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NEW CHARACTERIZATION TECHNIQUE FOR GLASS-WEAVE SKEW

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Abstract

A new test board design and analysis technique has been developed to measure the glass-weave skew effect in circuit boards. We demonstrate it is capable of a sensitivity of about 0.04 psec/inch. By measuring a variety of boards with various glass combinations we find a typical value of the worst case glass-weave skew can be on the order of 7 psec/inch. Using combinations of mechanical spread (MS), 2 ply and L-glass, this was reduced to 0.81 psec/inch.

Through the course of this study we discovered a major artifact which affects the entire industry and may contribute to the wide variation in reported glass-weave skew values. It is the precise alignment of the signal lines and the glass weave. Even a rotation of 0.3 degree will completely hide the true glass-weave skew effect.

If the glass weave and board edge can be precisely aligned to greater then about 0.5 degrees and guaranteed by the laminate and fab vendor, this alone may mitigate the glass-weave skew effect and be transparent to the board designer.

Author(s) Biography

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Eric is currently the Dean of the Teledyne LeCroy Signal Integrity Academy, at www.beTheSignal.com. Additionally, he is an Adjunct Professor at the University of Colorado - Boulder in the ECEE dept. Bogatin received his BS in physics from MIT and MS and PhD in physics from the University of Arizona in Tucson. He has held senior engineering and management positions at Bell Labs, Raychem, Sun Microsystems, Ansoft and Interconnect Devices. He has written six technical books in the field and presented classes and lectures on signal integrity world wide. In 2011, his company, Bogatin Enterprises, which he founded with his wife, Susan in 1990, was acquired by Teledyne LeCroy. After concluding his live public classes in 2013, he devoted his efforts into creating the Signal Integrity Academy, a web portal to provide all of his classes and training content online, for individuals and for companies.

Bill Hargin

Bill currently serves as the director of North American Marketing for Nan Ya Plastic's PCB laminate division in Taiwan. With more than 15 years of experience dealing with PCB signal integrity, Mr. Hargin authored multiple articles on signal integrity, contributing on the subject to the *Printed Circuits Handbook*, and served as product manager for Mentor Graphics' HyperLynx SI software. More than 10,000 engineers and PCB designers worldwide have taken Bill Hargin's workshop on high-speed PCB design, and Bill has spent much of the last 5 years focused on stackup, PDN design and PCB materials selection.

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Dharma Teja Paladugu is currently a graduate Masters student in Electrical Engineering department at University of Colorado Boulder. His focus is on RF & Electromagnetics and Signal Integrity. His research interests are in computational electromagnetics, active microwave devices. He completed his bachelors in Electronics and Communication Engineering at Amrita Viswa Vidhyapeetham, Coimbatore, India in 2015. He worked with Cadence Design Systems Inc. during summer 2016 for the improvement of PowerSI, a SI/PI analysis point tool from Sigrity. His hobbies include traveling, playing badminton and reading biographies.

Don DeGroot, CCN, don@ccnlabs.com

Dr. Don DeGroot operates CCN (www.ccnlabs.com), a test equipment and service business he co-founded in 2005 to support high-speed electronic design. Don has over 30 years experience in high-frequency electrical measurements and design, including his PhD degree from Northwestern University and 12 years of research at NIST. From 2006-2015, Don held a faculty position at Andrews University where he innovated project-based learning in electronic communications. He currently serves as Chair of the IPC D24 subcommittee on high-speed and high-frequency test methods. Don has published and presented over 100 technical papers on measurement science and electronic design research. He currently focuses on PCB interconnection and material characterization.

Amendra Koul

Amendra Koul is a Signal Integrity Technical Leader, working at Cisco systems, San Jose, CA, since 2010. He is responsible for signal and power integrity for catalyst access switching products at Cisco. While at Cisco, his work and research has been focused on power integrity, DDR4 designs/simulations, PCB material modeling/characterization and glass-weave skew, high speed serial interfaces, driving low cost system designs, developing and improving overall SI/PI methodology. He received his MSEE from Missouri University of Science and Technology.

Seungyong(Brian) Baek

Dr. Seungyong Baek is a Signal Integrity Technical Leader at CISCO in San Jose, USA since 2010, he has responsibility for analyzing SI/PI/EMI issues of CAT3k and CAT4k switching system. He worked 4.5 years for Silicon Image since 2005 and He received Ph.D degree in electrical engineering from Korea Advanced Institute of Science and Technology (KAIST), Daejeon, in 2005. He has been working with next generation high-speed backplane system and leading various switching ASIC program. Moreover, his researches include model development of high-speed serial I/O interfaces, developing improved SI/PI analysis methodology.

Mike Sapozhnikov

Mike Sapozhnikov is a Senior Signal Integrity Manager at Cisco Systems. He is responsible signal and power integrity for Catalyst access switching and ASR9K edge routing for both system and ASIC designs. Mike has over 19 years of experience in various signal integrity and hardware design roles as a manager and individual contributor. Mike received his B.S. in electrical engineering from San Jose State University.

Glass-weave skew is an Industry Problem

Glass-weave skew is an increasingly important problem for higher speed serial links running differential pairs. The problem arises when the time delay of one line in a differential pair is different for the other line. Most serial link specs state a maximum line to line intra-pair skew to be less than 20 percent of the UI. For 10 Gbps links, the UI is 100 psec and the maximum allowable skew is about 20 psec. For 28 Gbps links, the maximum allowable intra-pair-skew is about 8 psec. [1]

One source of intra-pair skew is a length difference between the p and n lines of a differential pair. A length difference of about 6 mils results in 1 psec of skew. Many routing tools enable constraint-driven layout to ensure that the line to line length difference is less than 5 mils.

The other dominant source of line to line skew is from the local variation in the dielectric constant the lines see due to the inhomogeneous nature of the glass-resin composite system. This effect is commonly called glass-weave skew (GWS). [2]

The occurrence of glass-weave skew is a statistical effect, dependent on the precise alignment of one line in a differential pair over a glass bundle and the other line over a more resin-rich region. Figure 1 shows an example of a cross section of a backplane stack up made with Megtron 6 material using 1078 glass weave showing the relative alignment of one signal line and the local glass weave.

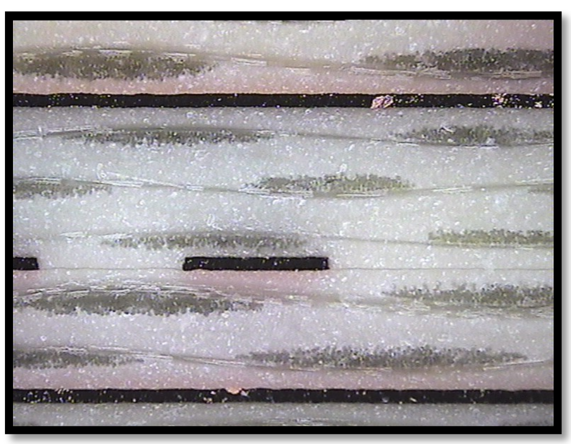

Figure 1. Cross section of a backplane trace showing the alignment of the signal line to a glass weave bundle. The two planes and the signal line are shown as the black horizontal lines. The small, flat ovals are the glass fiber bundles.

The random alignment of trace to fiber bundles makes GWS hard to replicate, and hard to diagnose. It appears as a channel with excess loss—with some cards working fine and others failing, but only with certain combinations of specific backplanes. Figure 2 is an example of the measured delay between the p and n lines of a 24-inch backplane channel showing 60 psec of skew. Over 24 inches, this is about 2.5 psec/inch of glass-weave skew.

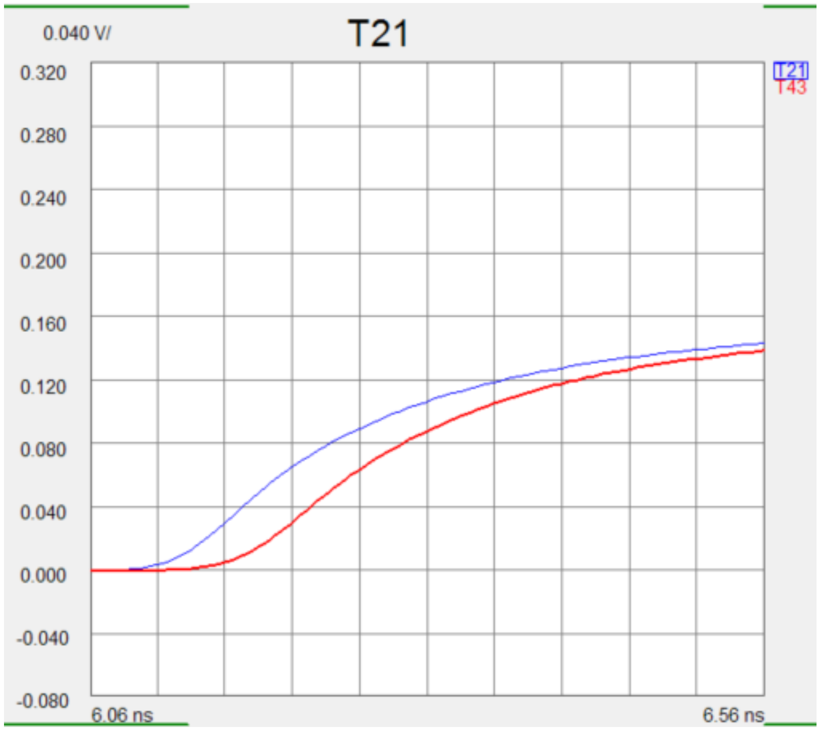

Figure 2. Measured delay between the p and n lines of a channel showing 60 psec of skew over 24 inches.

Many solutions have been proposed to mitigate this problem. [3] To evaluate the impact from glass weave and laminate construction on glass-weave skew, a test is required which will quantify the magnitude of the GWS effect so solutions can be evaluated and the extent of possible problems must be identified.

This was the motivation behind the development of this test method.

A New Glass-weave skew Test Method

General Process

As reported previously, [4] we developed a new test board design which allows the statistical measurement of glass-weave skew. It is based on using a series of 40, nominally identical, 4-inch long parallel lines with a pitch that is off from the glass weave pitch. As a reference, the same lines are constructed, but at 15 degrees to the glass weave axis. These act as a reference and should not show any GWS effect. Figure 3 shows an example of the test board used in this study.

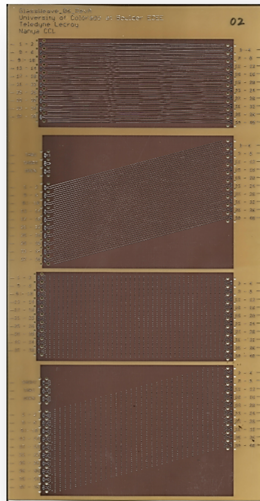

Figure 3. The test board used in this study. There are 40 lines parallel to the glass-weave axis and at 15 degrees, in both microstrip and stripline.

When the precise time delay of each line is measured, we expect a Moiré pattern of delays as the overlap of the glass weave and line pitch comes in and out of phase. This should produce a sinusoidal variation in the delay of each line. When there is no GWS effect, we expect to see some distribution of delays based on random variations in the dielectric thickness, local dielectric constant (Dk), line width, or thickness of a line.

In the panel, some of these boards were aligned to the weave axis and some to the fill axis so that the sensitivity of GWS to both axes could be measured. The placement of the test coupons on a panel is shown in Figure 4.

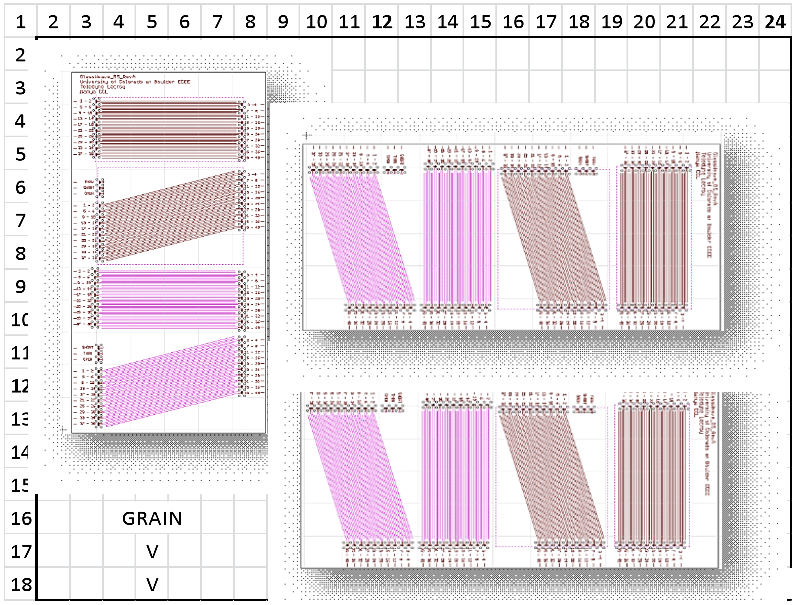

Figure 4. Alignment of the test coupons on a panel allowing for GWS testing along the weave and fill axes.

Measurement Method

Each line is 4 inches long, open at the far end. It is measured from one end with a pad configuration to match the industry standard SET2DIL footprint [5]. This allows the use of standard test fixtures to probe the board and interface to a network analyzer. This pad footprint is designed to test two lines. The pitch between the holes is 90 mils. This sets the pitch of each line in the array as 45 mils. Figure 5 shows a close up of the pad footprint at the end of the line.

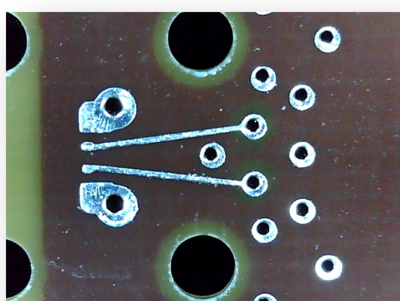

Figure 5. Close up of the pad footprint for probing the two lines in each repeat pattern. This is connecting to a stripline pair. The large clearance holes are for alignment pins. The four pads on the left are the G-S-S-G pads for the probe contact. The via field is where the signal lines transition to stripline layers.

An industry standard CCN nTegrity™ probe station [6] and Teledyne LeCroy SPARQ™ Network Analyzer [7] were used to perform the measurements of each line from 20 MHz to 30 GHz. The measurement system is shown in Figure 6.

Figure 6. Measurement system consisting of the CCN nTegrity probe fixture and Teledyne LeCroy SPARQ.

Analysis of the S-parameters

The two-port S-parameters from one end of a pair of open-ended lines is measured. This .s2p file is brought into MATLAB and parsed into the individual return losses of each line. The time domain impulse response is calculated for each line, using a simple inverse Fourier Transform, with one special consideration.

With a highest frequency of 30 GHz, the equivalent rise time of the time domain waveform is just ½ x 1/Fmax = 16 psec. In order to measure a much shorter one-way time delay, we require higher time step resolution than 16 psec. A simple technique was used to effectively up-sample the time domain impulse response and obtain higher sampling resolution. This involved the discrete inverse Fourier Transform using a very short time internal between the time points in the following expression:

$$V(t) = k \sum_{f=-f_{max}}^{f=f_{max}} \mathrm{imag}(S11(f)) \times \sin\left(2\pi f \times t\right) + \mathrm{real}(S11(f)) \times \cos\left(2\pi f \times t\right)$$

Based on the expected variation of about 200 fsec of jitter in the time base of the SPARQ, we selected a time interval to perform the numerical summation of 0.042 psec. The rise time of the time domain response did not reduce, but the time step interval did. When we calculate the impulse response, we are able to resolve the time position of the peak to within one time step interval, or 42 fsec. (This might be too much detail, but I think this type of up-sampling requires the device + test system to be a minimum phase system. Isn't that right? Minimum phase systems that have the same magnitude response also give the minimum group delay.)

To minimize the impact of the fixture and cable lengths on a precision time-delay measurement, we first measure the return loss of the nTegrity fixture with no board in place. Then the return loss with the board in place is measured. Since the ends of all interconnects are open-circuit, most of the signal comes back after a round trip line. Figure 7 shows an example of the measured impulse response from the return loss of the open fixture and lines for the two-port measurement.

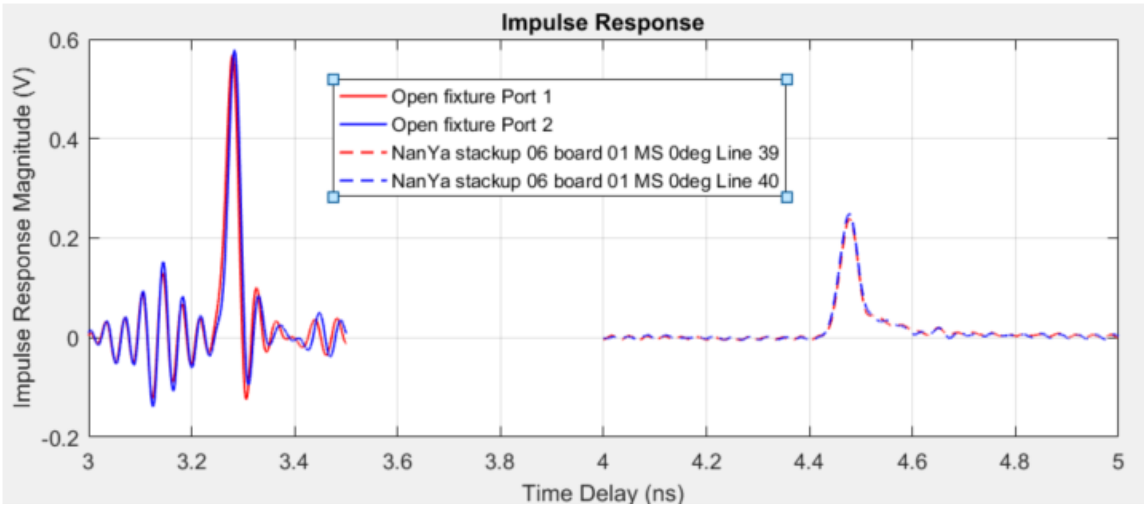

Figure 7. Example of the measured impulse response of the open fixture measurement and two lines connected to the fixture.

The one-way time is measured and the difference between the line and open fixture is recorded as the round-trip delay of just the line. This is divided in half to get the one-way delay of the line and then scaled by 4 inches, the length of each line. The final reported number is the one-way delay per inch of each line.

An absolute time step of 42 fsec corresponds to a one-way delay resolution of 21 fsec. And, with 4 inch lines, this is about 5 fsec/in as the system resolution.

A number of sets of S-parameter files were synthesized from ideal transmission lines to test the calibration of this MATLAB algorithm confirming a resolution of 5 fsec/inch.

Instrument Performance Specs

Four tests were performed to evaluate the limits to the system and any standard errors. In the first test, the same line was measured 40 times, without removing it from the fixture. This is a test of the repeatability of the time-base jitter in the SPARQ instrument.

The typical time base jitter of similar instruments in the Teledyne LeCroy family is below 200 psec, rms. Figure 8 shows the measured variation of the equivalent time delay per inch for 40 repeated measurements. The delay reported is the difference in delay between consecutive measurements. This calculated standard deviation is 0.02 psec/inch.

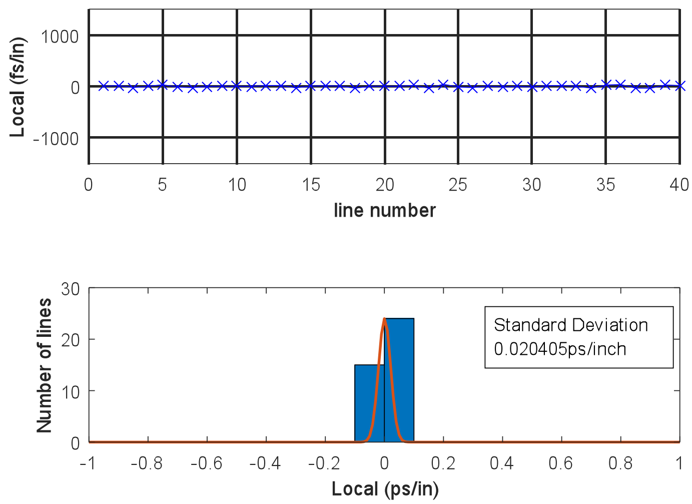

Figure 8. Measured delays per inch of the same line measured 40 times without removing it from the fixture.

This equivalent delay per inch rms value of 20 fsec/inch can be expanded to the absolute delay by multiplying by 8 (2x for the round trip time and 4x for the length). This is 160 fsec rms jitter. This is very close to the instrument time-base jitter spec of less than 200 fsec. This sets the fundamental limit (sensitivity) of the smallest GWS effect that can be measured, using a 4-inch line, at 0.02 psec/inch.

Next, the same line was measured 40 times, removing it from the fixture and re-aligning it. This represents the impact of the fixture misalignment on the delay skew. Figure 9 shows the measurements and the fitted standard deviation value of 0.044 psec/in.

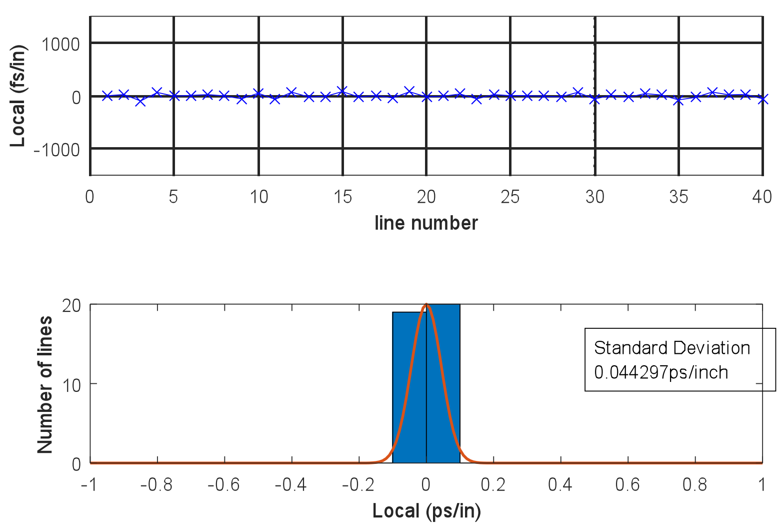

Figure 9. Measured delay values from the same line measured 40 times, removed from the fixture each time.

The alignment to the fixture does seem to add additional delay to each measurement. This is probably due to a variation in the position of the probe tips on the pads, causing a variable length in each measurement. Assuming the time-base jitter and the fixture misalignment skew are uncorrelated, the contribution to the delay skew from just the fixture misalignment is

$$delaySkew_{fixture} = \sqrt{delaySkew^2_{measured} - delaySkew^2_{timeBase}} = 0.039 p\sec/in$$

This corresponds to a one-way time variation of 0.039 psec/in x 4 inches = 0.156 psec. At roughly 6 mils/psec propagation velocity, this corresponds to an rms misalignment in each measurement of less than 1 mil, representing the repeatability in the nTegrity fixture alignment.

The third test for the system is a measurement of the delay skew among all 40 lines in the array of lines which are rotated 15 degrees to the glass-weave axis. These should show no glass-weave skew effect. Their skew will have the contributions from the time-base jitter of the SPARQ and the alignment variation of the fixture, plus any real variation from line to line.

This measurement represents the real limit to how much line-to-line skew can be measured as a real variation due to the GWS effect. Figure 10 is an example of the measured delay skew variation for the case of a microstrip array at 15 degrees to the glass-weave axis.

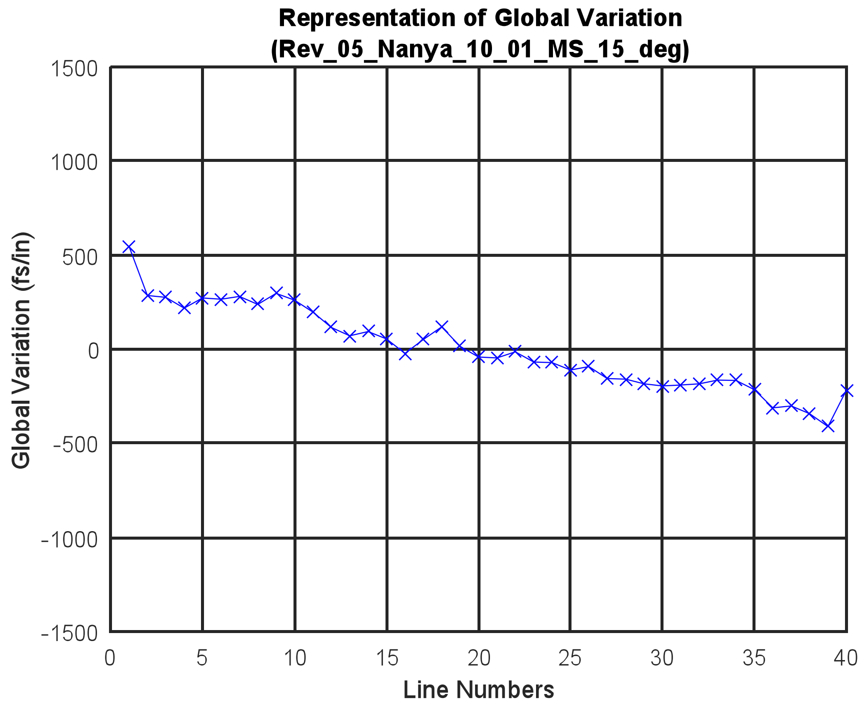

Figure 10. Measured delay skew for all 40 lines of microstrip test lines rotated at 15 degrees to the glass-weave axis. (Taking the average of all 40 lines as the reference.)

In some cases, there appears to be a real variation in the delay across the 40 lines. This may be due to a real Dk variation, or global thickness variation. In this example, there is a real variation from the lines on one end of the array to the other end of almost 1 psec/inch. This is a variation of about 0.7%. It is still very small, but swamps the line to line variation we want to see. It makes no sense calculating an rms value, as this is not a Gaussian distribution.

Instead, to avoid this artifact, we calculate the adjacent line to adjacent line delay skew. This eliminates the global variation. The line to line skew is displayed and the standard deviation, assuming a Gaussian distribution, calculated. An example of the global variation, the local variation, and the distribution of the local, line to line skew for this board—with microstrip lines rotated 15 degrees to the glass-weave axis—is shown in Figure 11.

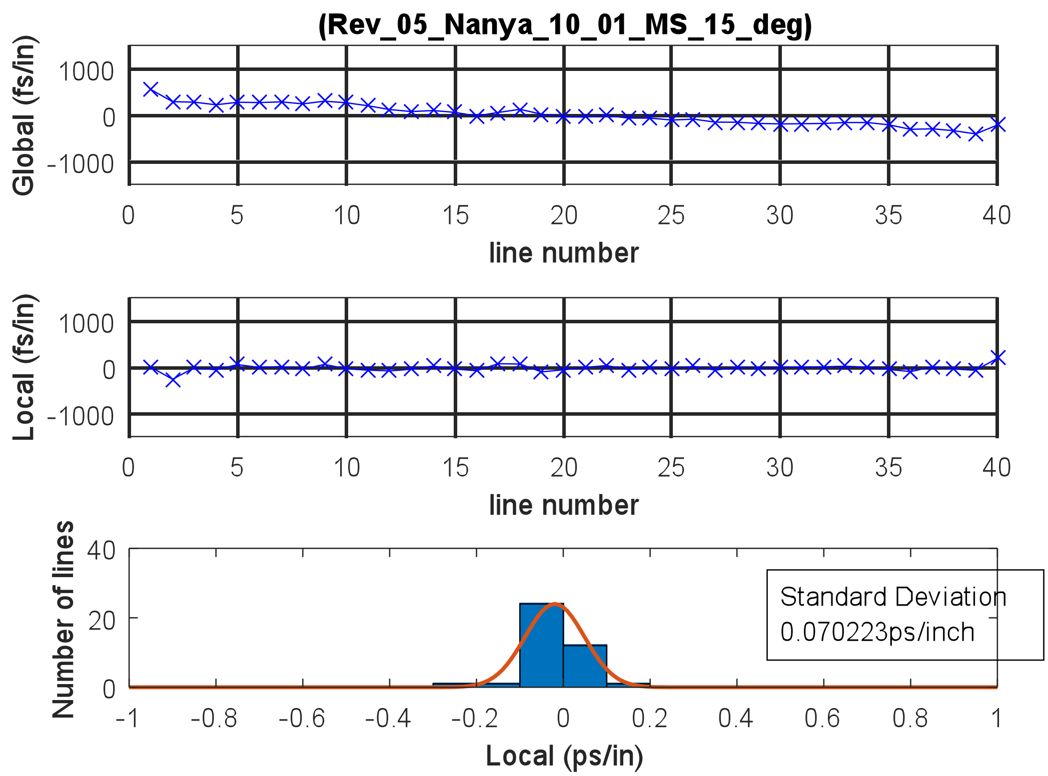

Figure 11. Global and local variation in the adjacent line-to-line delay skew and its distribution.

The line-to-line skew rms value is measured as 0.070 psec/in in this example. This is a typical value measured for all the boards, both microstrip and stripline. The total time delay per inch of a line is about 150 psec/inch. The rms variation in the line to line delay skew is about 0.07/160 = 0.04 percent variation.

It is incredible that the intrinsic line to line variation is only 0.04%. This includes all the variations in line width, dielectric thickness, and real Dk variation. Most of the arrays of lines rotated 15 degrees to the glass weave axis show an rms line to line variation of less than 0.08 psec/inch. This sets the limit to how much line to line skew variation can be resolved with this test pattern on this material system.

The last test of the quality of the measurement process is the reproducibility of the delay skew for the same lines over a period of a few weeks. Figure 12 shows the measured global delay skew per inch of all 40 lines in a specific board with the lines aligned to the glass weave axis. This plot includes the measurements of the same lines measured two weeks apart.

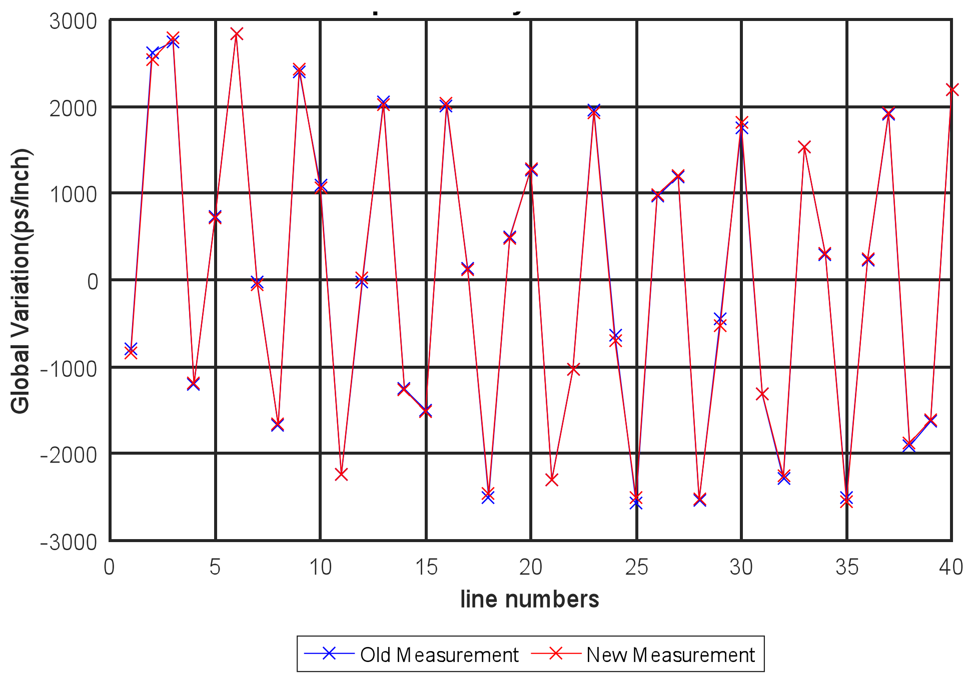

Figure 12. Measurements of the same 40 lines repeated two weeks apart—showing the same values with less than 40 fsec/in rms difference. The lab temperature and humidity were held to +/- 3 degC and 20 to 40 percent rH over this time.

System performance values are shown in Table 1.

	Absolute time variation (psec)	Absolute one-way TD of the line (psec)	Equivalent delay skew (psec/inch)
Time Step Resolution	0.042 psec	0.021 psec	0.005 psec/inch
Intrinsic SPARQ jitter	0.170 psec	0.085 psec	0.020 psec/inch
Fixture repeatability	0.374 psec	0.187 psec	0.044 psec/inch
Typical rms line variation for 15 deg	0.680 psec	0.340 psec	0.080 psec/inch
Nominal Line TD	1300 psec	650 psec	162 psec/inch

Table 13. Summary of the system performance specs.

Glass-Weave skew Expectations Going in

Going into this project, and based on previous research and experience, we had the following expectations that the Design of Experiment (DOE) was intended to validate and refine:

- 15-degree route should have lower skew than 0-degree route
- Striplines should have lower skew than microstrip lines
- Thicker laminates should show slightly lower skew than thinner ones
- L glass should have lower skew than E glass
- Mechanically-spread glass should be better than non-spread glass
- Dual-ply constructions should have lower skew than single ply
- Signals parallel to the fill direction should have lower skew than the warp direction
- Among constructions used in the study, we expected 2113, 2116 and 3313 glass to perform the best; with 1078 and 1080 in the next tier; and 1067 glass performing with higher skew, as compared to the other constructions

A Significant Artifact in Production Boards

Late in this program, when the measured delay-skew distributions were not consistent with the expectations (rule #9) [8], we discovered a significant artifact present in most of the boards fabricated for this study. We believe this is also a significant issue industry-wide.

Under magnification, it's possible to measure the precise alignment of the glass weave to the lines in the microstrip structures. We measured this alignment and found that most boards had misalignment between the signal line and glass-weave that was greater than 0.15 degrees. An example of a close up of the glass weave and signal lines is shown in Figure 13.

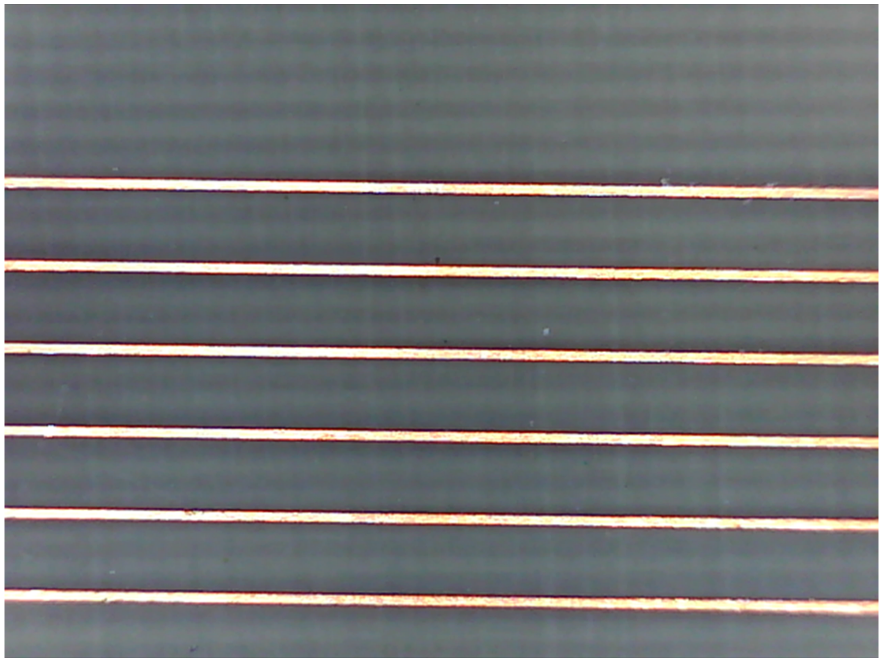

Figure 14. Close up of the glass weave and the signal lines for microstrip. Length of the image is 0.6 inches.

It is possible to measure the alignment angle between the glass-weave axis and the signal lines. Over the 4 inches of the line, we count the number of glass-weave pitches, n, which pass underneath each signal line. The angle is given by

$$\text{angle[rad]} = \frac{\text{Pitch}_{\text{glassWeave}} \times \text{n}}{\text{4inches}} \quad \text{and} \quad \text{angle[deg]} = \frac{\text{Pitch}_{\text{glassWeave}} \times \text{n}}{\text{4inches}} \times 57.3$$

For example, in this test board, if there is 1 complete glass-weave pitch shift for the glass weave over the 4 inches of the line (i.e., n = 1), then there will be significant averaging of the glass-weave skew and the measured skew will not be the result of variations in the glass-weave construction, but the micro alignment between the signal lines and the glass.

The angle when n = 1 is just 0.32 degrees.

We measured the alignment angle for each board fabricated for this study, for the microstrip lines only. We could not see the glass fabric in the fill direction, so only report alignment to the weave direction. Nor could we see the alignment for the stripline traces. Figure 14 shows the distribution of angles we measured.

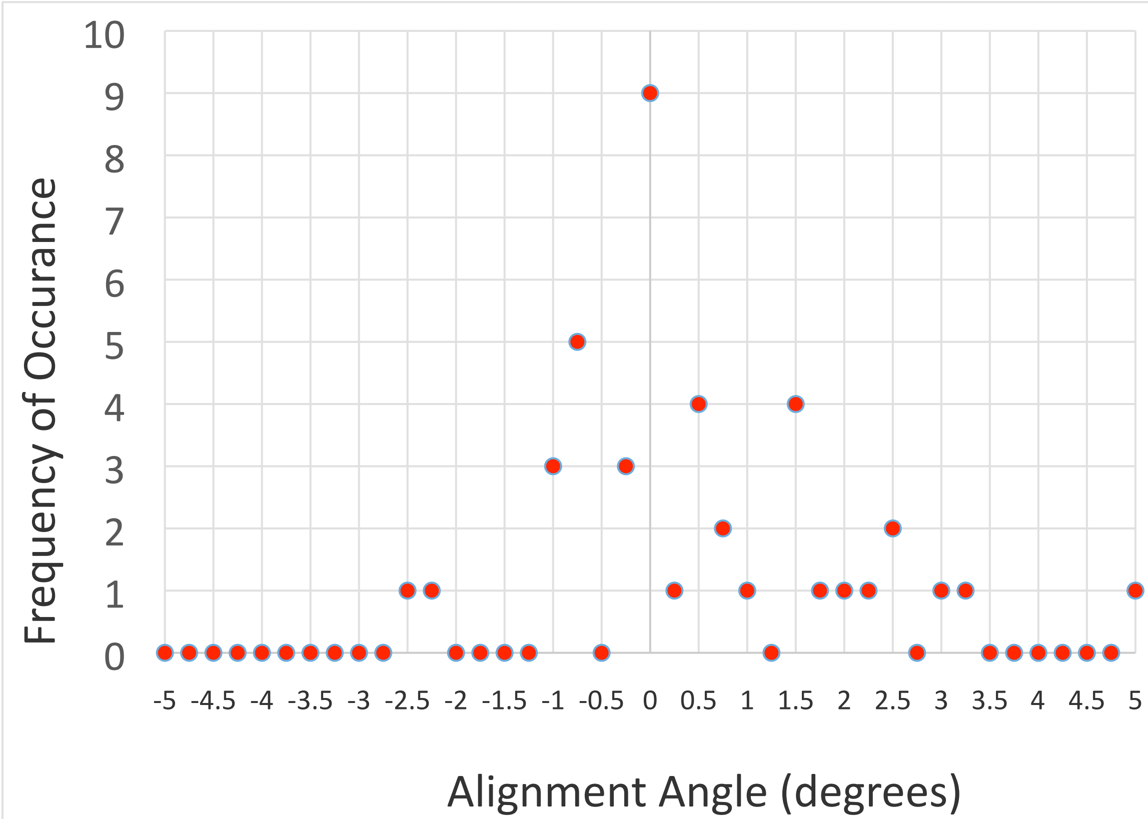

Figure 15. Distribution of alignments between the glass weave and the signal lines for all boards in this study. The nominal alignment is 0 degrees.

Most of the boards had a misalignment that was greater than 0.5 degrees. This is a significant amount of shift and suggests that all the measurements of glass-weave skew for these boards are not intrinsic to the glass weave effect, but dominated by the alignment angle.

If this small misalignment is a common feature in production boards, it suggests why there seems to be so much confusion in the industry about quantifying the glass-weave skew effect. If it is large enough, this small misalignment may completely hide the glass-weave skew effect. The GWS effect inherent in a particular construction will be present and measureable if the angle is very small. This may explain why some reports offer widely varying values of skew for the same glass weave style.

A Simple Model

A simple model allows us to estimate the impact on the delay skew in typical channels from glass-weave skew based on the alignment angle.

The distance between cycles of the signal line over the center of the glass weave, then over the resin, then over the glass, as the glass weave pitch drifts under a signal line is given by

$$Len_{cycle}[in] = \frac{P_{GlassWeave}[mils]}{angle[rad]} \times 10^{-3}$$

Over an entire cycle of the line moving over glass, then resin, the delay skew will be completely averaged out, and there will be no net effect. However, the worst case would be from the residual length that only completes half of this cycle.

If the maximum peak to peak glass-weave skew is GWS, in psec/inch, then the maximum line to line skew is when the signal travels a half cycle:

$$Skew\left[p\sec\right] = GWS\left[p\sec/in\right] \times \frac{1}{2} Len_{cycle}\left[in\right] = \frac{1}{2} GWS \times \frac{P_{GlassWeave}[mils]}{angle[rad]} \times 10^{-3}$$

In a channel with a bit rate of BR, in Gbps, the maximum skew allowed is about 20 percent of the UI. The relationship between the maximum-allowed skew and the minimum angle to assure there is less than the maximum allowed line to line skew is as follows:

$$\frac{0.2}{BR\left[Gbps\right]} \times 10^{3} > \frac{1}{2} GWS\left[p\sec/in\right] \times \frac{P_{GlassWeave}[mils]}{angle[rad]} \times 10^{-3}$$

Or

$$angle[rad] > \frac{10^{-6}}{0.4} GWS\left[p\sec/in\right] \times BR\left[Gbps\right] \times P_{GlassWeave}[mils]$$

Or

$$angle[deg] > 0.000143 \times GWS\left[p\sec/in\right] \times BR\left[Gbps\right] \times P_{GlassWeave}[mils]$$

For example, if the actual peak to peak GWS = 7 psec/in and the BR is 10 Gbps and the glass-weave-pitch is 20 mils, then the minimum angle to have the worst case glass weave induced skew less than the maximum allowed level is

$$angle[deg] > 0.000143 \times 7 \times 10 \times 20 = 0.2\deg$$

At 28 Gbps, this angle is

$$angle[deg] > 0.000143 \times 7 \times 28 \times 20 = 0.6\deg$$

This suggests that if the angle between the signal line and the glass-weave skew is greater than about 0.6 degrees, the glass-weave skew effect should be marginally acceptable in all channels operating at 28 Gbps. And in the 10 Gbps case, less than half a degree.

However, there is a slight concern in a small-angle rotation. As noted in boards with signal lines rotated 12 degrees to the glass weave axis, the periodic behavior of signal line passing over glass then resin, then glass creates "Bloch Wave" resonances at about 35 GHz. [9]

We would expect similar Block Wave resonances but at a lower frequency, and of a small magnitude. This is an area that needs further investigation.

As a rough test of this simple model, we went through all the microstrip test lines we measured and compiled the measured line to line time-delay skew, as an rms value—roughly similar to the peak to peak value—and compared these with the angle between the lines and the glass weave. We compared these values to a simple model based on the relationship above, using a typical value of 5 psec/inch. This is shown in Figure 15.

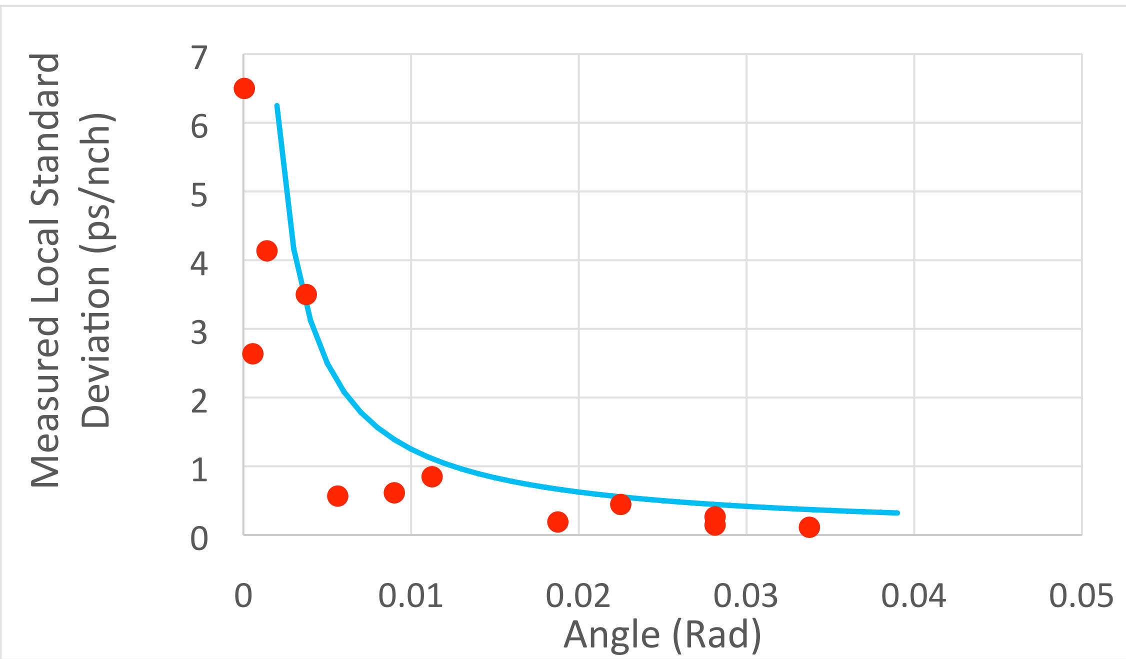

Figure 16. Measured delay skew in psec/inch (red dots) for different glass-weave to signal line angle, compared to the simple model, as the blue line.

Industry Impact

This agreement between, measured data and the model predictions suggests that the actual angle between the signal line and the glass-weave may be the dominant factor affecting measured glass-weave skew. When evaluating the glass-weave skew effect observed in test boards reported in the industry, if the actual angle between the glass weave and the signal line is not known, conclusions drawn about the merits of one solution over another may be erroneous.

We believe this is the reason there is so much contradictory information about the glass-weave skew to expect from various glass configurations when based on anecdotal studies. [10]

If this angle can be controlled by the laminate board manufacturer, and maintained at angles larger than roughly 0.6 to 1 degree, it may offer a new, low cost, means of mitigating the glass-weave skew effect at a level that would be transparent to the designer and allow the use of almost any glass weave style. However, it remains to be seen whether this is doable as part of a high-volume manufacturing process

Analysis of the Measured Boards

In evaluating the role of the glass weave and the laminate construction in the glass-weave skew effect in this study, only boards which were measured as having less than a half cycle of glass-weave shift across the 4 inches of test-line length, or an angle of less than 0.14 degrees, were included, and then only the results from microstrip lines. We could not measure the angle in stripline and so these were not included.

Altogether, out of the 46 boards that were fabricated, only 10 had less than a 0.14-degree angle between the signal lines and the glass-weave axis. An example of the measured delay skew for a laminate with 1 x 1067, non-spread E-glass is shown in Figure 16.

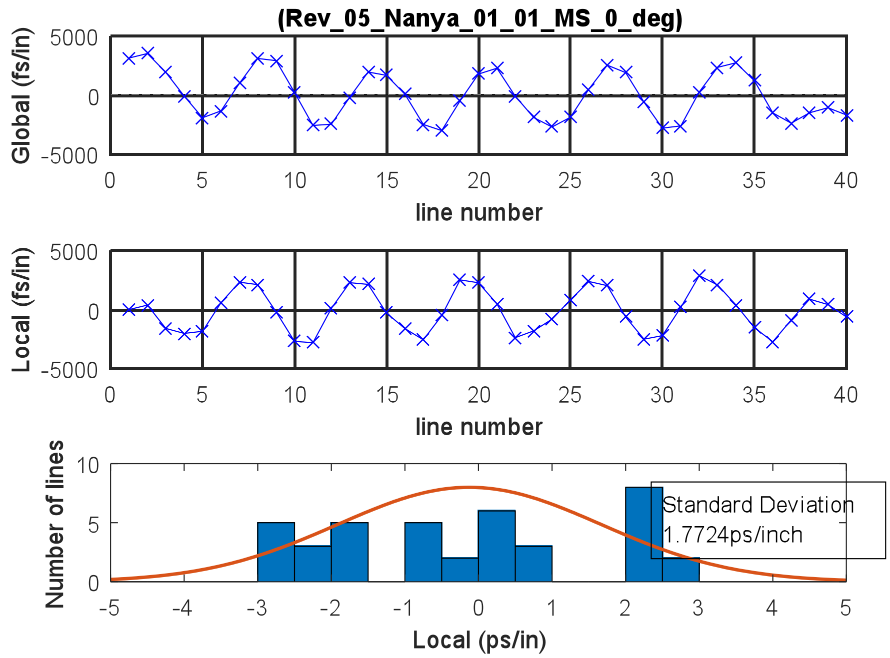

Figure 17. Measured delay skew for a microstrip with 1 x 1067 non-spread E-glass.

In this example, the global variation in delay shows no apparent systematic change across the 40 lines. We believe this is the Moiré pattern created by the overlay of the line pitch of 45 mils and the glass-weave pitch of about 15 mils. This would give a periodicity of about every 5 lines, which is what is observed.

If this is the case, then a good metric of the glass-weave skew effect is the peak to peak variation of the delay skew measured in the global variation. In this case, it is 6.5 psec/inch. This is the metric of the glass-weave skew effect in this laminate.

Summary of all the Board Measurements

Most of the boards (79 percent) had misalignment that was greater than 0.5 degrees. This is a significant amount of shift, and suggests that all the measurements of glass-weave skew for these boards are not intrinsic to the glass weave effect, but dominated by the alignment angle. As a result, we performed detailed analysis on just 10 of the boards (21 percent) whose results were representative of their constructions in Table 2, below.

Construction	GWS Results
1 x 1067 non-spread E glass	6.5 psec/inch
1 x 1067 non-spread E glass	7.6 psec/inch
2 x 1067 non-spread E glass	1.23 psec/inch
1 x 1078 non-spread E glass	6.8 psec/inch
1 x 1078 spread E glass	7.0 psec/inch

2 x 1078 spread L glass	0.81 psec/inch
1 x 2113 non-spread E glass	3.5 psec/inch
1 x 2116 spread E glass	2.67 psec/inch
1 x 3313 non-spread E glass	5.7 psec/inch
1 x 3313 non-spread E glass	5.6 psec/inch

Table 2. A summary of the measured peak to peak glass-weave skew values across various laminate configurations. Each of these constructions had less than 0.5 degrees of angular rotation between the signal lines and the weave.

While we ended up with a limited data set of boards where the signal lines and glass-weave were well aligned, there are still some important observations that can be made.

Reproducibility is Very Good.

Two boards of identical construction, each of a single-ply with 3313 non spread E-glass, and both with less angle between the signal line and glass weave than could be measured, showed a delay skew of 5.7 psec/inch and 5.6 psec/inch. The agreement is very close for two independent boards.

In the case of the two boards constructed of a single- ply of 1067, both gave about the same glass-weave skew of 6.5 psec/inch and 7.6 psec/inch. The higher delay skew board had a measured alignment angle of less than 0.08 degree, the measurement threshold. The measured alignment of the lower delay skew board was 0.16 degrees. This slight difference may account for the measured difference in the delay skew. Taking this into account, the agreement is very good.

Laminates with Lower Glass-weave skew

The single-ply 2113 non-spread and mechanically-spread 2116 gave glass-weave-skew values of 3.5 psec/inch and 2.67 psec/inch, respectively—with both of these results being slightly better than the results for 3313 glass, and significantly better than the other weaves. There is no way of knowing the contributions from mechanical spreading verses the glass style.

This suggests that these may be glass weave candidates with slightly lower glass-weave-skew sensitivities. These results were roughly in line with our performance expectations for these weaves. Figures 17 and 18 show the measured glass-weave-skew for the 2113 and 2116 two boards.

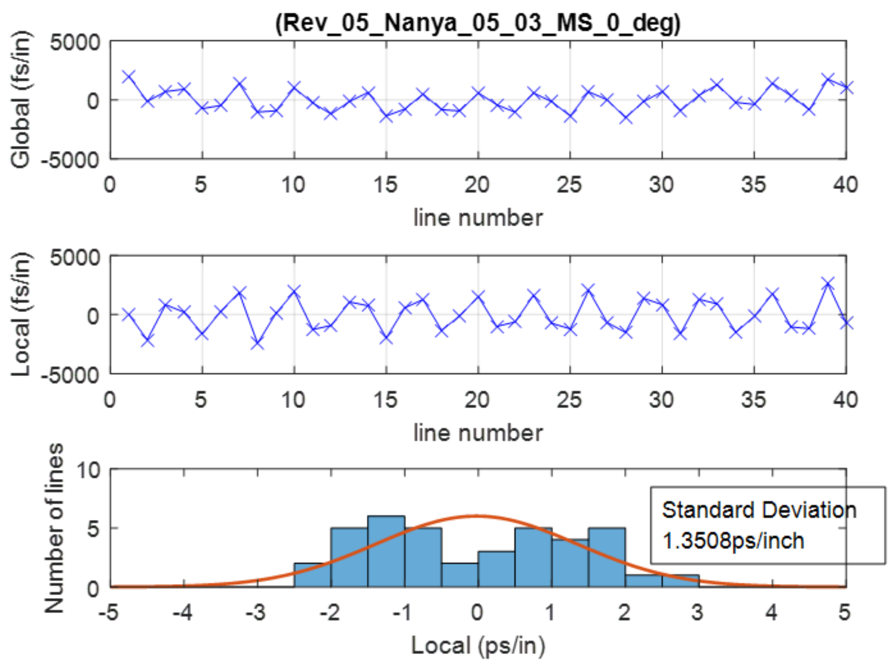

Figure 18. Measured glass-weave skew for the 1 x 2113 non spread E-glass board.

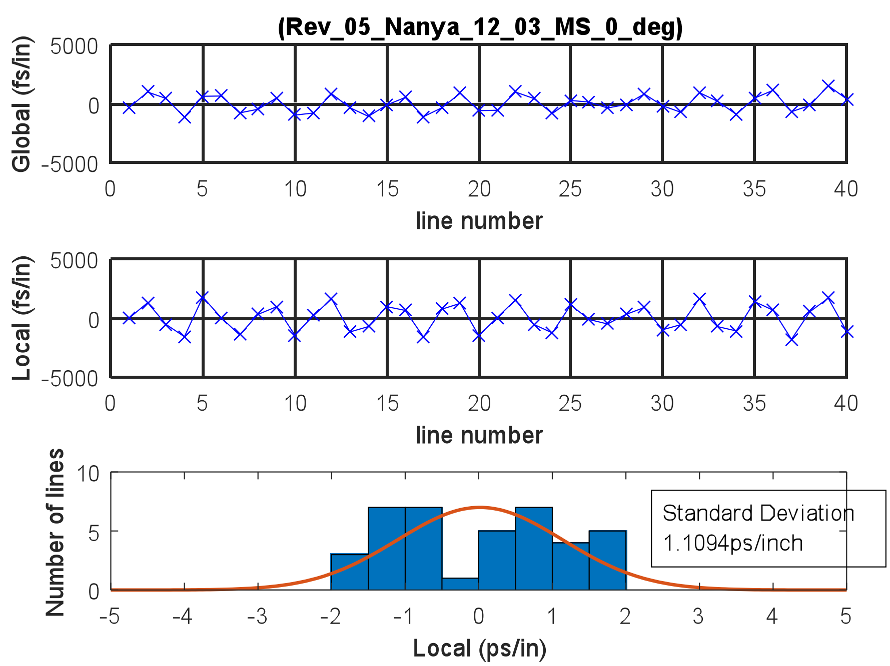

Figure 19. Measured glass-weave skew for the 1 x 2116 mechanically spread E-glass board.

Impact from Mechanically Spread or Non-spread

There was only one direct comparison between non-spread and mechanically spread glass. The boards with 1 x 1078 using E-glass were constructed as mechanically spread and non-spread. There was no real difference between them. The spread glass had a delay skew of 7.0 psec/inch while the non-spread glass had a delay skew of 6.8 psec/inch. This one comparison isn't enough from which to generalize a valid comparison.

Dual-Ply Laminates have Dramatically Lower GWS than Single Ply

Table 2 shows results from two boards fabricated with a single ply of non-spread 1067 E glass. A third board had an identical construction, but with two plies of 1067 glass. The single-ply boards showed glass-weave skew of 6.5 and 7.6 psec/inch, respectively, while the two-ply board had a measured value of 1.23 psec/inch—a notable difference.

The lowest measured delay skew for a board with a shallow alignment angle was with dual-ply, mechanically spread 1078 L glass. This was 0.81 psec/inch. This board used three significant features we would expect to reduce the amount of glass weave sensitivity. Across a 20-inch run length, this would result in 16.2 psec of skew, well within the 20 psec typical spec for a 10 Gbps link.

Next Steps

The analysis of the measured delay skew pattern is based on a Moiré pattern generated between the line pitch and the glass-weave skew pitch. One next step is to apply a simple model to extract the amplitude of the overlap and obtain a more accurate figure of merit.

By looking at the details of the pattern, we should also be able to analyze the slight angular misalignment between the glass weave and signal line and take this into account in the model.

Armed with the observations of the importance of the micro alignment, we can now qualify boards that met this criterion and performance additional measurements of a wide variety of boards.

Finally, the most important consequence of a slight angle between the signal lines and the glass-weave skew is the potential for Block Wave reflections and their impact on the insertion loss. This will be analyzed so that an optimized angle can be selected.

Summary

For 10 Gbps links, the UI is 100 psec, and the maximum allowable skew is about 20 psec. Most of the arrays of lines rotated 15 degrees to the glass-weave axis show an rms line to line variation of less than 0.08 psec/inch.

A new technique was developed to measure the glass-weave skew sensitivity of a circuit board laminate with a sensitivity level of about 0.04 psec/inch. We've applied this method to measure the delay skew of a variety of glass weave styles and find many of them to be on the order of, and less than, 7 psec/inch. The combination of mechanically spread, 2-ply and L-glass resulted in the lowest skew, at 0.8 psec/inch.

In the course of this study, an important artifact was uncovered that dramatically affected the measurement of glass-weave skew. Without measuring the precise alignment of the signal lines and the glass weave, it was impossible to base any conclusions on how the glass features affect the glass-weave skew sensitivity.

If this angle can be controlled by the laminate supplier or PCB fabricator, it may offer a new, low cost means of mitigating the glass-weave skew for high-speed differential signals.

In evaluating the role of the glass weave and the laminate construction in the glass-weave skew effect in this study, only boards which were measured as having less than a half cycle of glass weave shift across the 4 inches of test-line length, or an angle of less than 0.14 degrees, were included, and then only the results from microstrip lines. We could not measure the angle in stripline and so these were not included.

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10. See for example, https://www.altera.com/content/dam/altera-www/global/en_US/pdfs/literature/an/an528.pdf

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