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Modelling Skew and Jitter induced by Fiber weave effect in PCB dielectrics

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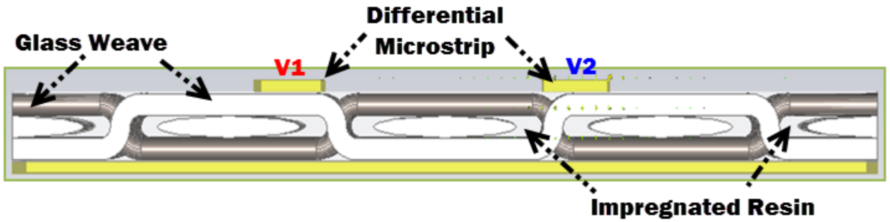
Outline

- 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

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 with typically 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 t-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 proposed in this paper**

See overview of publications on the subject in the paper…

Model for non-uniform dielectric across traces

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

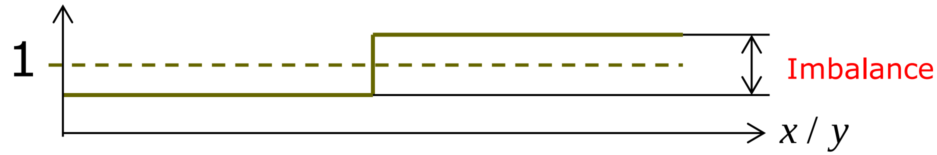
Unit Imbalance Factor corresponds to volume average resin percentage defined for the given PCB material globally;

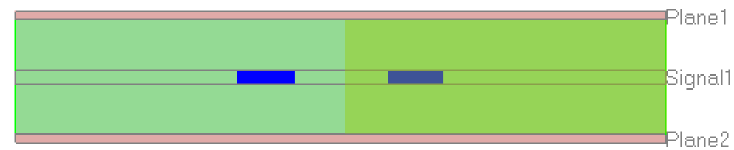
Variation upwards corresponds to higher volumetric content of glass (higher dielectric constant and smaller polarization losses);

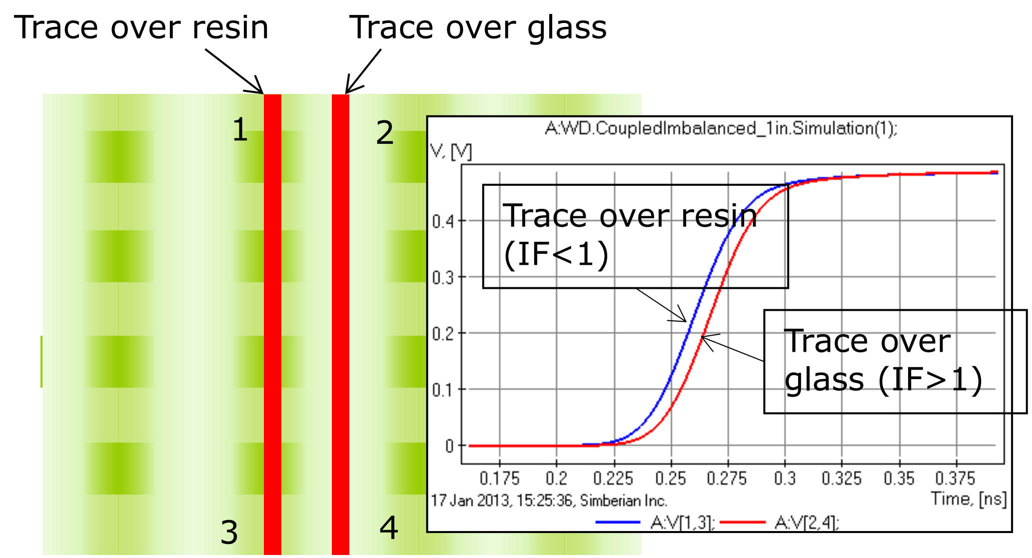
Variation downward corresponds to higher volumetric content of the resin (smaller dielectric constant and larger polarization losses);

Quasi-static field solver is used to build such model

Imbalance Factor = 1±0.5*Imbalance







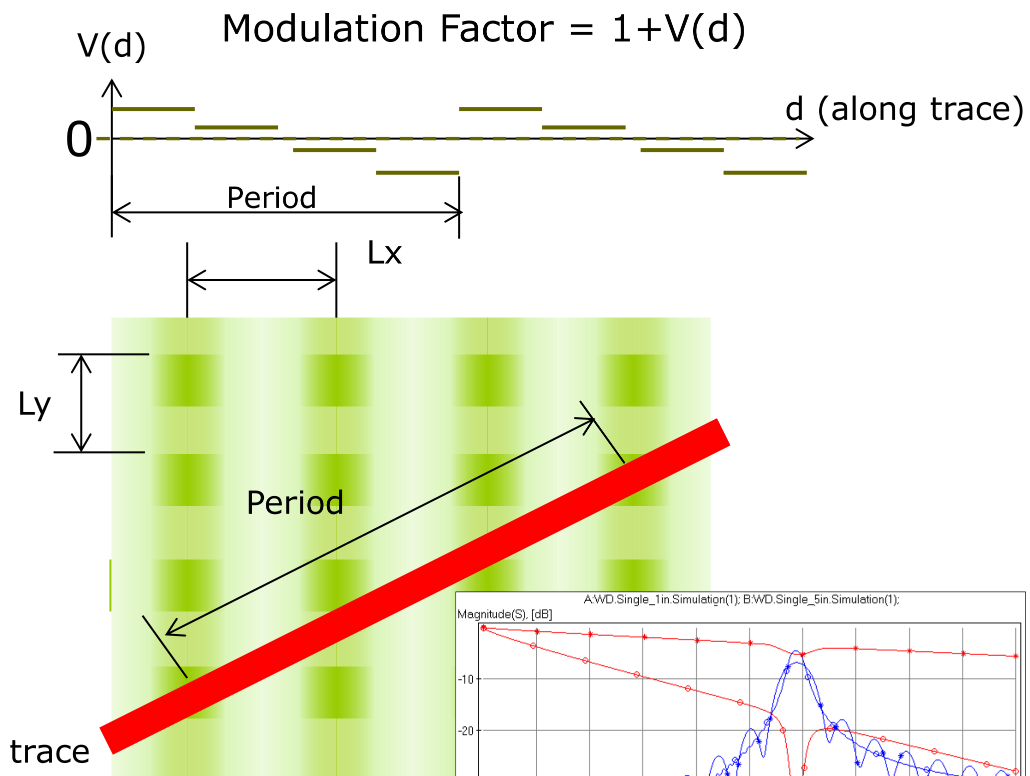
Model for non-uniform dielectric along traces

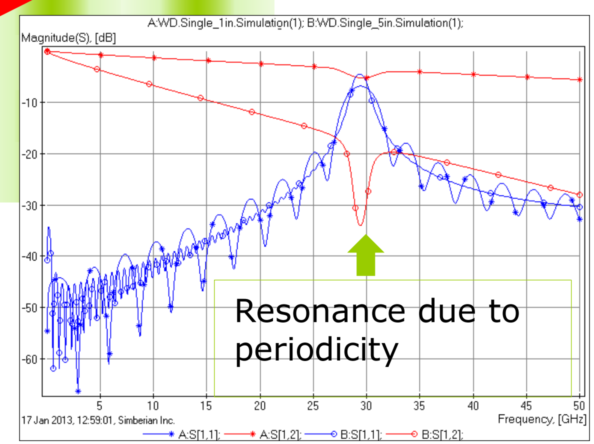
We use the **Modulation Factor** to characterize dielectric properties variation (specified either with step values as shown on the right or with periodic functions of length);

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

Causal model for dielectric with changing properties – Option 1

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

Multi-pole Debye model:

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

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

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

$\phi = 1$ 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 dielectric with changing properties – Option 2

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

Wiener upper boundary model (layered dielectric):

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

Wiener lower boundary model (comb-like dielectric):

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

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

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

$\phi = 1$ 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;

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

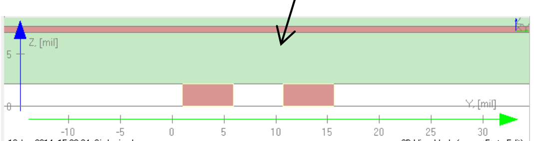
Test Board Stackup to investigate 2 materials from Isola

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**	

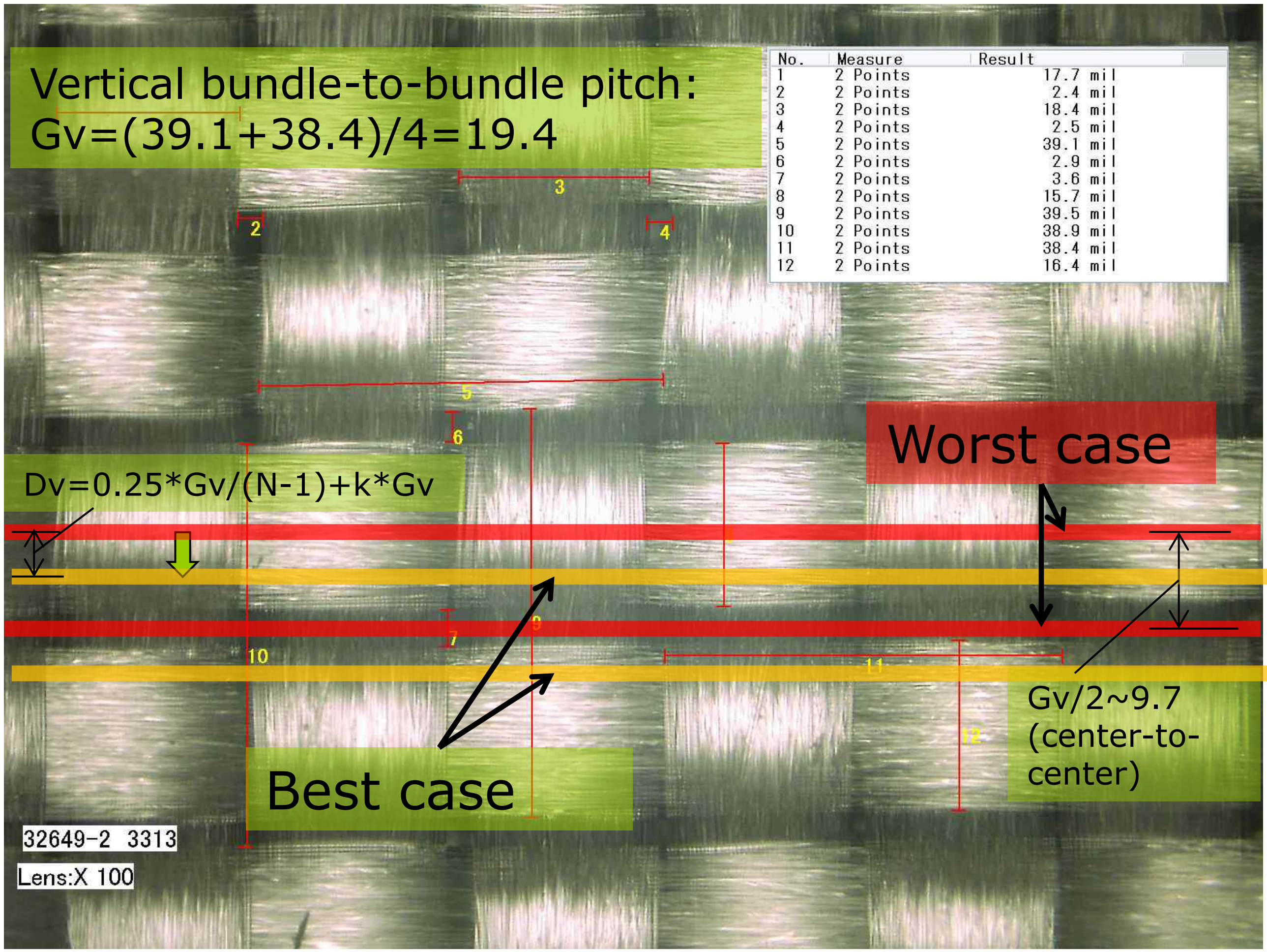
Gigasync: Wideband Debye model because of glass and resin have close DK

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;

Example of trace placement to identify worst case for 3313 glass (similar for 2116)



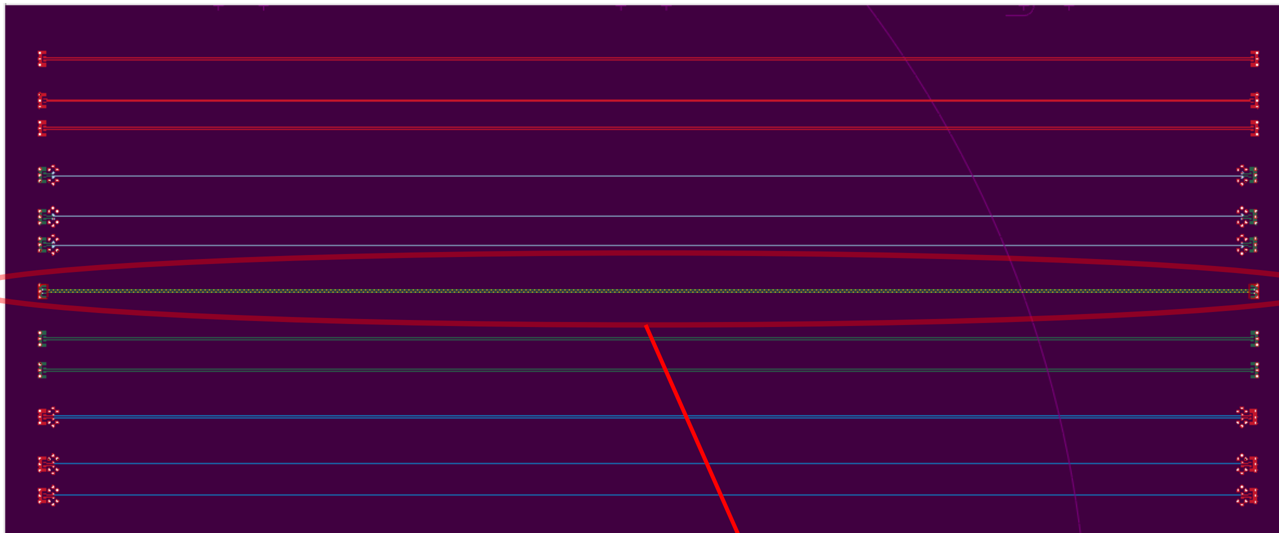
Gv=(39.1+38.4)/4=19.4
Center-to-center: Ds=9.7
Dv=0.25*Gv/(N-1)+k*Gv (offset)
5 samples with offset
Dv=1.2+k*19.4 mil

Tightly coupled pairs: trace width 4.9 mil, separation 4.8 (Kv=0.21, center to center 9.7 mil);

Loosely coupled pairs: trace width 9 mil, separation 39.5 mil (Kv=0.012, center to center 9.7+2*19.4 mil);

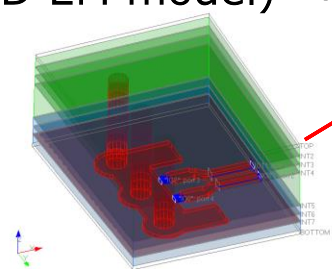
Kv is voltage coupling coefficient for quarter-wavelength line segment;

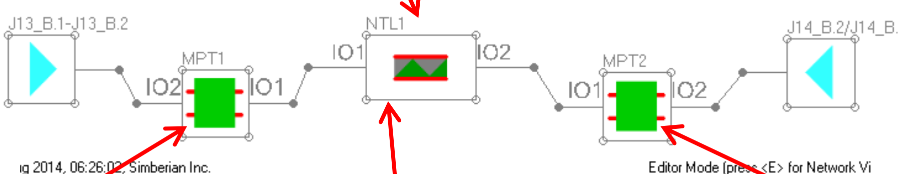
De-compositional model of a test structure



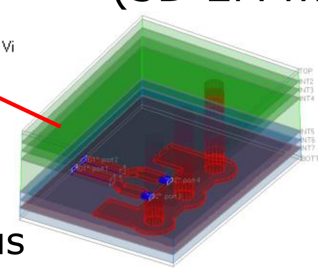
Simbeor 2013 software is used for all computations (pre and post-layout analysis with non-uniform t-lines)

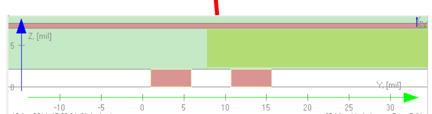
Probe launch (3D EM model)





Probe launch (3D EM model)





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

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

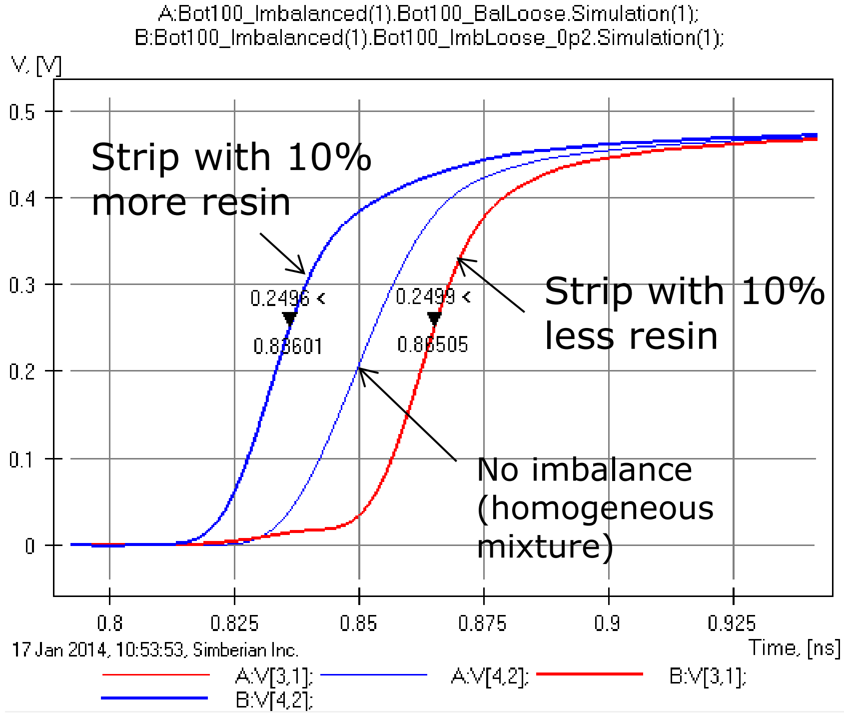
1. Use 5 ps/inch as the maximal possible skew due to FWE and adjust the **Imbalance Factor** for loosely coupled line to observe the same skew;
2. Estimate jitter due to skew in loosely coupled lines;
3. Define **Modulation Factor** along the line with the same amplitude as the imbalance and see effect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

Disclaimer: Board with loosely coupled traces is not measured yet. This is numerical example based on published data. No solder mask and no roughness.

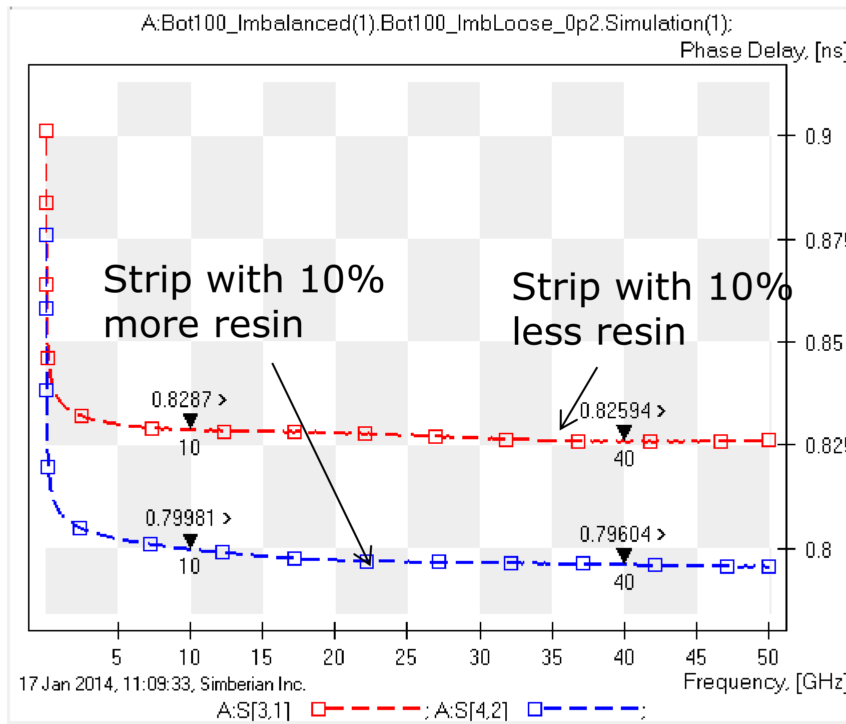
Identification of imbalance with the worst case skew

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



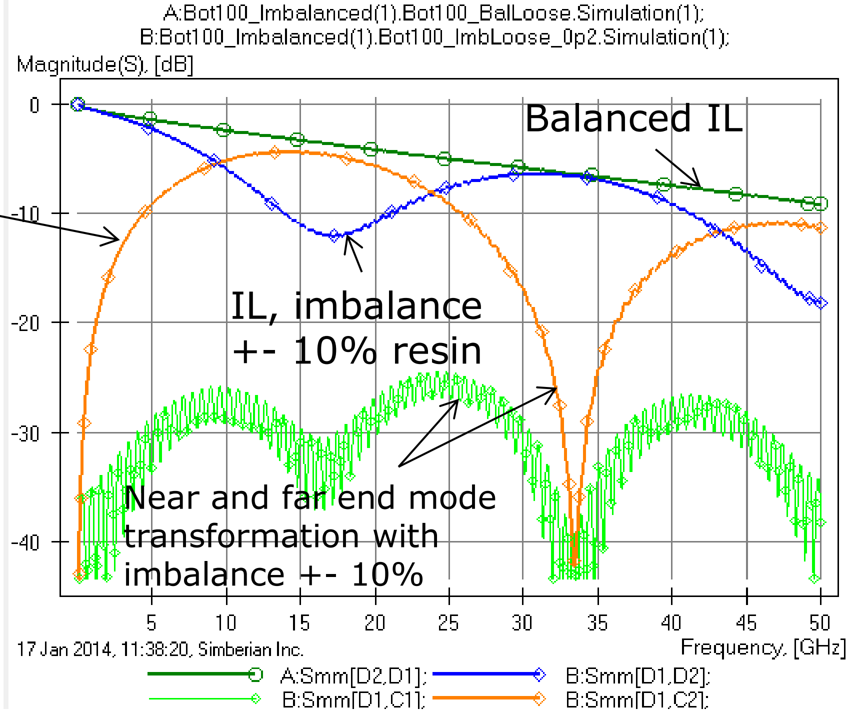
Single-ended transmission phase delay



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 with Imbalance 0.2 (+- 10% of resin);
Mode transformation also degrades differential insertion loss (IL);

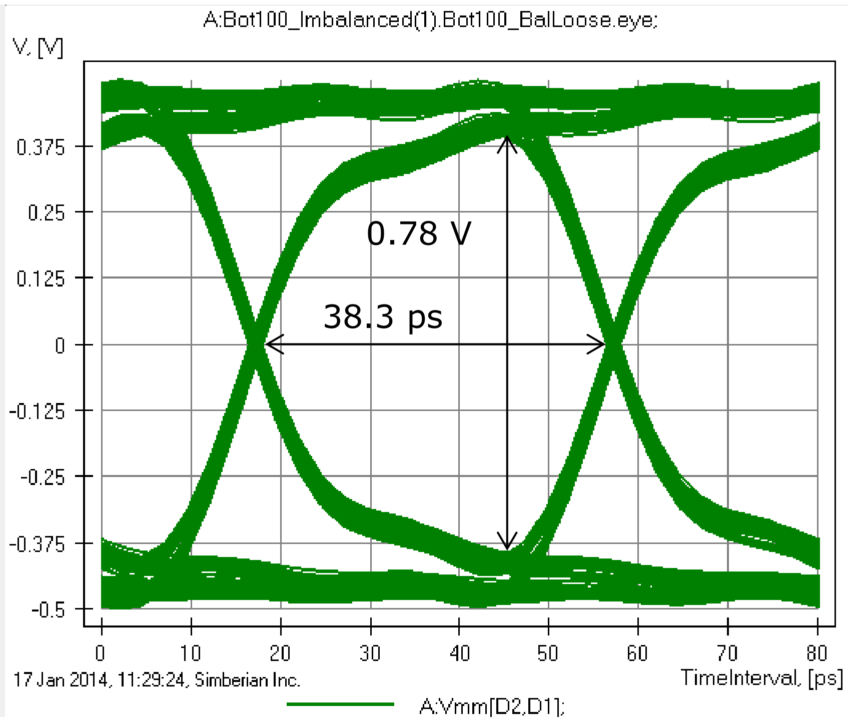
Optionally, far end mode transformation parameter can be used to evaluate the imbalance – it is zero for symmetric traces;

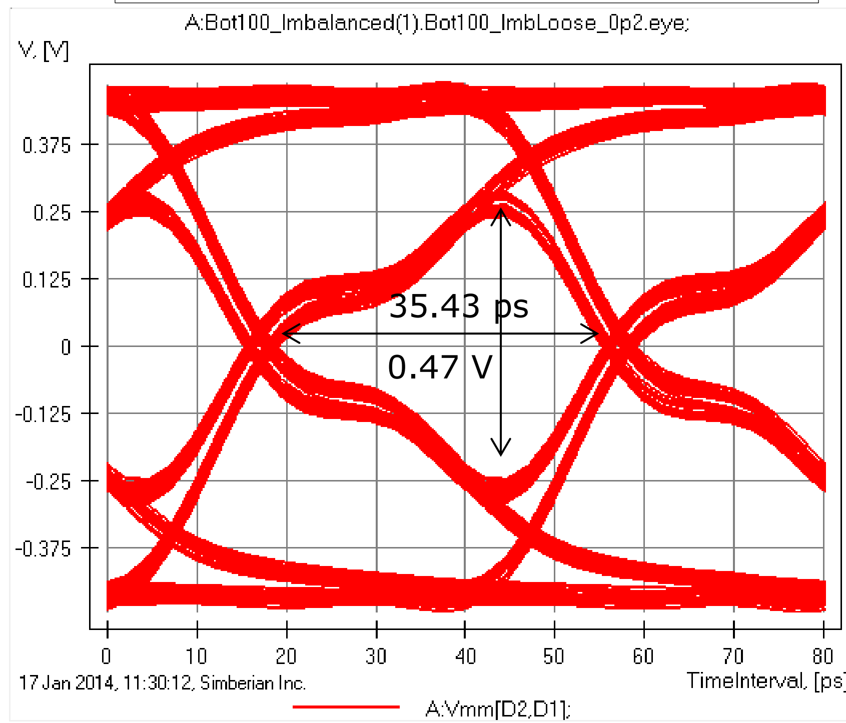


Impact of worst case skew on jitter (loosely coupled traces)

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

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



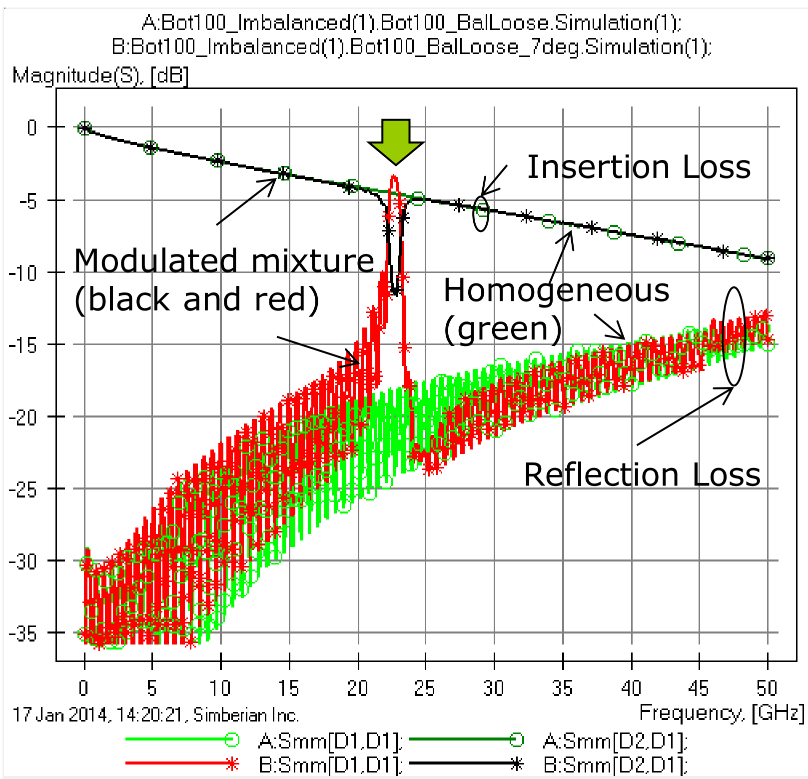


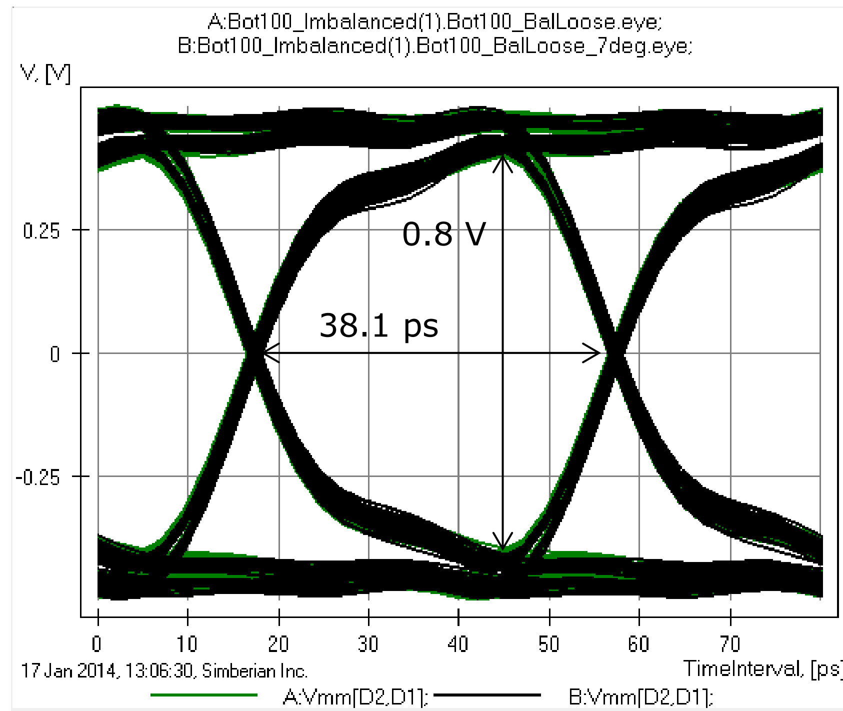
Substantial reduction of eye width (timing jitter) and eye height is expected

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)

Test board for tightly coupled traces

This board was manufactured, simulated and investigated experimentally

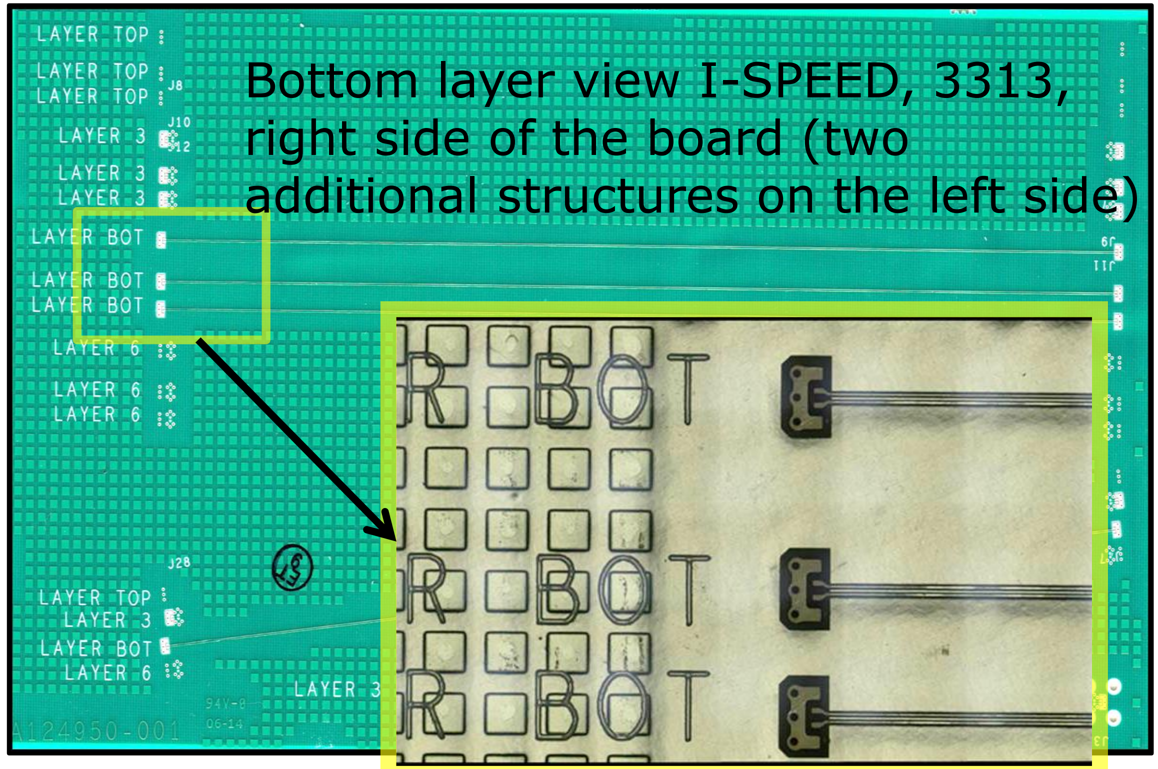
5 microstrip structures with offset for I-SPEED/3313 on the bottom side;

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**;

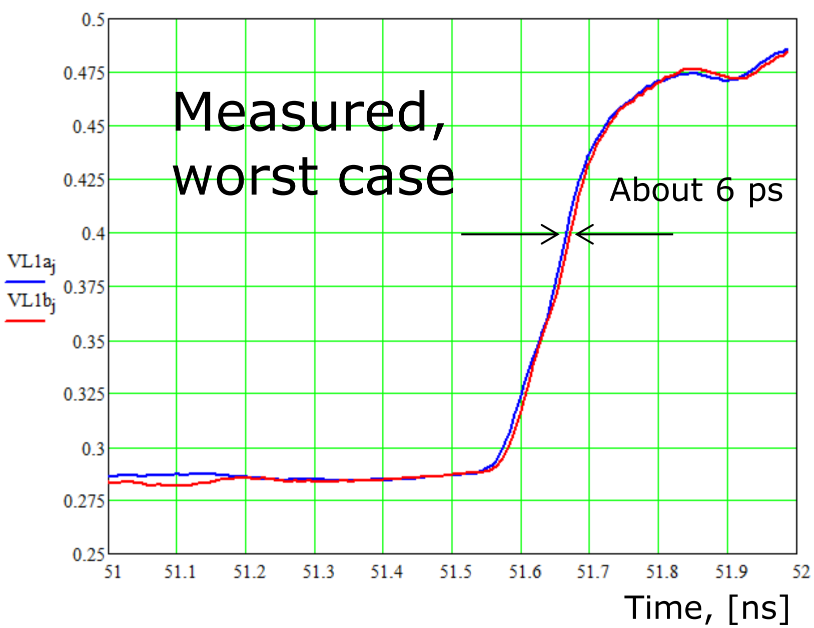
Analysis with **Simbeor software**;

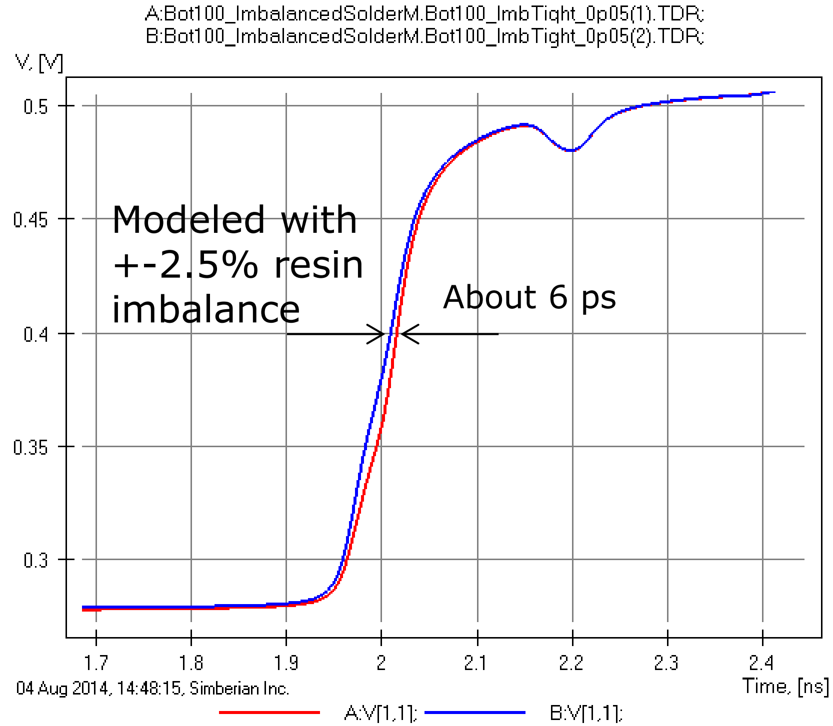


All simulations for tightly coupled traces are done with 2.2 mil conformal solder mask with DK=3.8, LT=0.01 at 1 GHz and conductor roughness (Modified Hammerstad model with SR=0.35 and RF=3.7)

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)

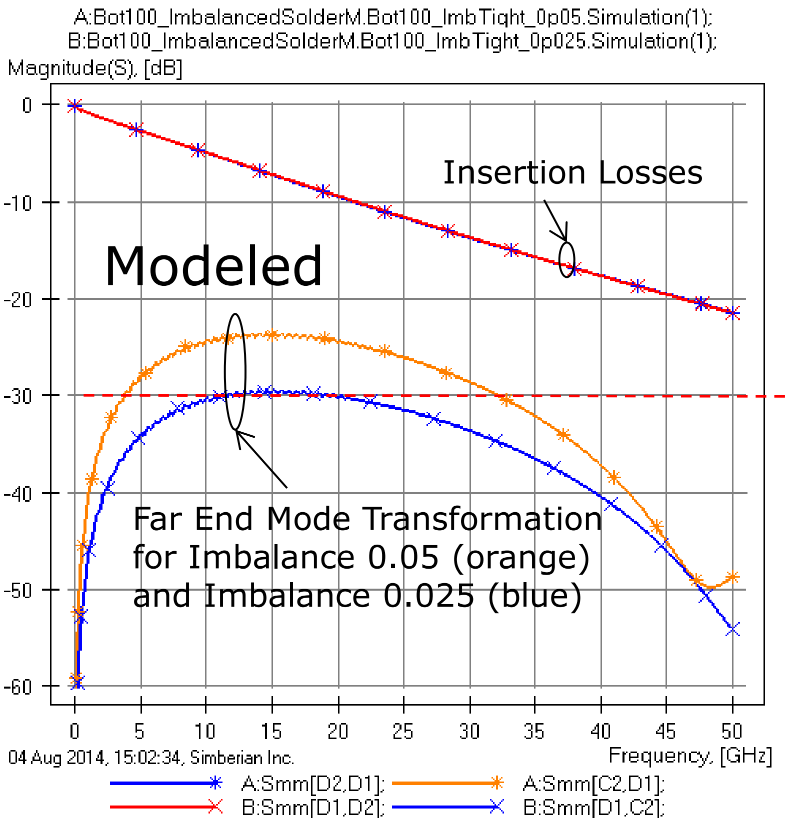


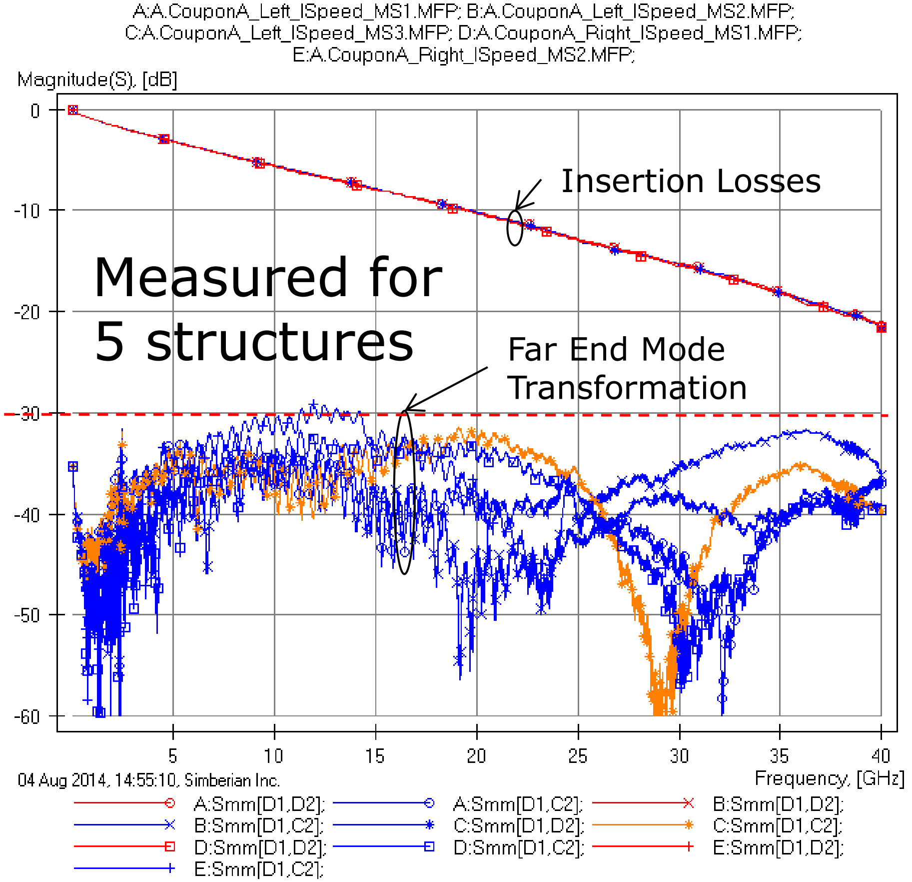


TDR measurements and simulation are done with all ports open;

S-parameters, tightly coupled traces

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



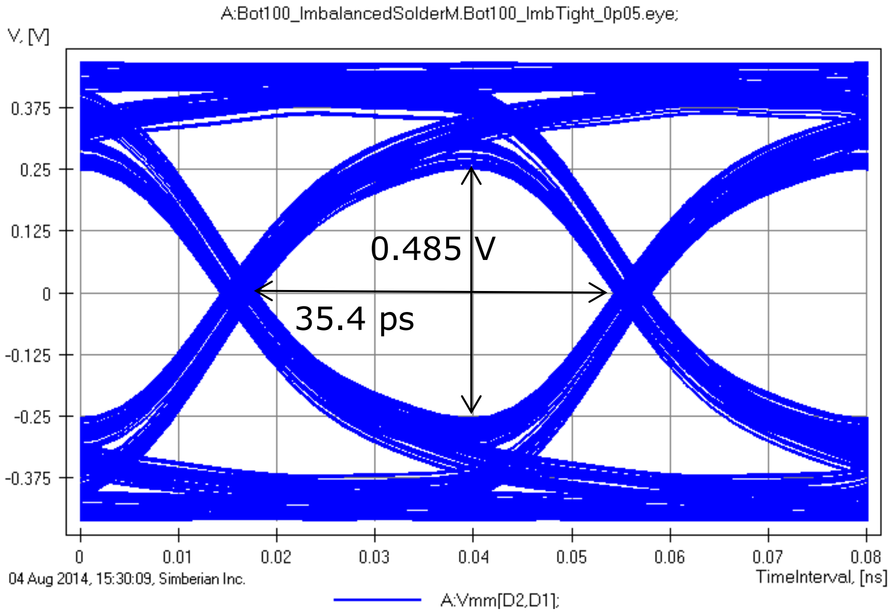


Mode transformation is smaller than expected from the TDR measurements – the imbalance is closer to 0.025

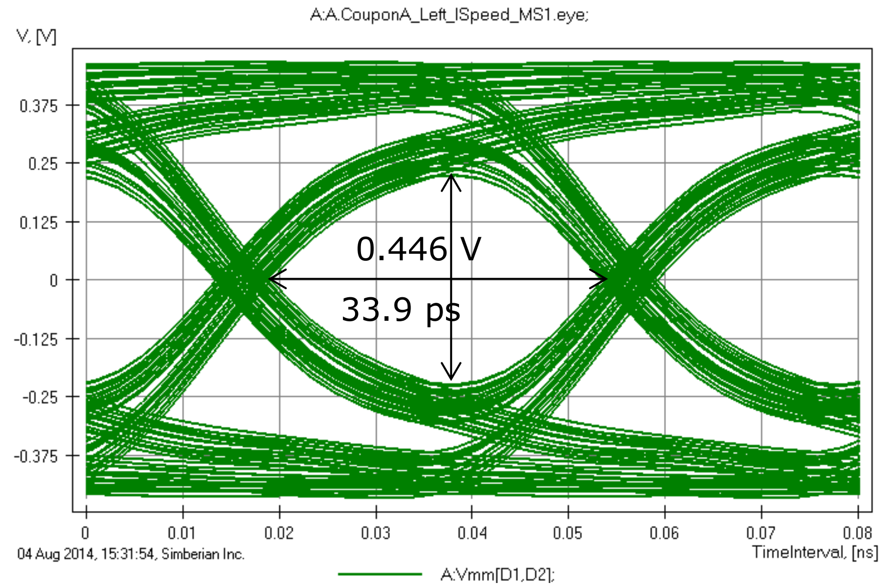
Imbalance impact on eye diagram

- 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)



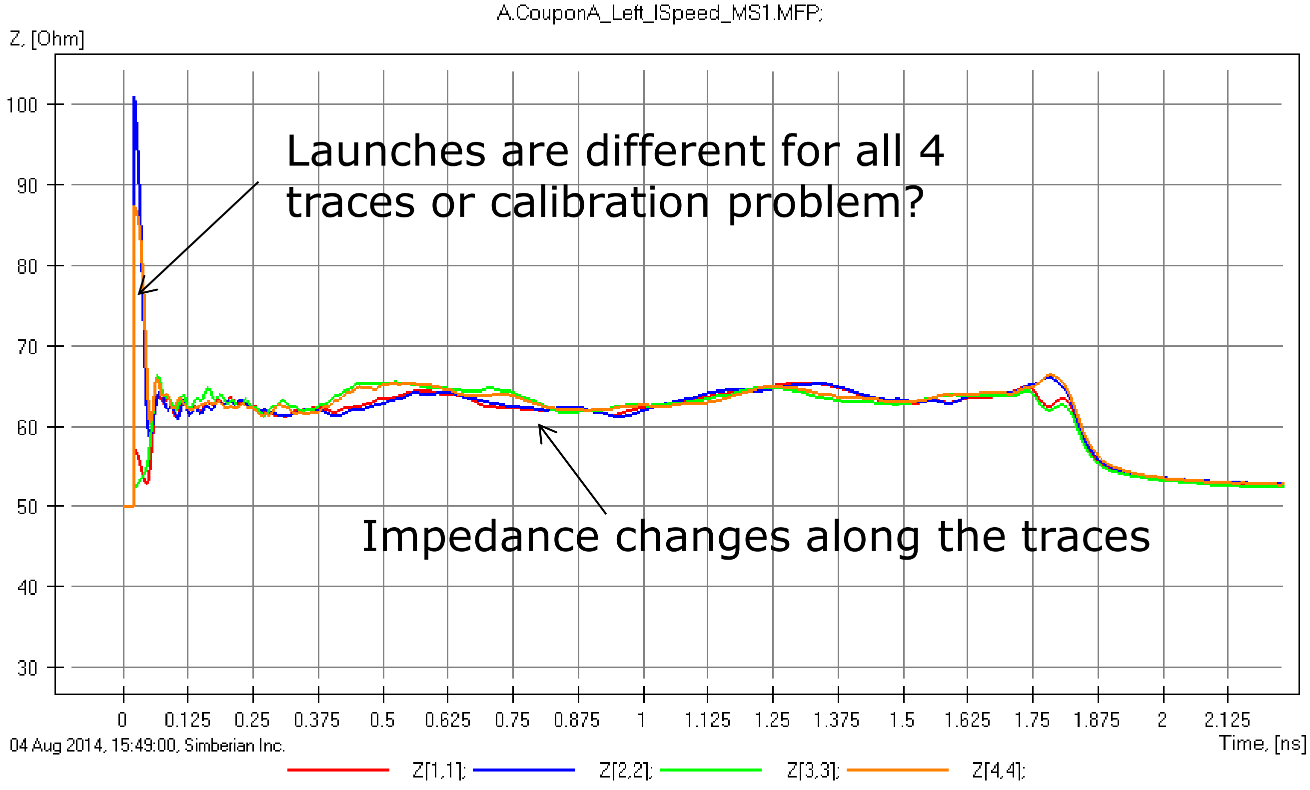
Computed from measured S-parameters for MS1 (worst case)



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 measured S-parameters with Gaussian step 16 ps rise time



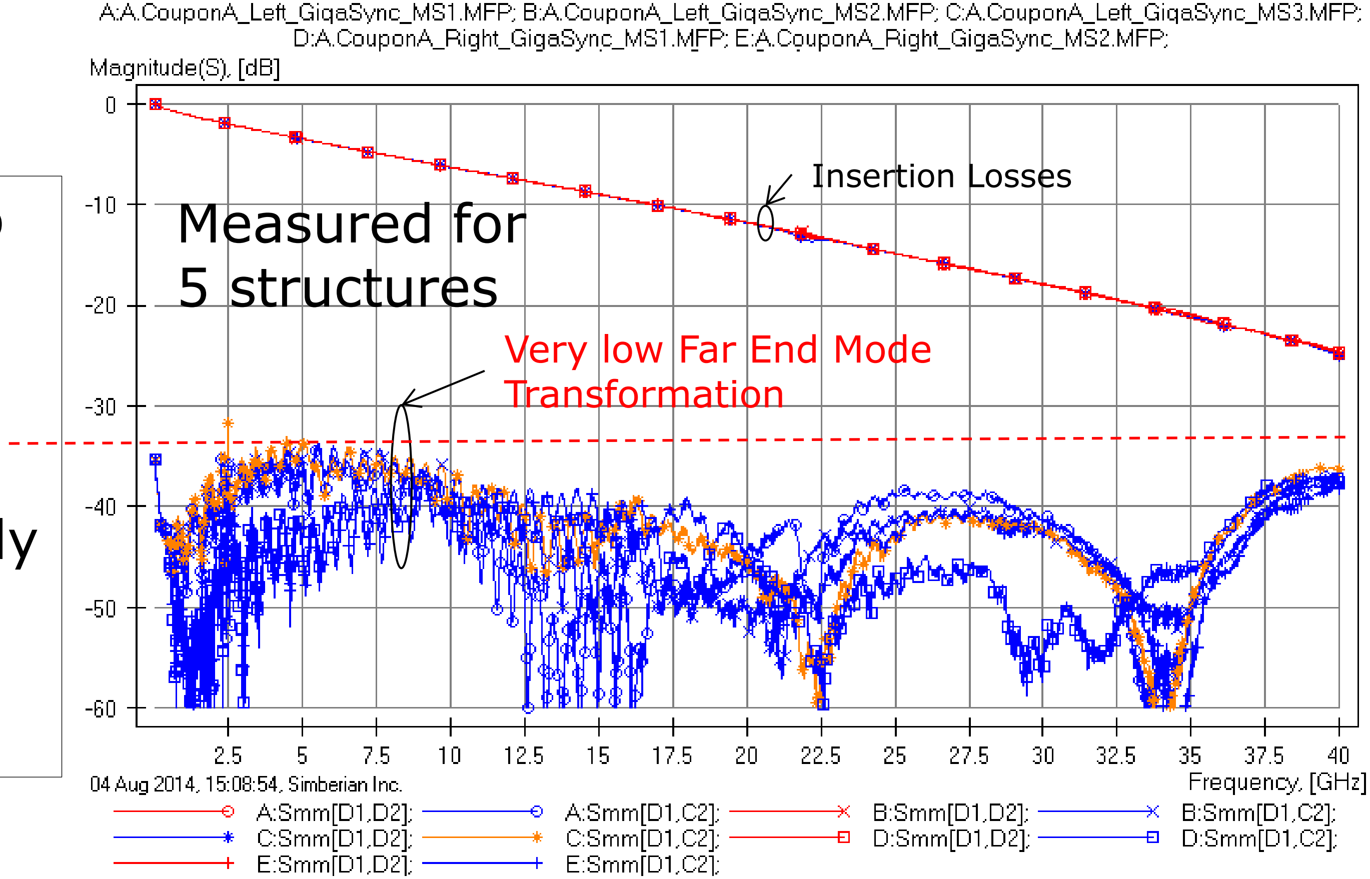
These effects are more considerable then investigated imbalance?

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



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
- Almost no effect of periodicity on jitter for loosely coupled pairs is observed
- No significant effect of imbalance on tightly coupled microstrip traces
  - Traces may be not exactly parallel to fiber weave on manufactured boards (will be verified further)
  - Solder mask and spread glass style may have greatly reduced the expected impact on skew and jitter for loosely coupled traces
- This is work in progress - stay tuned…