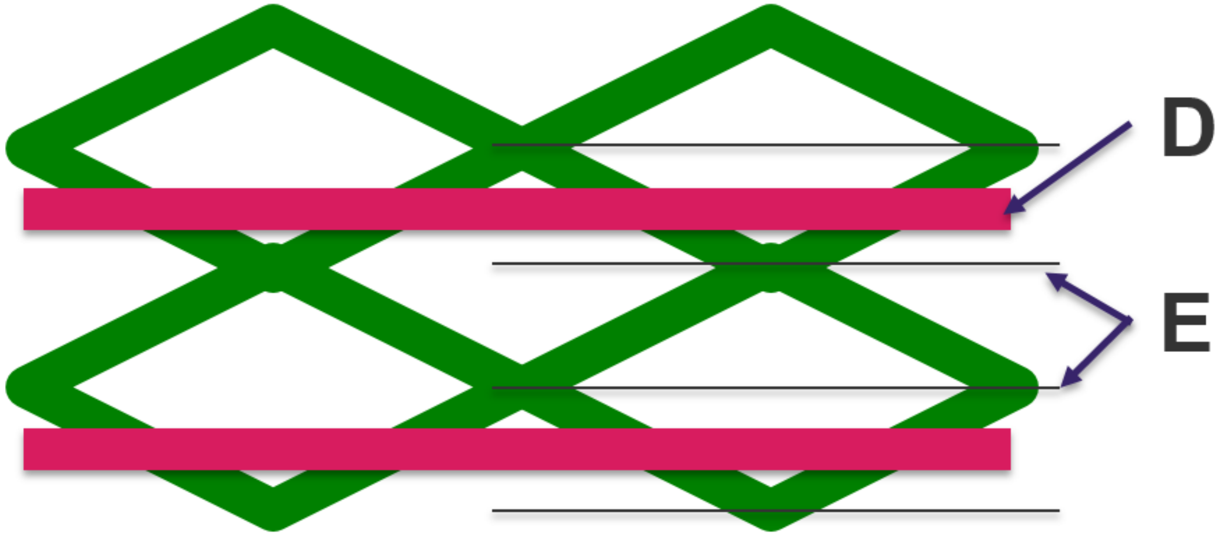
C: The shortest length of the cross hatch pattern should be less than ½ of the longest length.



Altering the Cross Hatch Patterns to Reduce Signal Distortions

D: Single-ended traces should be centered between cross hatch intersections.

E: Two or more cross hatch intersections between each single ended trace will help reduce crosstalk.

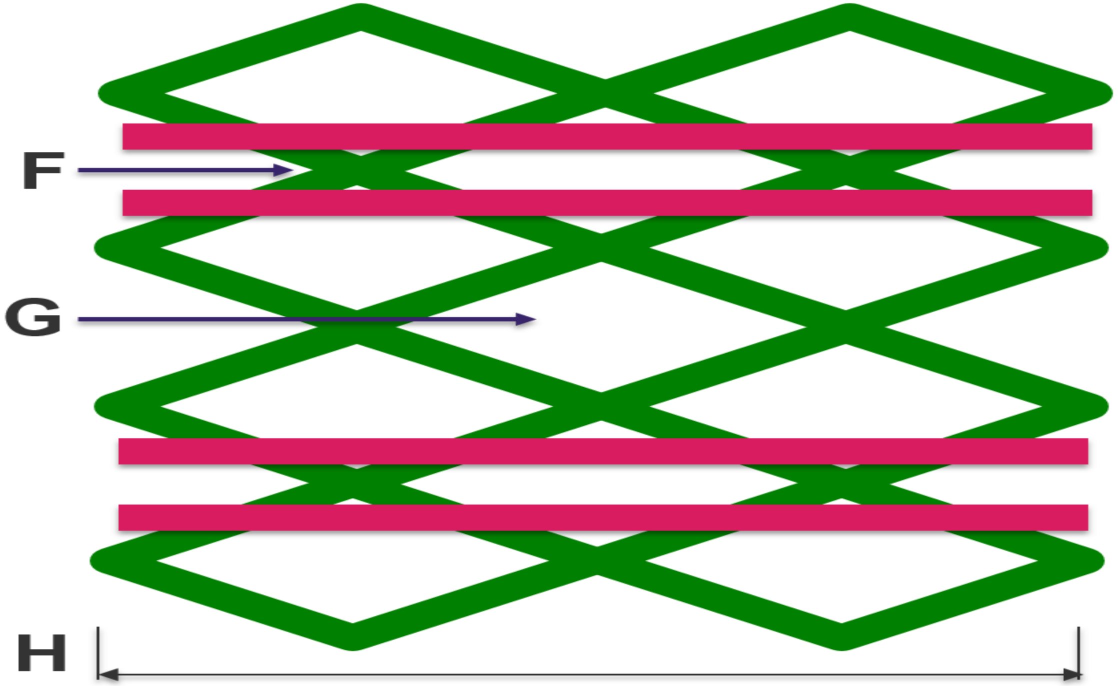


Altering the Cross Hatch Patterns to Reduce Signal Distortions

F: Differential traces should straddle cross hatch intersections.

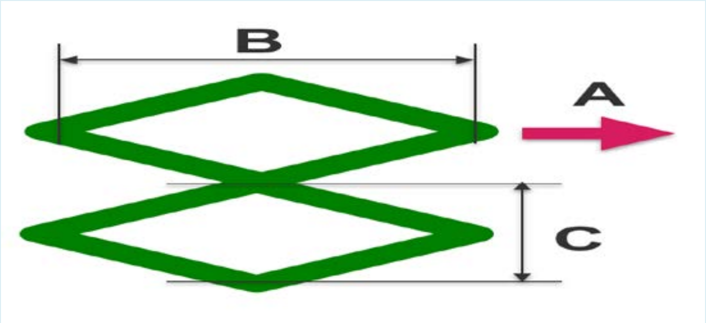
G: One or more empty crosshatch diamonds between differential pairs will help reduce crosstalk.

H: Total transmission line lengths less than approximately 2.5 cm (1 inch) exhibit much less distortion than those greater than 8 to 12 cm (approximately 3 to 5 inches).



Summary

- By properly selecting the cross-hatch pattern, size and orientation, it is possible to reduce signal distortions and crosstalk to an acceptable level.



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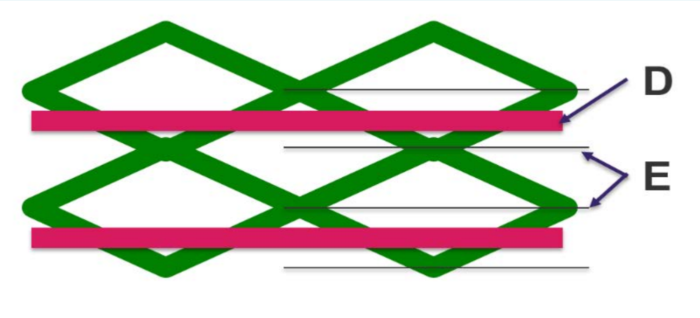

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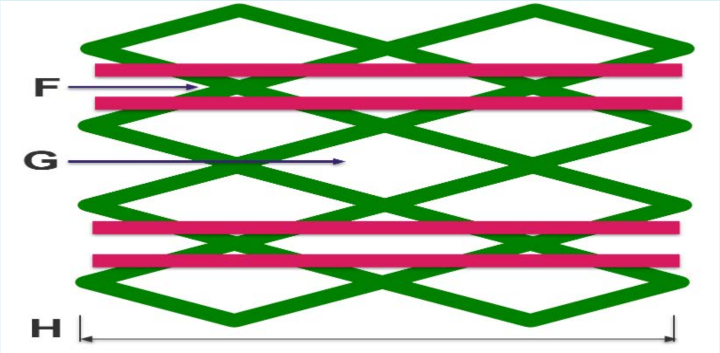

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G: One or more empty crosshatch diamonds between differential pairs will help reduce crosstalk.

H: Total transmission line lengths less than approximately 2.5 cm (1 inch) exhibit much less distortion than those greater than 8 to 12 cm (approximately 3 to 5 inches).

Manufacturing constraints may limit the smallest physical dimensions that can practically be manufactured, which in turn can limit the maximum usable frequency of the interconnect.