Quantifying Timing Skew In Differential Signaling using Practical Fiber Weave Model

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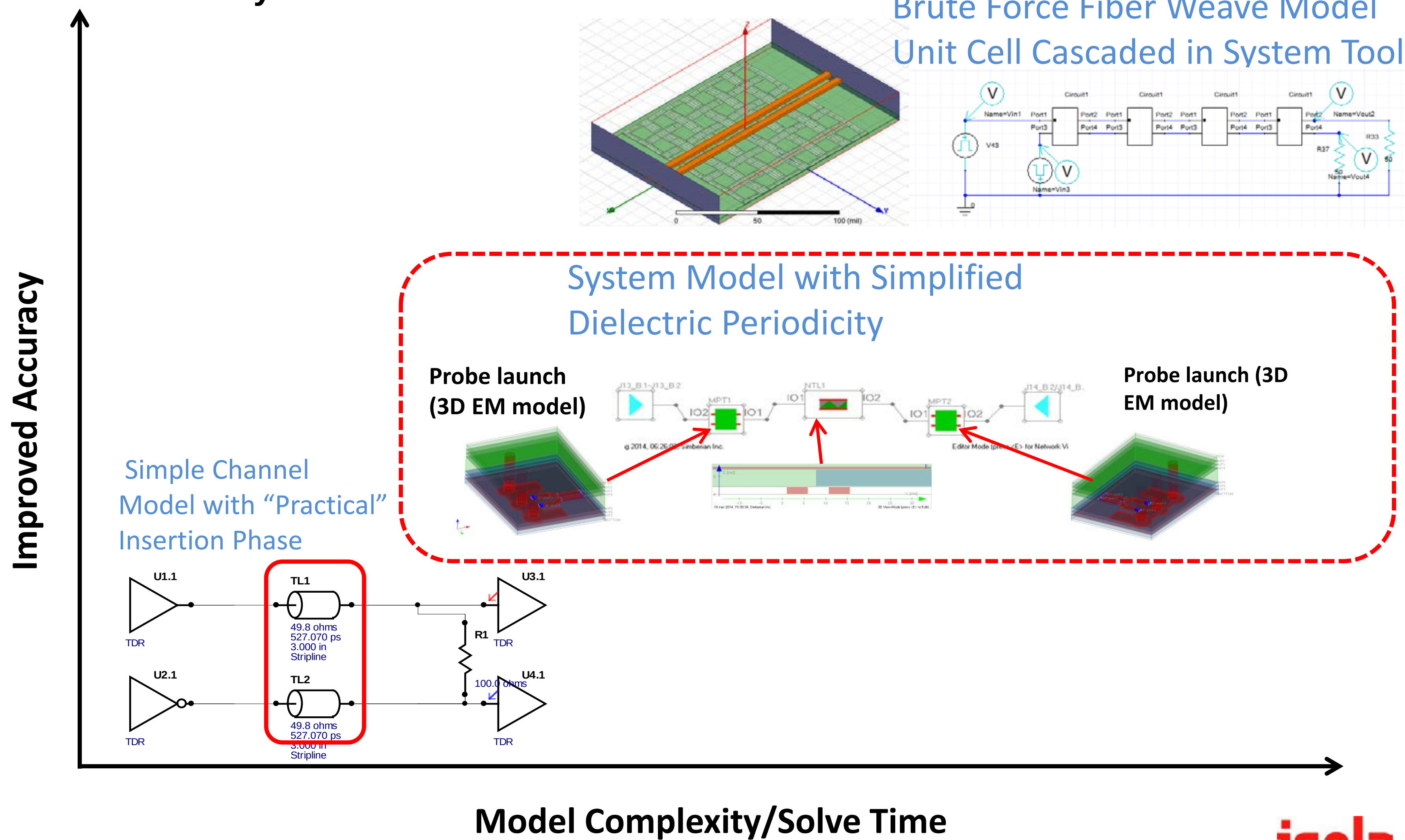
Outline

- **Practical Fiber Weave Effect Model for Skew and Jitter**
  - Introduction
  - Modeling fiber-weave effect with non-uniform transmission line segments
  - Printed circuit board test vehicle
  - Model identification with loosely coupled traces
  - Model identification and measurement validation with tightly coupled traces
  - Conclusion
- **Isola Low-Skew Product Solutions**
  - Tachyon™100G
  - GigaSync™
  - Chronon™

Skew Modeling Methods

- **Many Skew Modeling Methods are Available with Variable Levels of Complexity and Accuracy**



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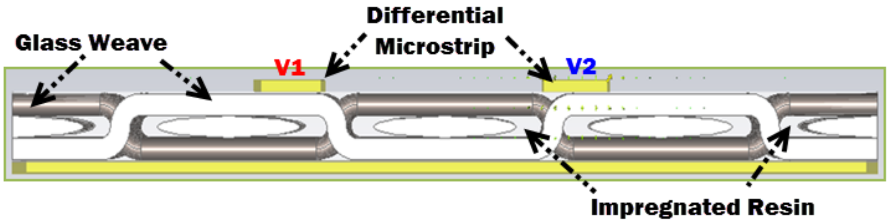
Introduction

- **Communication data links on PCBs are running at bitrates of 10-30 Gbps and beyond**
  - Design of interconnects for such links is a challenging problem that requires electromagnetic analysis with causal material models from DC to 20-50 GHz
- **Woven fabric composites are typically used as insulators to manufacture PCBs**
- **Both fabric fiber and resin are composite materials have different dielectric constant (DK) and loss tangent (LT) properties:**

Typical Dielectric Material Property	DK	DF
Glass Weave	4.4 - 6.1	0.002 - 0.007
Resin	3.2	0.003 - 0.027



- **Dielectric inhomogeneity in transmission line cross-section causes mode conversion or skew**
- **Inhomogeneity along the line causes resonances in insertion and reflection losses**
- **Both effects may contribute to deterministic jitter and have to be modelled and mitigated if necessary**
- **A practical fiber-weave effect model is presented**

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Model for Non-uniform Dielectric Across Traces

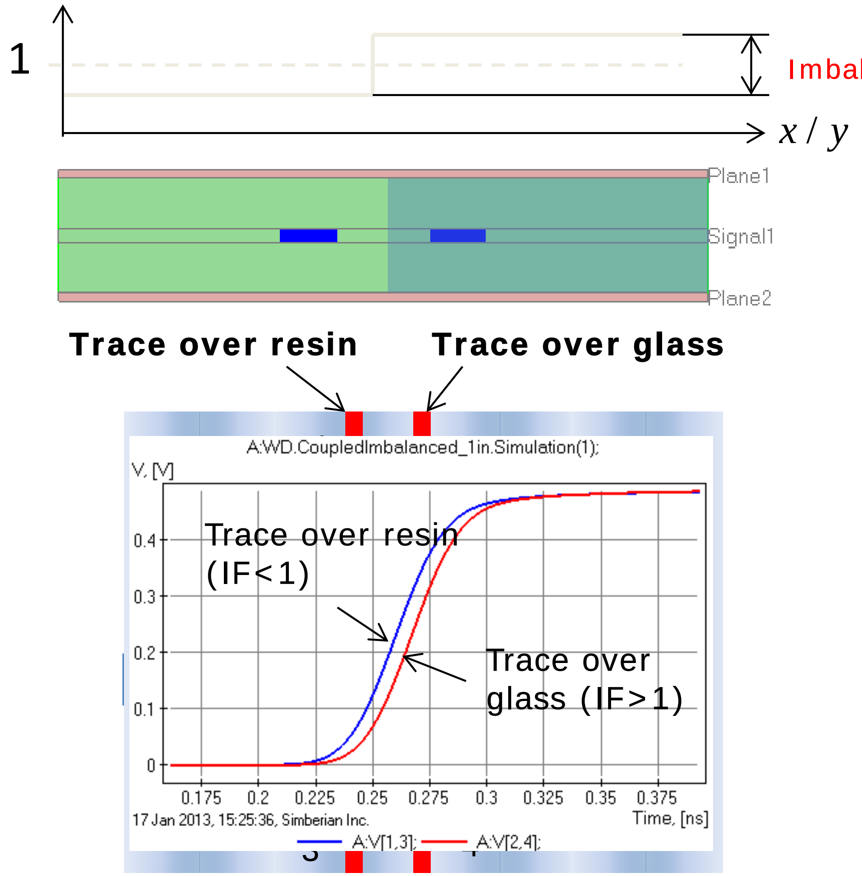
We use the **Imbalance Factor** to characterize dielectric properties variation (specified with Imbalance as shown on the right);

Unit Imbalance Factor corresponds to volume average resin percentage defined for the given PCB material globally;

Variation upwards corresponds to higher volumetric content of glass (higher dielectric constant and smaller polarization losses);

Variation downward corresponds to higher volumetric content of the resin (smaller dielectric constant and larger polarization losses);

Quasi-static field solver is used to build such model



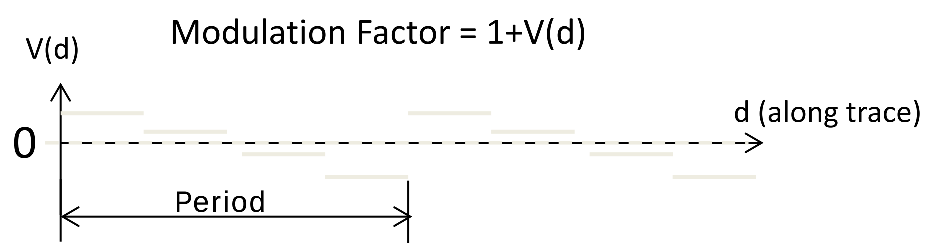
Model for Non-uniform Dielectric Along Traces

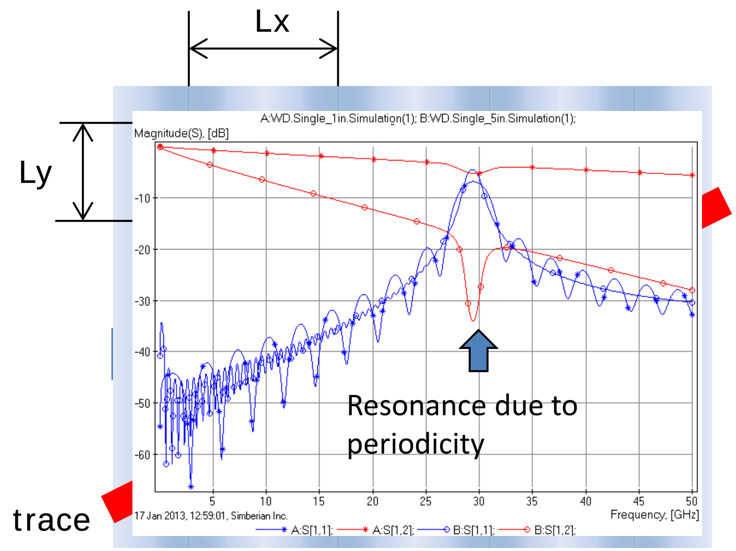
Modulation Factor is used to characterize dielectric property variation (specified either with step values as shown on the right or with periodic functions of length);

Unit Modulation Factor corresponds to volume average resin percentage defined for the given PCB material globally;

Variation upwards corresponds to higher volumetric content of glass (higher dielectric constant and smaller polarization losses);

Variation downward corresponds to higher volumetric content of the resin (smaller dielectric constant and larger polarization losses);





Concatenation of t-line segments with adjusted dielectric properties is used to model this effect

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Causal Model for Variable Dielectric Properties Option 1

- **Apply product of Imbalance and Modulation Factors to dielectric constant at infinity (causal adjustment):**

Multi-pole Debye model:

$$\varepsilon(f) = \phi \cdot \varepsilon(\infty) + \sum_{n=1}^{N} \frac{\Delta\varepsilon_n}{1 + i\frac{f}{fr_n}}$$

Wideband Debye model (aka Djordjevic-Sarkar):

$$\varepsilon_{wd}(f) = \phi \cdot \varepsilon(\infty) + \varepsilon_{rd} \cdot F_d(f)$$

$$F_d(f) = \frac{1}{(m_2 - m_1)\cdot \ln(10)} \cdot \ln\left[\frac{10^{m2} + if}{10^{m1} + if}\right]$$

Other causal models can be adjusted similarly

$$\phi = \mathrm{ImbalanceFactor} \cdot \mathrm{ModulationFactor}$$

$\phi = 1$ corresponds to the original "homogenized" model;

$\phi > 1$ increases the dielectric constant at infinity and automatically decreases the loss tangent;

$\phi < 1$ decreases the dielectric constant at infinity and automatically increases the loss tangent;

Causal Model for Variable Dielectric Properties Option 2

- **Apply product of Imbalance and Modulation Factors to volume fraction in mixing formulas (also causal):**

Wiener upper boundary model (layered dielectric):

$$\varepsilon_{eff,\max} = \phi \cdot f \cdot \varepsilon_2 + \left(1 - \phi \cdot f\right) \cdot \varepsilon_1$$

Wiener lower boundary model (comb-like dielectric):

$$\varepsilon_{eff,\min} = \frac{\varepsilon_1 \cdot \varepsilon_2}{\phi \cdot f \cdot \varepsilon_1 + \left(1 - \phi \cdot f\right) \cdot \varepsilon_2}$$

$$\phi = \text{ImbalanceFactor} \cdot \text{ModulationFactor}$$

$\phi = 1$ corresponds to the original “homogenized” model;

$\phi > 1$ increases the dielectric constant and automatically decreases the loss tangent;

$\phi < 1$ decreases the dielectric constant and automatically increases the loss tangent;

Hashin-Shtrikman and Maxwell-Garnett models can be adjusted similarly

Assuming dielectric 2 is glass with higher DK and lower LT, dielectric 1 is resin with lower DK and higher LT and both simulated with causal models

Test Board for Numerical Experiments and Experimental Validation

Test Board Stackup to investigate 2 materials from Isola

Material : GigaSync/I-SPEED

LYR	Type	Structure (Stack up)	Cu weight (oz)	Construction	Thickness after lam (mil)	DK/DF
	ImAg Finish					
1	TOP		0.5 + plating		2.1	
	prepreg			Gigasync 2116 - RC 60%	5.0	4.13/.0067
2	GND		0.5		0.6	
	core			Gigasync 2116	4.5	4.13/.0066
3	S3		0.5		0.6	
	prepreg			Gigasync 2116 - RC 60%	4.4	4.13/.0067
4	GND		0.5		0.6	
	core			I-SPEED 3X1652	19.0	3.72/.007
5	GND		0.5		0.6	
	prepreg			I-SPEED 3313 - RC 61.5%	4.4	3.50/.007
6	S6		0.5		0.6	
	core			I-SPEED 3313	4.0	3.65/.007
7	GND		0.5		0.6	
	prepreg			I-SPEED 3313 - RC 61.5%	4.8	3.50/.007
8	BOT		0.5 + plating		2.1	
	ImAg Finish					
				Pressed thickness	**53.9**	

Gigasync: Wideband Debye model because of glass and resin have close DK

I-SPEED: Wiener average mixture of S-glass with Dk=5 and LT=0.001 and 61.5% resin with Dk=2.8 and LT=0.011 @ 1 GHz (produces Dk=3.5, LT=0.007 as in specifications)

6-inch microstrip differential links with probe launches on top (GigaSync 2116) and bottom (I-SPEED 3313) of the board;

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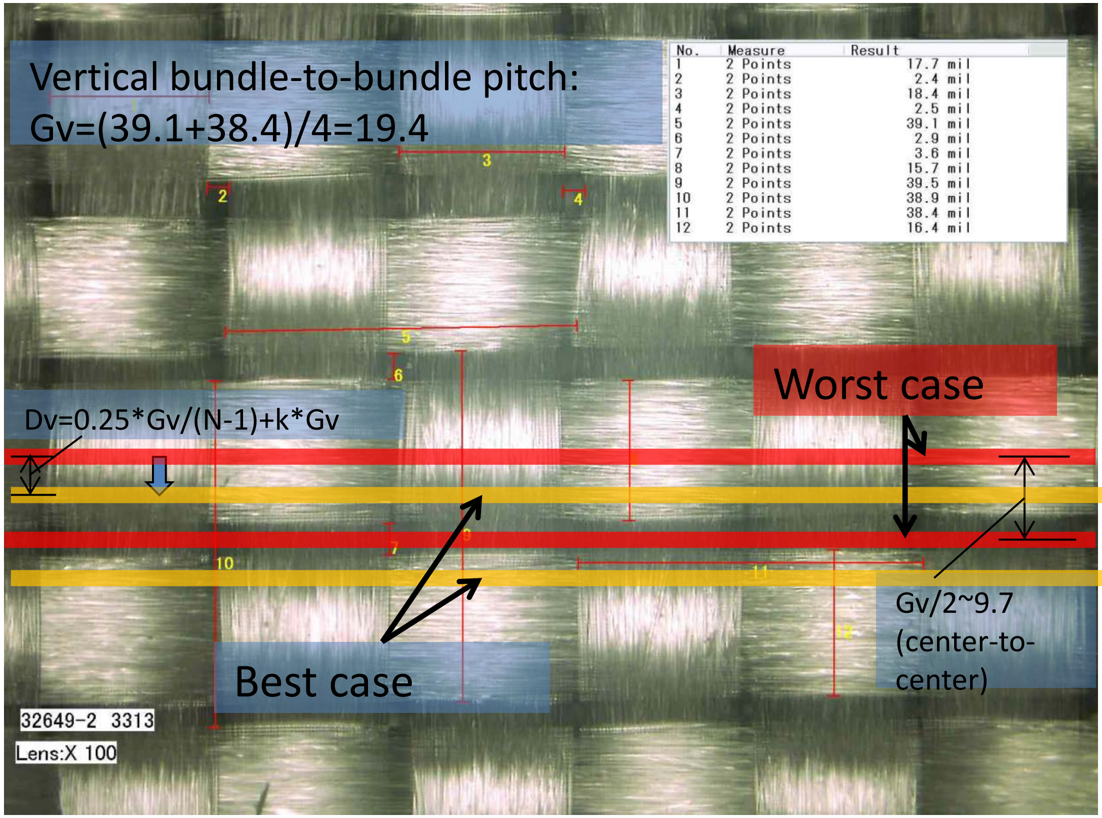
Two Cases Considered

- Loosely coupled pairs: trace width 9 mil, separation 39.5 mil (Kv=0.012, center to center 9.7+2*19.4 mil)
- Tightly coupled pairs: trace width 4.9 mil, separation 4.8 (Kv=0.21, center to center 9.7 mil)



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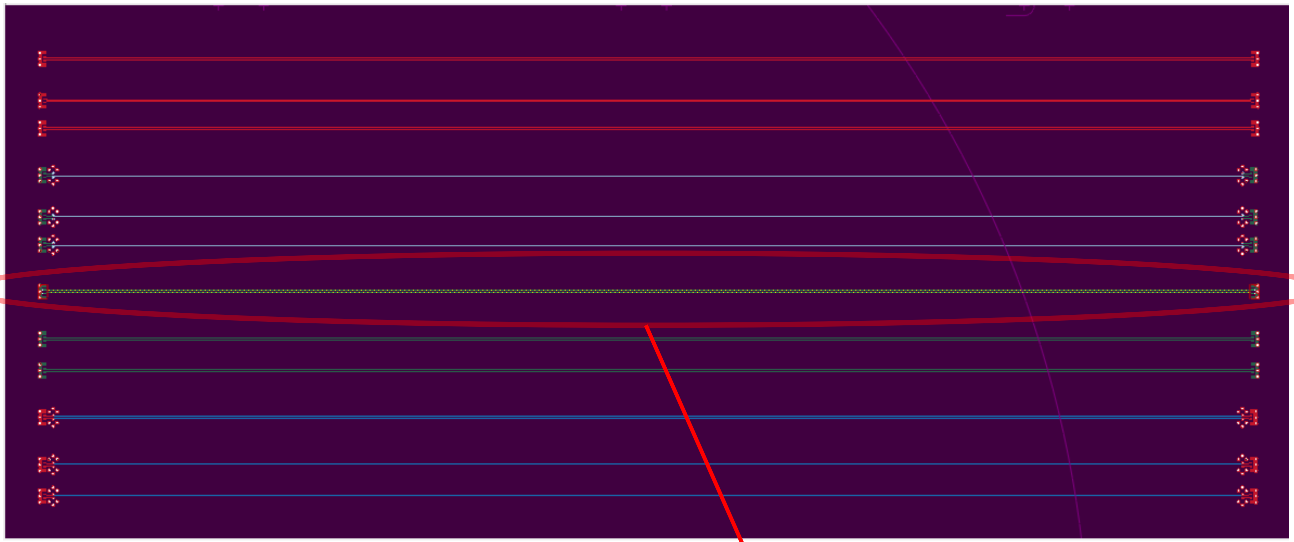
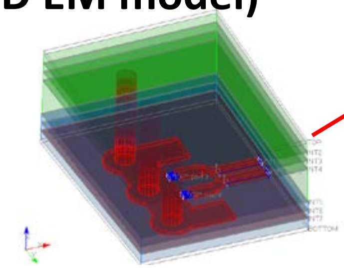
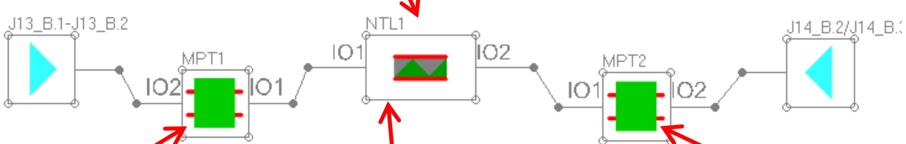
De-compositional Model of Test Structure



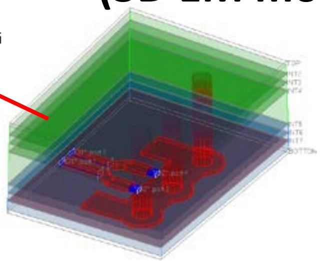
Simbeor 2013 software is used for all computations (pre and post-layout analysis with non-uniform t-lines)

Probe launch
(3D EM model)





Probe launch
(3D EM model)



6-inch segment of t-line with inhomogeneous dielectric – non-uniform t-line model

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Model identification for worst case skew (numerical example)

From: ***L. Ritchey, J. Zsio, R. Pangier, G. Partida, "High speed signal path losses as related to PCB laminate type and copper roughness", DesignCon 2013*.**

TEST PCB SKEW DATA, pSec 6 SAMPLES								
			VERTICAL 9"				HORIZONTAL 14"	
MATERIAL	WEAVE	MINIMUM	MAXIMUM	AVERAGE		MINIMUM	MAXIMUM	AVERAGE
IS415	3313	0	8	5		30	123	88
FR408HR	3313	1	8	5		3	43	20
FR408HRIS	8313	0	7	4.6		6	20	11.8
I-SPEED	3313	3	10	4.5		1	59	18
I-SPEED LOW DK	8313	1	4	2.3		5	12	7.5
I-TERA	3313	1	12	6		1	13	9.5
I-TERA LOW DK	8313	1	4	2.5		4	59	24.6

Worst case observed on I-SPEED with 3313 glass style in un-coupled traces is 59 ps or 4.2 ps/inch

1. Use 5 ps/inch as the maximal possible skew due to FWE and adjust the **Imbalance Factor** for loosely coupled line to observe the same skew;
2. Estimate jitter due to skew in loosely coupled lines;
3. Define **Modulation Factor** along the line with the same amplitude as the imbalance and see effect on jitter;

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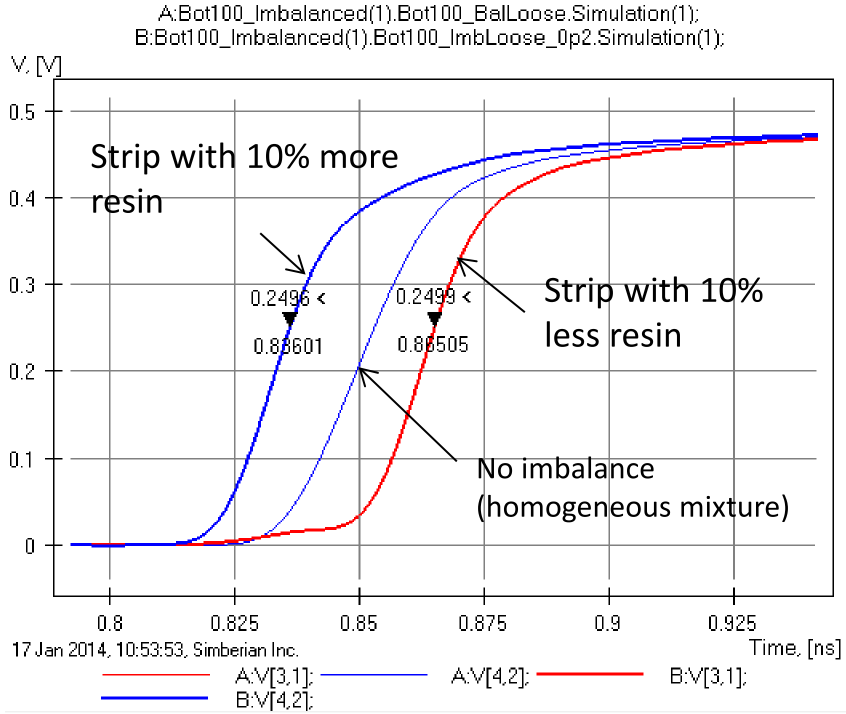
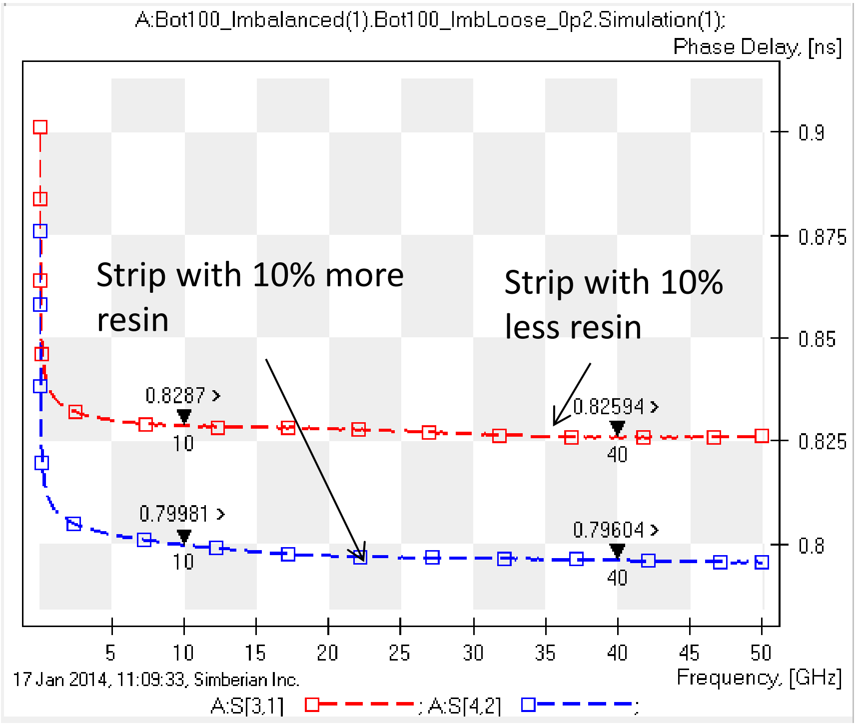
Identification of Imbalance for Worst Case Skew

Imbalance = 0.2 (Imbalance Factor 0.9/1.1 or resin content +/-10%) produces skew 5 ps/inch in loosely coupled differential pair

Single-ended TDT with 20 ps Gaussian step



Single-ended transmission phase delay



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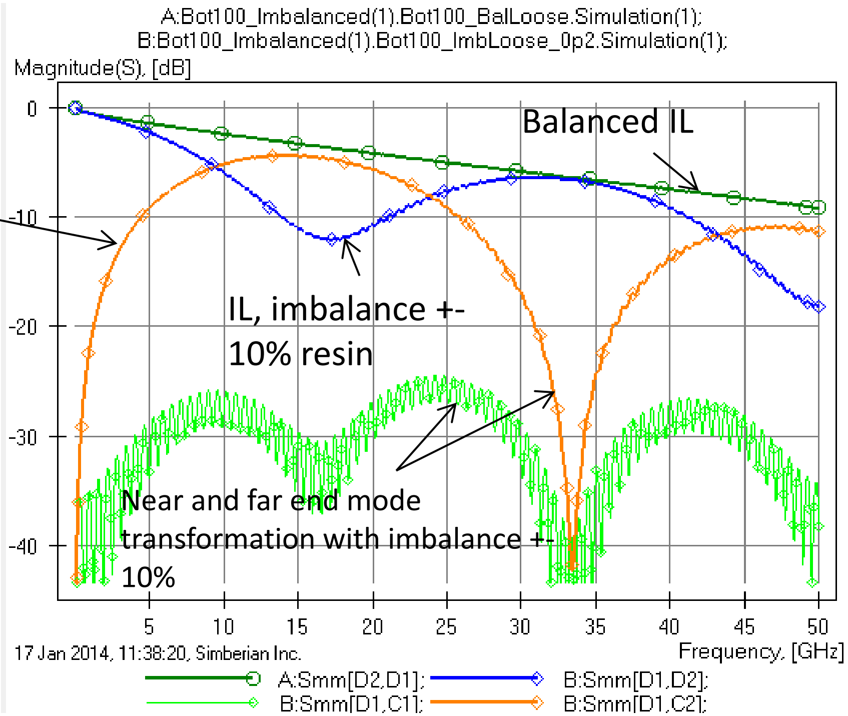
Impact of the worst case imbalance on insertion loss and mode transformation (loosely coupled traces)

Differential to common mode transformation is zero if no imbalance;
Very large far end mode transformation observed with Imbalance 0.2 (+- 10% of resin);
Mode transformation also degrades differential insertion loss (IL);

Optionally, far end mode transformation parameter can be used to evaluate the imbalance – it is zero (-infinity dB) for symmetric traces;



Mode transformation is shown to be good way to quantify imbalance effect on PCB composite dielectric

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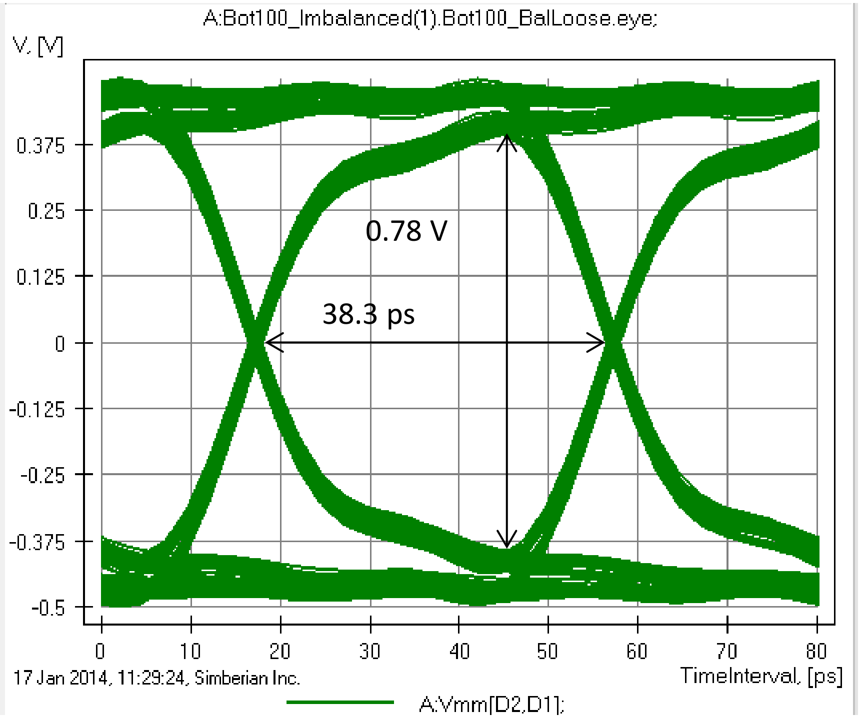
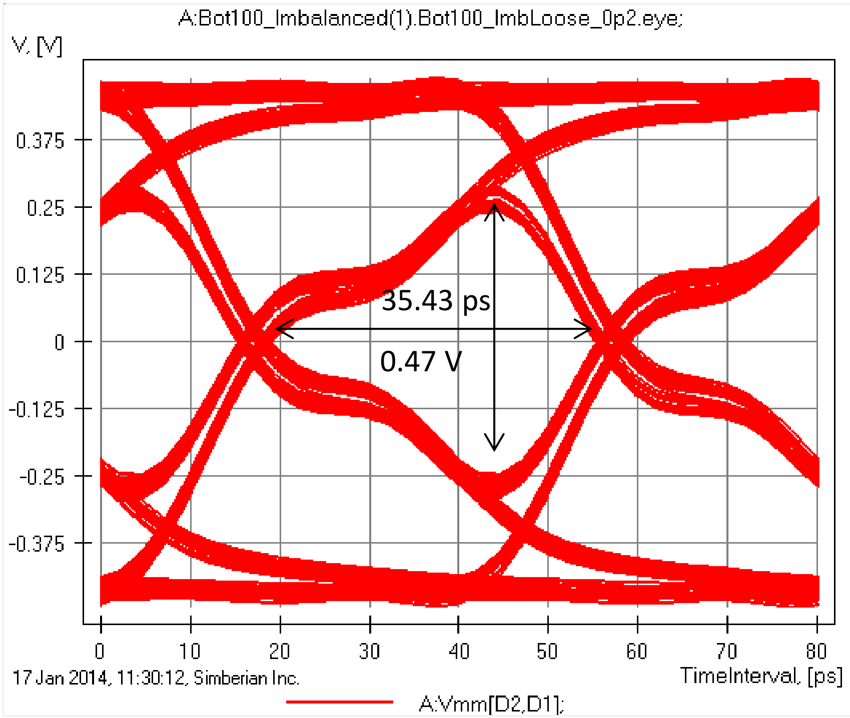
Impact of worst case skew on jitter (loosely coupled traces)

25 Gbps PRBS 7 signal, 10 ps rise and fall time

No Imbalance (homogeneous mixture)	Imbalance = 0.2 (10% variation) (+/- 10% of resin content)

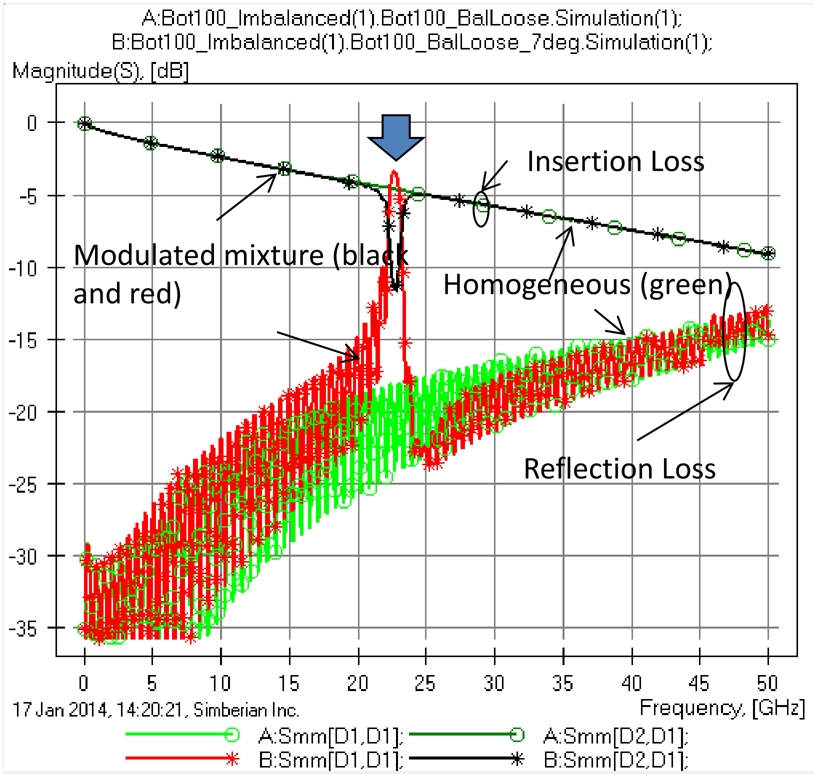




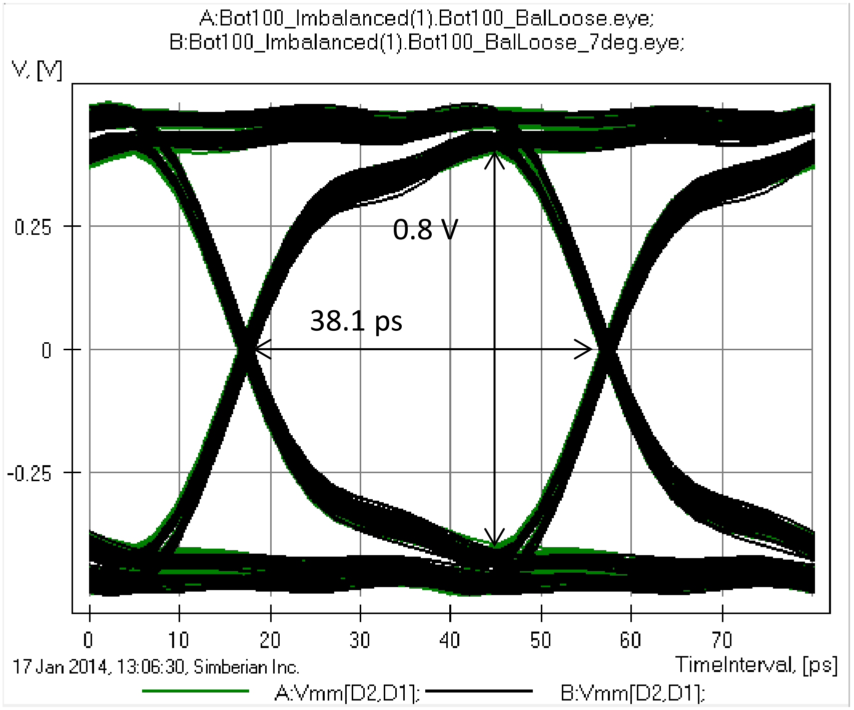
Substantial reduction of eye width (timing jitter) and eye height is expected For case of 10% imbalance – worse case for I-Speed with 3313 glass weave

Impact of +-10% resin content variation along the line (loosely coupled traces)

Strips are running at 7 degree to horizontal fiber – no imbalance, maximal modulation period 164 mil, amplitude 0.2 (+/-10% variation of the resin content)



25 Gbps, PRBS 7, 10 ps rise and fall – no significant changes in eye



No substantial effect on jitter expected (due to narrow band of the resonance)

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Test Board for Tightly Coupled Traces

This board was manufactured, simulated and investigated experimentally

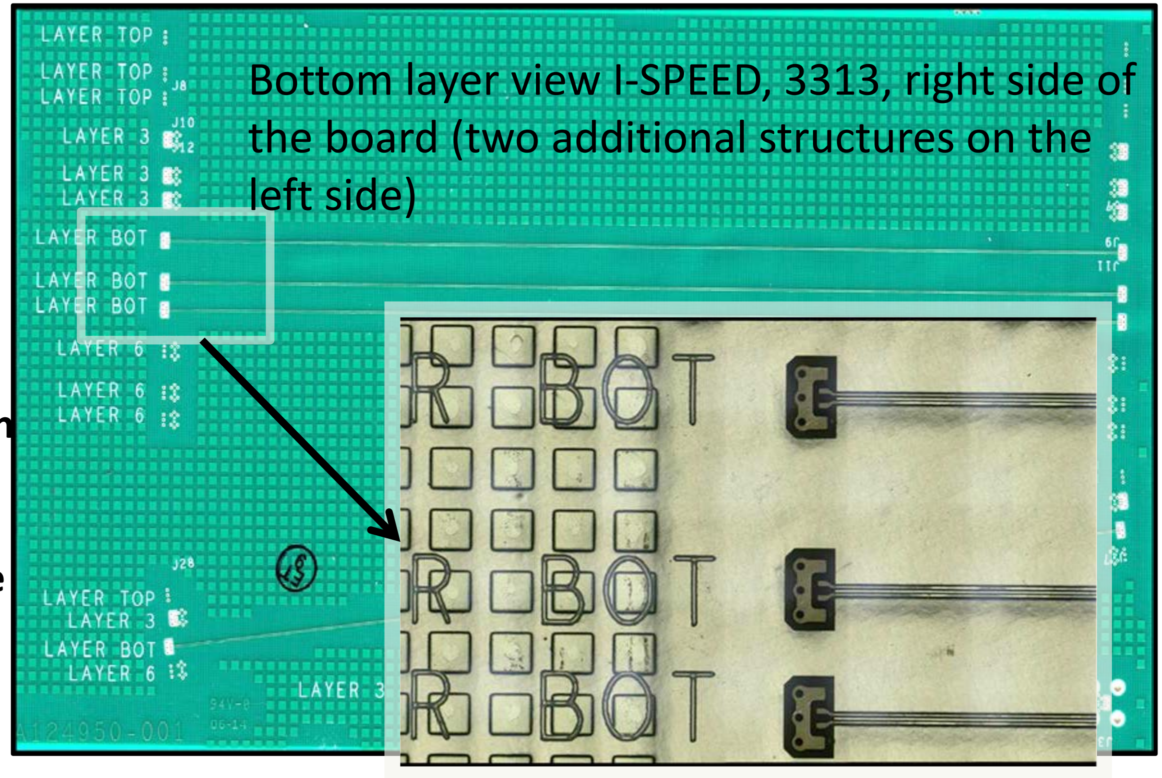
5 microstrip structures with offset for I-SPEED/3313 on the bottom side;

5 microstrip structures with offset for Gigasync/2116 on the top side;

TDR measurements are done by Brian Butler from Introbotix;

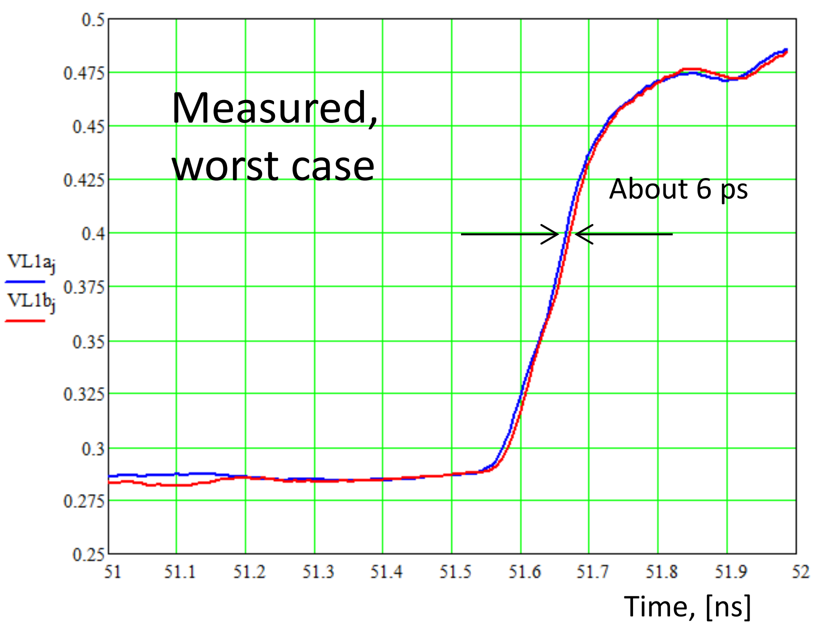
S-parameter measurements are done by Reydezel Torres Torres from INAOEP;

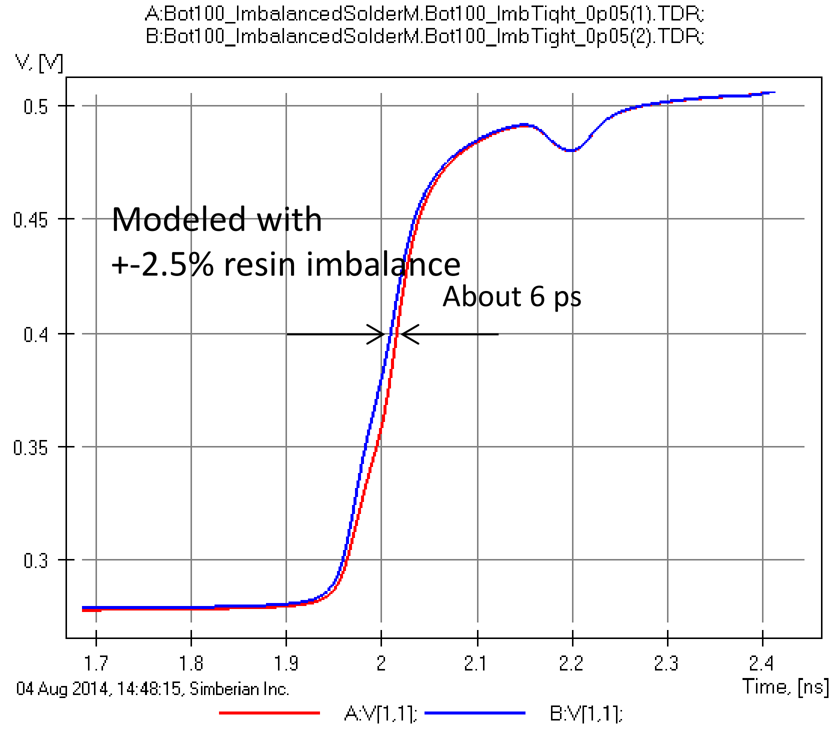
Analysis with Simbeor software;



Direct TDR measurements for tightly coupled traces

- **Worst case for MS1 - about 6 ps (1 ps per inch) produces Imbalance = 0.05 (Imbalance Factor 0.975/1.025)**



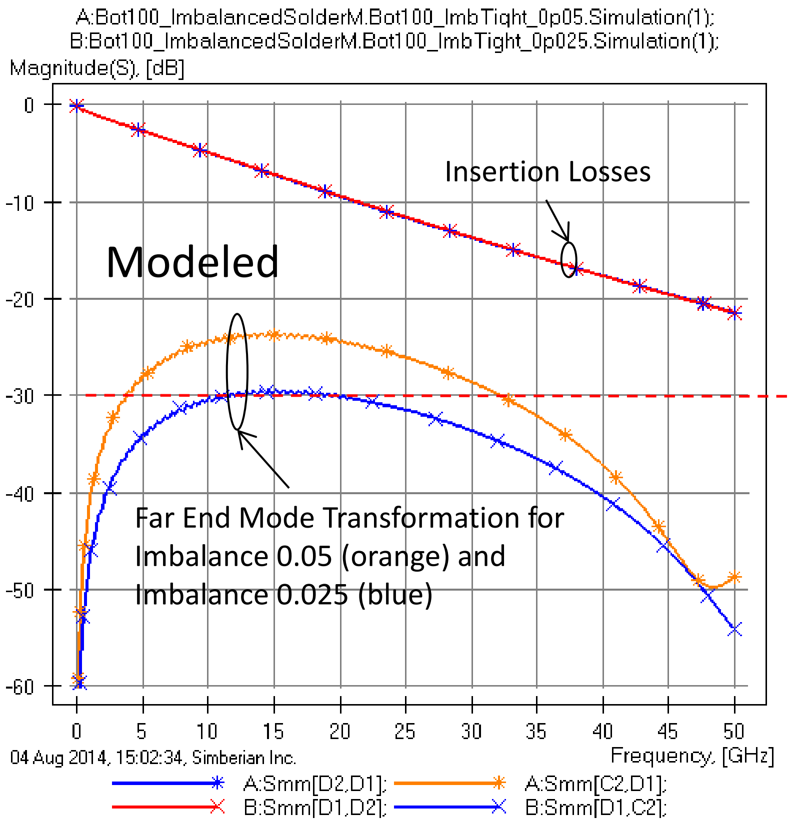


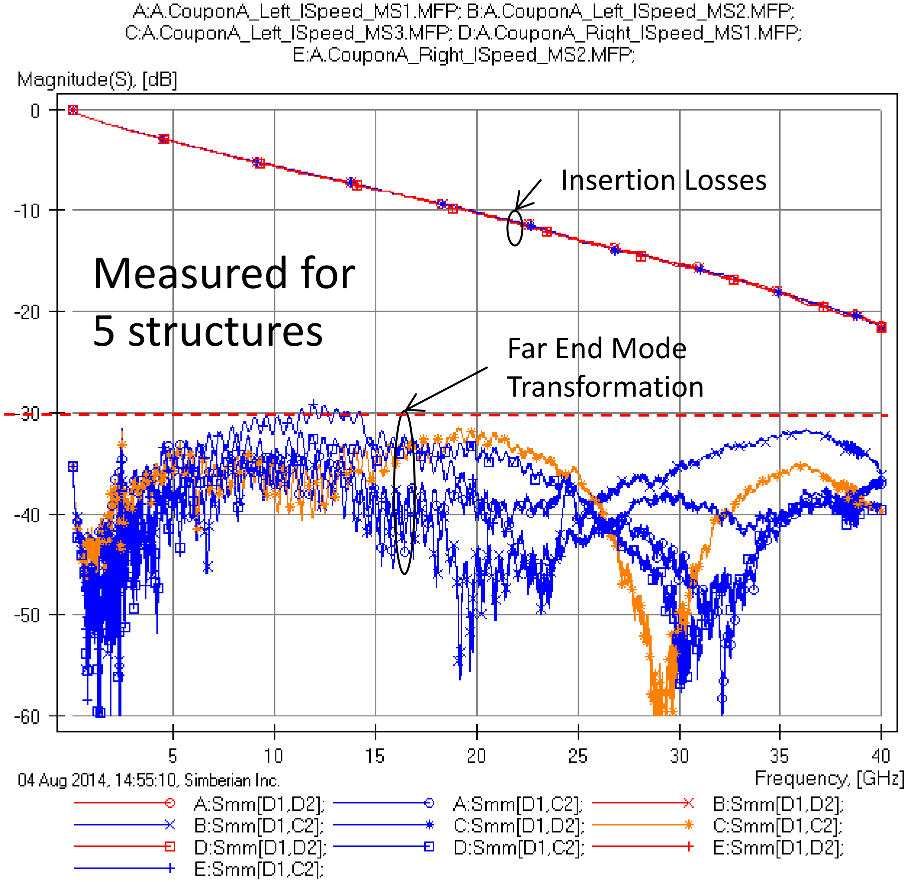
TDR measurements and simulation are done with all ports open

Tight coupling case is much less sensitive to material variations

S-parameters, Tightly Coupled Traces

- **6-in links on I-SPEED/3313:**



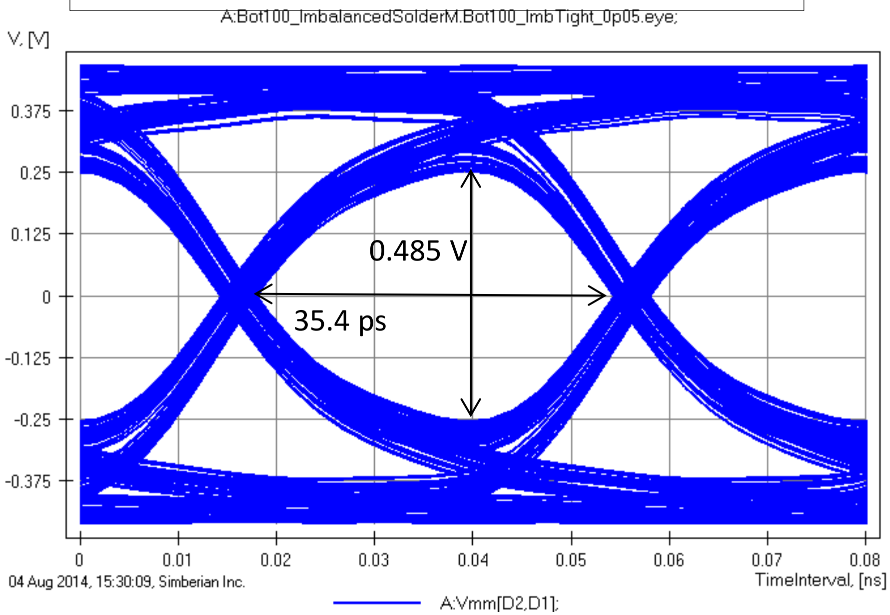


Mode transformation is smaller than expected from the TDR measurements – the imbalance is closer to 0.025 (+,- 1.25% resin variation) versus assumption of 0.05

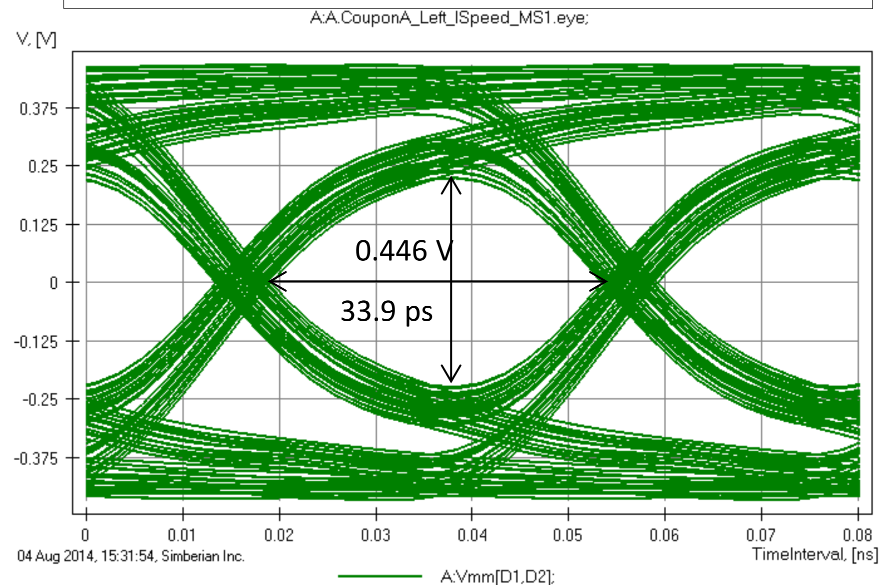
Imbalance Impact on Eye Diagram

- **6-in links on I-SPEED/3313; Signal: 25 Gbps, PRBS 7, 10 ps rise time;**

Simulated with Imbalance 0.05 (+/- 2.5% resin, worst case)



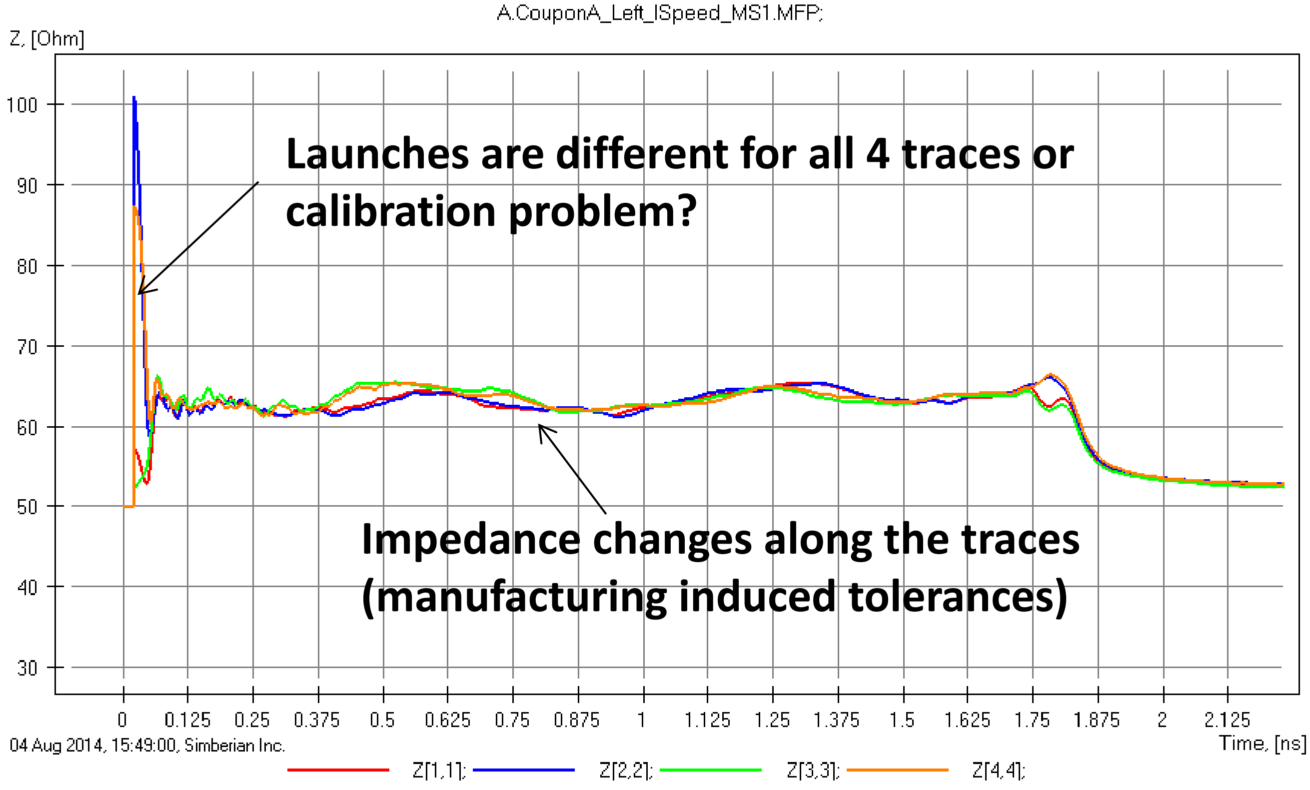
Computed from measured S-parameters for MS1 (worst case)



Analysis with Balanced strips produce practically the same eye (no visible difference); Why simulated and measured eyes are slightly different? – see next slide…

Why eyes are slightly different?

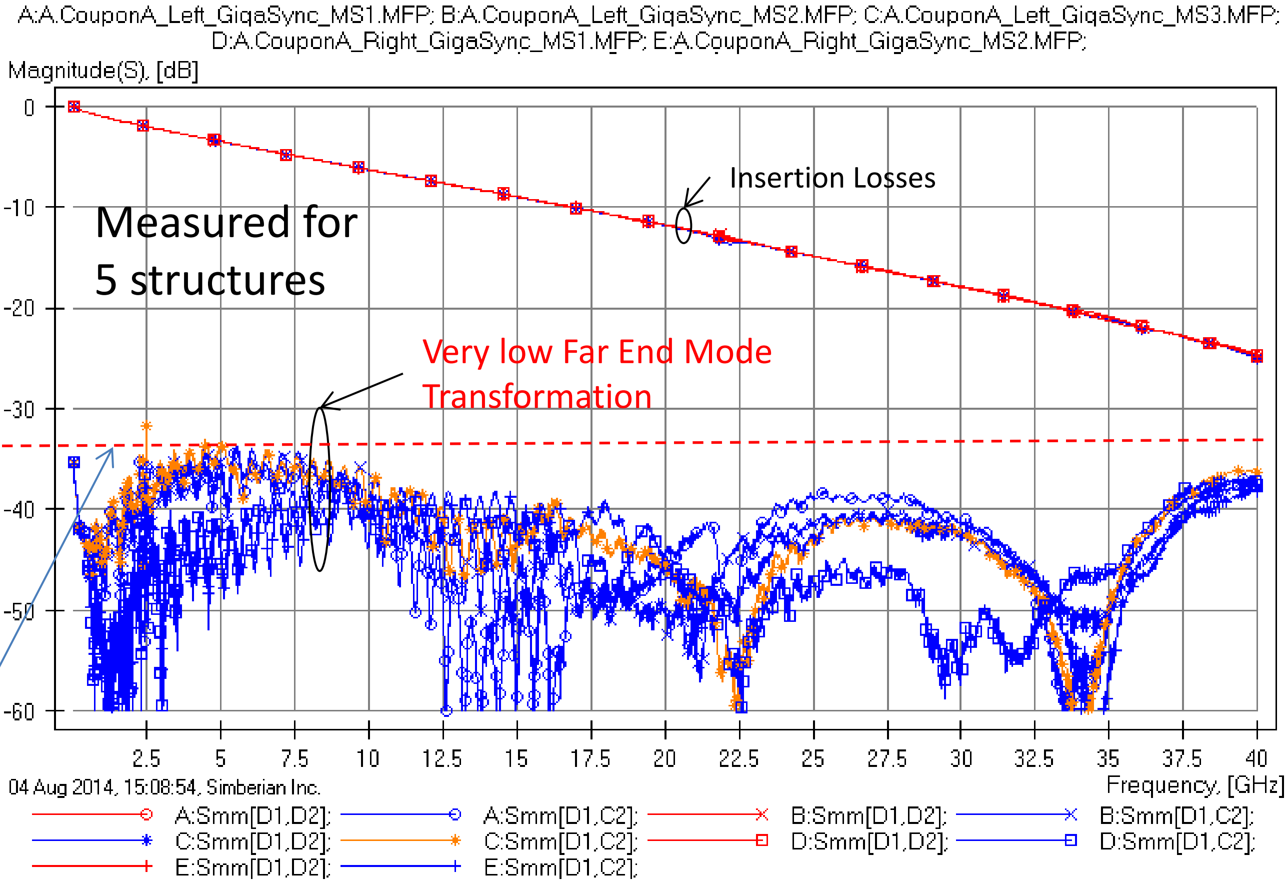
- **6-in links on I-SPEED/3313; single-ended TDR computed from <u>measured S-parameters</u> with Gaussian step 16 ps rise time**



These effects are more considerable than investigated imbalance of 0.05?

S-parameters, tightly coupled traces

- **6-in links on GigaSync/2116:**



Practically no imbalance – no need to simulate ☺

Skew is nearly undetectable for this material

Far end mode transformation parameter (differential at port 1 to common at port 2) now below -35dB, producing nearly undetectable skew

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Conclusion: Fiber-Weave Effect (FWE) modelling

- **New causal non-uniform imbalanced transmission line model for prediction of FWE on signal propagation in PCB interconnects has been introduced**
  - Imbalance Factor is used for inhomogeneity across traces
  - Modulation Factor is used for inhomogeneity along traces
  - Both factors are applied either to DK at infinity for simple dispersive models or to volume fraction in two dielectric mixture formulas
- **Model parameters can be identified with either worst case skew or worst case far end mode transformation (diff. to common)**
- **Usability of the models are illustrated with examples of practical investigation of corner cases for I-SPEED and GigaSync dielectrics (www.isola-group.com/products)**
- **Proposed models are implemented in Simbeor software (www.simberian.com)**

Conclusion: Fiber-Weave Effect (FWE) and Jitter

- **FWE impact on jitter and eye height for a 25 Gbps signal were evaluated:**
  - Numerical experiments conducted for loosely coupled pairs
  - Numerical and experimental investigations for tightly coupled pairs
- **Significant effect of imbalance on jitter for loosely coupled microstrip pairs has been observed**
- **Little effect of periodicity observed on jitter for loosely coupled pairs is observed**
- **No significant effect of imbalance on tightly coupled microstrip traces**
- **Consistent tightly-coupled traces are not easily achieved in practice, so design considerations revert to loosely coupled case**

Isola Low-Skew Product Solutions

Tachyon® 100G

Ultra Low Loss, Leadfree Laminates and Prepregs
for
HSD Applications

Tachyon® 100G Value Proposition

- Engineered To Improve Insertion Loss on the Most Demanding High Speed Digital Designs
- Tachyon-100G is recommended For 40+ Gb/s Backplane and Line Cards
- Constructions have been Optimized to Improve CAF and Lead-free Assembly Performance
- Complete Line of Laminates And Prepregs With Spread Glass Weaves To Minimize Micro-Dk Effects Of Glass Fabrics And to Mitigate Skew
- HDI Design Friendly
- Can be Used in Hybrid Builds as Prepregs and Laminates Because of the Low Cure Lamination Cycle

Chronon®

Next Generation Low Loss, Low Skew & Leadfree Laminates and Prepregs for HSD Applications

Chronon Value Proposition

- Engineered To Eliminate Skew Issues In Differential Pairs On High Data Rate Designs
- Targeted For 40+ Gb/s Designs (Backplanes And Line Cards) That Require More Bandwidth
- Optimized Constructions To Improve Lead-free Assembly Performance
- Offer Laminates And Prepregs With Engineered Glass Weaves To Minimize Micro-Dk Effects Of Glass Fabrics And to Mitigate Skew
- Eliminates the Need To Rotate Circuitry on The Laminates
- UL Approved In Same Family As I-Tera®MT and Chronon® Simplifying UL Recognition Process PCB Fabricators

High-Speed Digital Products
Lee Ritchey SI TV

Speeding Edge Signal Integrity Test Vehicles

Courtesy of Speeding Edge

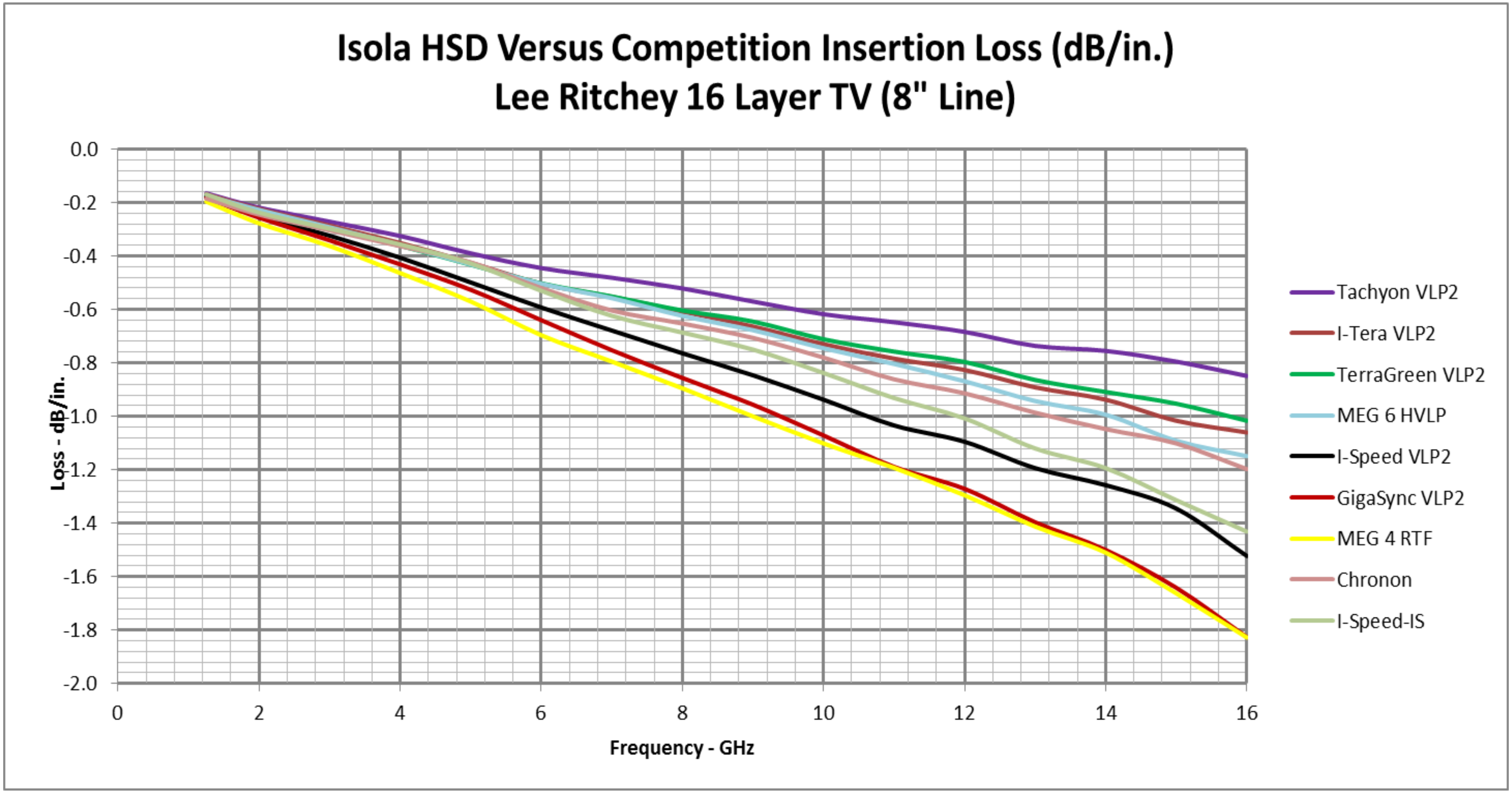
16 Layer SI TV Stackup

Layer #	Material Type	Material Construction	**Copper Type S = RTF, X = HVLP**	Material Pressed Er (at ~2 GHz)	Material Unpressed Thickness (mils)	Material Pressed Thickness (mils)	Picture	Copper Thickness (mils)	Copper Thickness (oz)
						0.7	Solder Mask		
1							1	2.2	1.5
	Prepreg	1 x 3313 RC = 57%		3.68	4.3	4.1	Prepreg		
2			**X**				2	0.6	0.5
	Core	1 x 3313 RC = 55%	core	3.72		4	Core		
3			**X**				3	0.6	0.5
	Prepreg	2 x 3313 RC = 57%		3.68	8.6	8.3	Prepreg		
4			**X**				4	0.6	0.5
	Core	1 x 3313 RC = 55%	core	3.72		4	Core		
5			**X**				5	0.6	0.5
	Prepreg	2 x 3313 RC = 57%		3.68	8.6	8.3	Prepreg		
6			**X**				6	0.6	0.5
	Core	1 x 3313 RC = 55%	core	3.72		4	Core		
7			**X**				7	0.6	0.5
	Prepreg	2 x 3313 RC = 57%		3.68	8.6	8.3	Prepreg		
8			**X**				8	0.6	0.5
	Core	3 x 1652 RC = 50%	core	3.82		18	Core		
9			**X**				9	0.6	0.5
	Prepreg	2 x 3313 RC = 57%		3.68	8.6	8.3	Prepreg		
10			**X**				10	0.6	0.5
	Core	1 x 3313 RC = 55%	core	3.72		4	Core		
11			**X**				11	0.6	0.5
	Prepreg	2 x 3313 RC = 57%		3.68	8.6	8.3	Prepreg		
12			**X**				12	0.6	0.5
	Core	1 x 3313 RC = 55%	core	3.72		4	Core		
13			**X**				13	0.6	0.5
	Prepreg	2 x 3313 RC = 57%		3.68	8.6	8.3	Prepreg		
14			**X**				14	0.6	0.5
	Core	1 x 3313 RC = 55%	core	3.72		4	Core		
15			**X**				15	0.6	0.5
	Prepreg	1 x 3313 RC = 57%		3.68	4.3	4..1	Prepreg		
16							16	2.2	1.5
						0.7	Solder Mask		
						--------		--------	
						97.3	110.1	12.8	
						Material Thickness	Total Thickness	Copper Thickness	

Signal Integrity Test Vehicle Highlights

- **Differential Pair lengths from 15” to 60” with a backplane and daughter card configuration**
- **Reverse Treat Copper (RTF) and VLP-2 Copper used in the same board**
- **Measurement Opportunities**
  - Differential skew
  - Loss tangent
  - Dielectric constant
  - Effect of copper roughness on overall loss
- **Amphenol Exceed connectors used**
- **Any combination of boards/different laminate material can be plugged together to represent classic backplane daughter card configuration**

S-Parameter Product Comparisons



Courtesy of Speeding Edge

Insertion Loss Data

GHz	Tachyon (VLP2)	Teragreen (VLP2)	I-Tera (VLP2)	Meg6 (HVLP)	Chronon (VLP2)	I-Speed (VLP2)	Gigasync (VLP2)	Meg4 (RTF)
1.25	-0.165	-0.175	-0.169	-0.173	-0.185	-0.179	-0.183	-0.196
2.00	-0.219	-0.231	-0.224	-0.228	-0.245	-0.251	-0.256	-0.278
3.00	-0.271	-0.298	-0.286	-0.293	-0.304	-0.324	-0.341	-0.363
4.00	-0.325	-0.361	-0.351	-0.359	-0.363	-0.406	-0.431	-0.464
5.00	-0.390	-0.433	-0.425	-0.431	-0.424	-0.499	-0.526	-0.570
6.00	-0.445	-0.503	-0.504	-0.504	-0.520	-0.593	-0.640	-0.696
7.00	-0.481	-0.551	-0.553	-0.558	-0.604	-0.679	-0.753	-0.795
8.00	-0.521	-0.604	-0.608	-0.624	-0.653	-0.764	-0.856	-0.895
9.00	-0.570	-0.645	-0.664	-0.678	-0.706	-0.846	-0.956	-1.000
10.00	-0.618	-0.711	-0.730	-0.745	-0.780	-0.938	-1.071	-1.101
11.00	-0.648	-0.758	-0.784	-0.804	-0.861	-1.034	-1.189	-1.193
12.00	-0.684	-0.796	-0.826	-0.869	-0.914	-1.095	-1.271	-1.295
13.00	-0.736	-0.864	-0.891	-0.943	-0.986	-1.194	-1.396	-1.413
14.00	-0.755	-0.909	-0.938	-0.994	-1.048	-1.258	-1.500	-1.510
15.00	-0.795	-0.953	-1.016	-1.091	-1.101	-1.345	-1.641	-1.663
16.00	-0.849	-1.016	-1.060	-1.149	-1.198	-1.523	-1.826	-1.828

Courtesy of Speeding Edge

Skew Data Product Comparison

	Vertical Skew on 9" Line (ps)			Horizontal Skew on 14" Line (ps)		
Products	**Minimum**	**Maximum**	**Average**	**Minimum**	**Maximum**	**Average**
IS415	0	8	5	30	123	88
I-SPEED	3	10	4.5	1	59	18
I-TERA IS	1	4	2.5	4	59	24.6
FR408HR	1	8	5	3	43	20
MEG 6	0	4	2	2	37	13
MEG 4	1	2	1	4	28	13
I-TERA #2	0	1	2	0	23	8
FR408HR IS	0	7	4.6	6	20	11.8
I-TERA #1	1	12	6	1	13	9.5
I-SPEED IS	1	4	1.3	5	12	7.5
I-SPEED #2	2	4.5	2.8	0	11	3.7
TerraGreen	0	5	3	2	9	5
I-SPEED IS #2	0	3	0.9	0	8.5	3.1
Tachyon	2	4	3	1	8	4
Chronon	**0**	**2**	**1**	**1**	**5**	**3**
GigaSync #1	0	4	1	0	4	2
GigaSync #2	0	2	1	0	3	2

Courtesy of Speeding Edge

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Conclusions

- **Isola has two high performance product offerings for skew mitigation**
  - Tachyon
  - Chronon
- **Products offer process compatibility with Isola low-cost materials in hybrid constructions**
- **Availability is immediate and materials have been sampled and thoroughly tested**
  - Alcatel MRT5
  - Cisco SI TV

References

Y. Shlepnev, C.Nwachukwu, “Modelling Skew and Jitter induced by Fiber weave effect in PCB dielectrics”, IEEE International Symposium on Electromagnetic Compatibility, Raleigh, North Carolina, August 2014.

Thank You!