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

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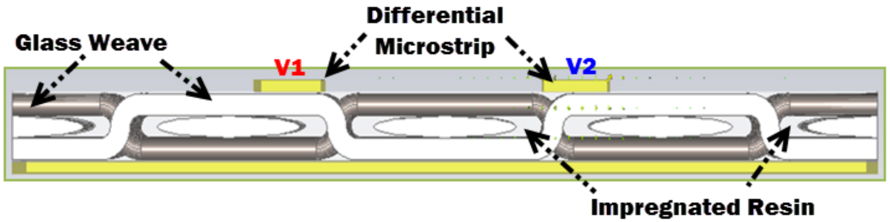
# Outline

- 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);

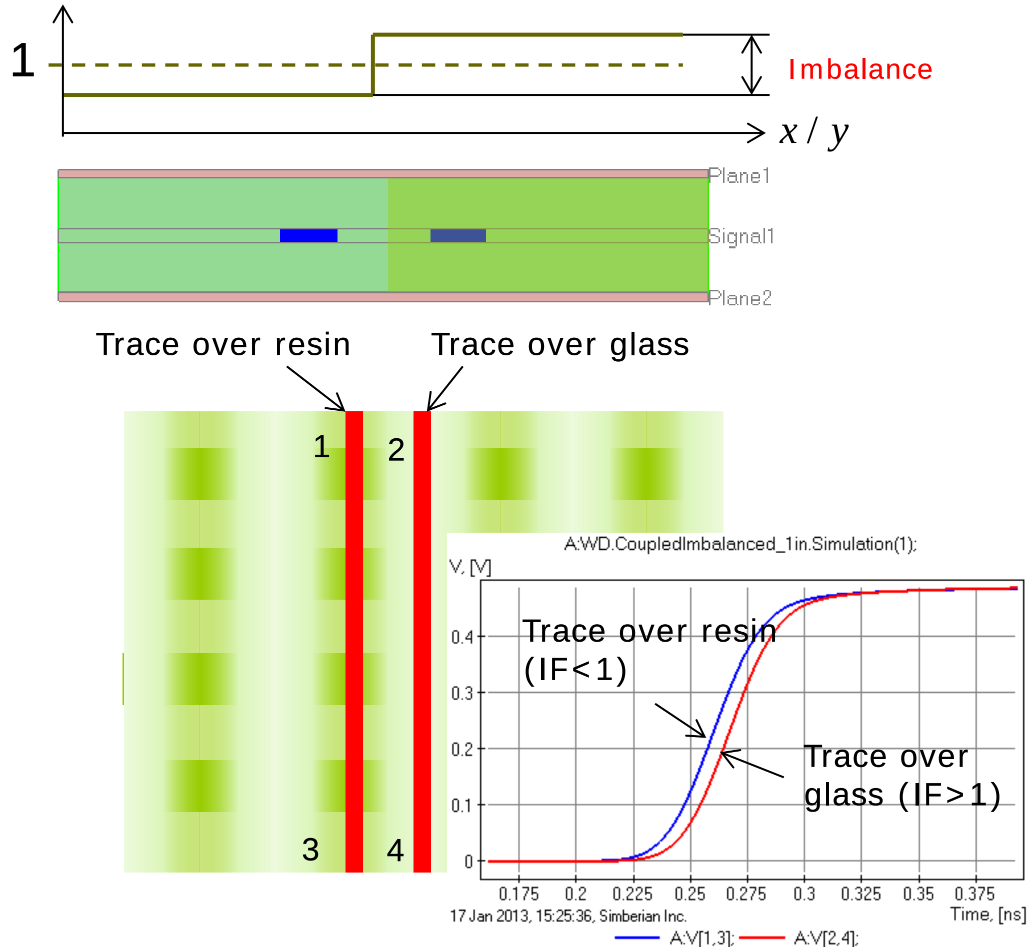
**Unit Imbalance Factor** corresponds to volume average resin percentage defined for the given PCB material globally;

**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);

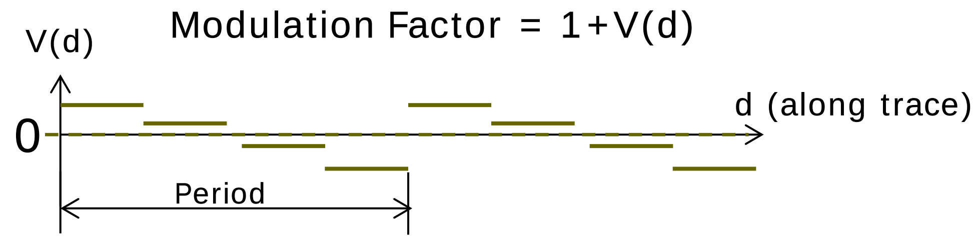
Quasi-static field solver is used to build such model

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;

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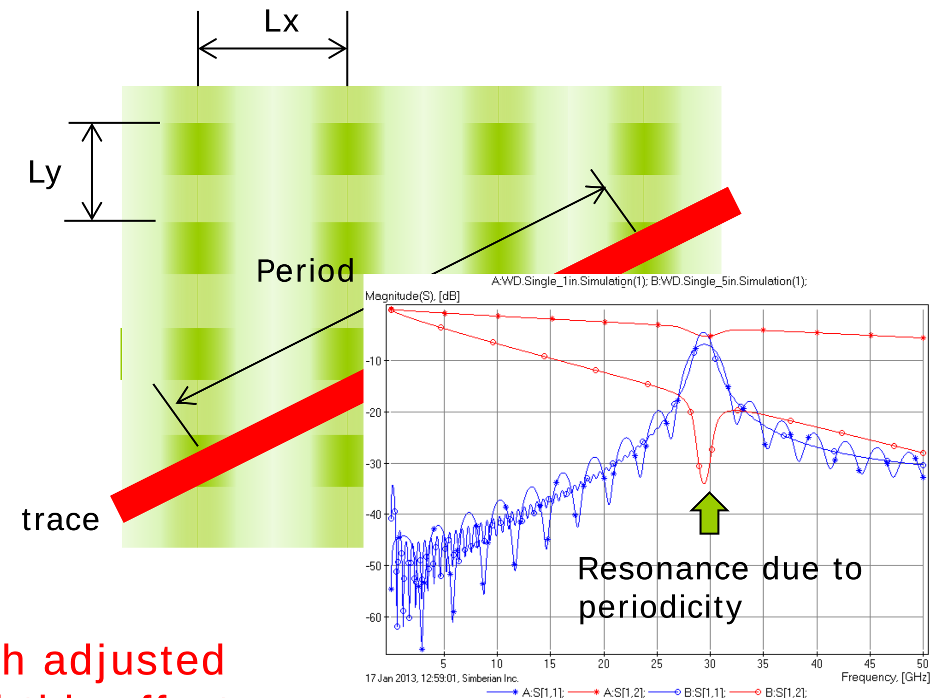
**Variation downward** corresponds to higher volumetric content of the resin (smaller dielectric constant and larger polarization losses);




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 ):

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

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

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

$\phi = 1$ 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;

Other causal models can be adjusted similarly

# 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):

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

Wiener lower boundary model (comb-like dielectric):

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

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*

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# Test board for numerical experiments and experimental validation

## Test Board Stackup to investigate 2 materials from Isola

Material : GigaSync/I-SPEED

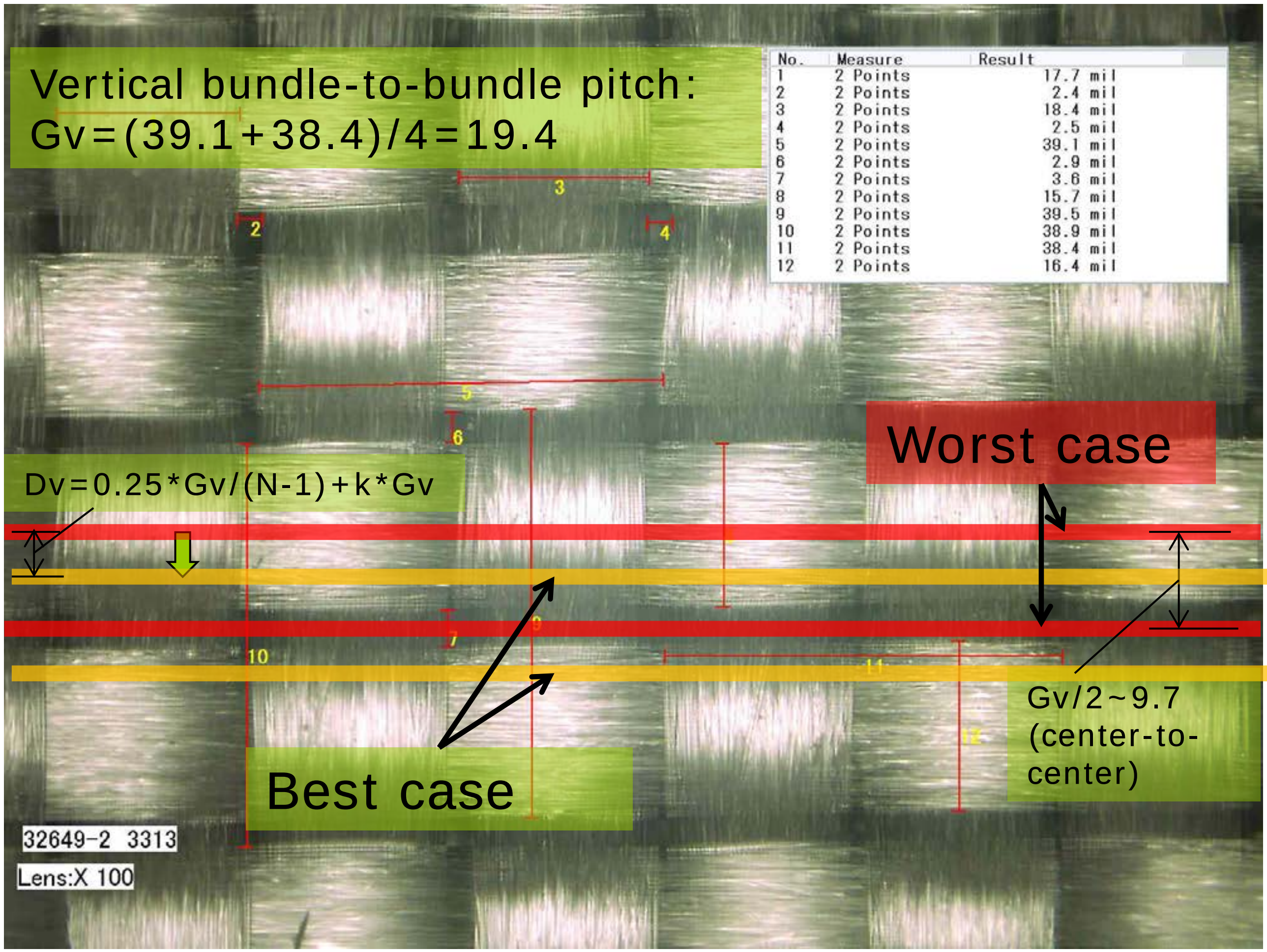
| LYR | Type | Structure (Stack up) | Cu weight (oz) | Construction | Thickness after lam (mil) | DK/DF |
|---|---|---|---|---|---|---|
| | ImAg Finish | | | | | |
| 1 | TOP | | 0.5 + plating | | 2.1 | |
| | prepreg | | | Gigasync 2116 - RC 60% | 5.0 | 4.13/.0067 |
| 2 | GND | | 0.5 | | 0.6 | |
| | core | | | 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)



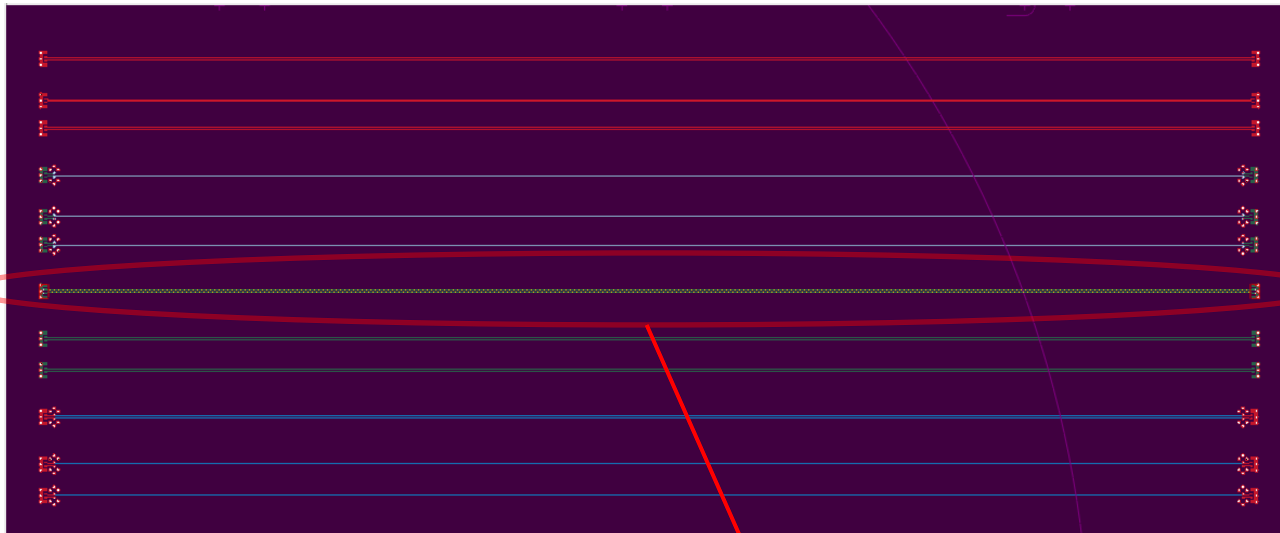

Gv=(39.1+38.4)/4=19.4
Center-to-center: Ds=9.7
Dv=0.25*Gv/(N-1)+k*Gv (offset)
**5 samples with offset**
**Dv=1.2+k*19.4 mil**

**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);

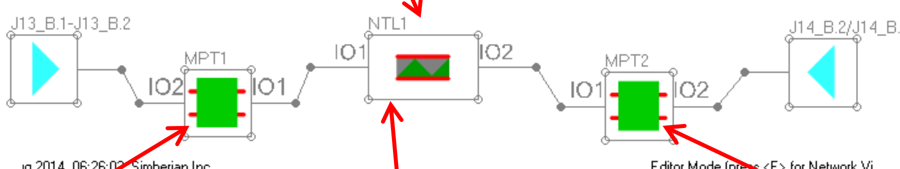
Kv is voltage coupling coefficient for quarter-wavelength line segment;

# De-compositional model of a test structure

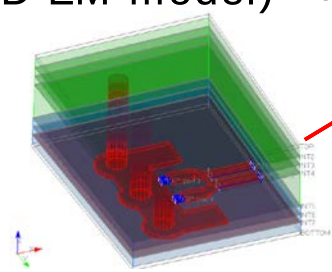


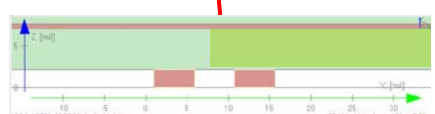
Simbeor 2013 software is used for all computations (pre and post-layout analysis with non-uniform t-lines)

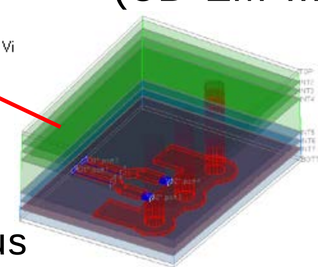
Probe launch (3D EM model)




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**

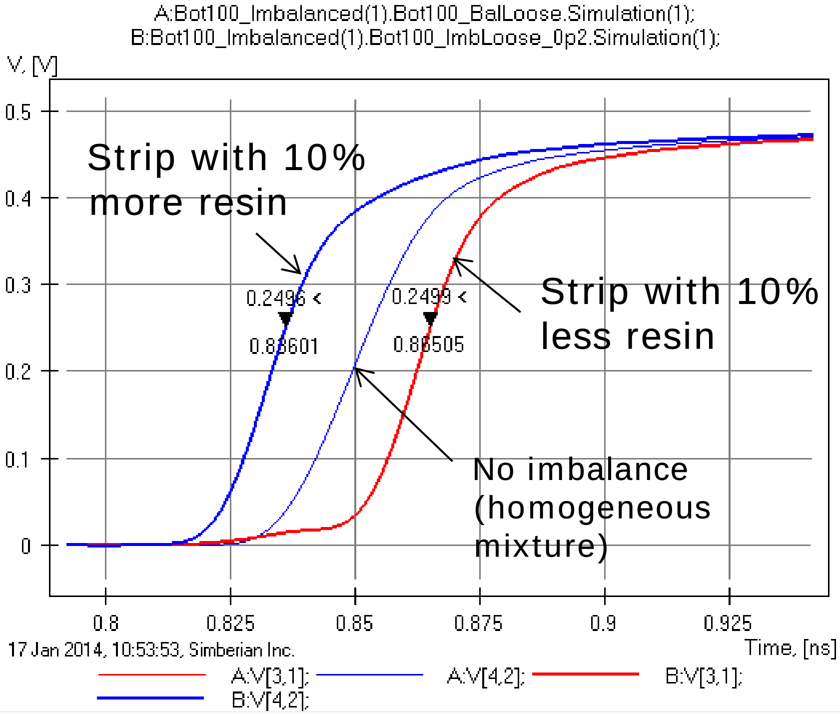
1. Use 5 ps/inch as the maximal possible skew due to FWE and adjust the **Imbalance Factor** for loosely coupled line to observe the same skew;
2. Estimate jitter due to skew in loosely coupled lines;
3. Define **Modulation Factor** along the line with the same amplitude as the imbalance and see effect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

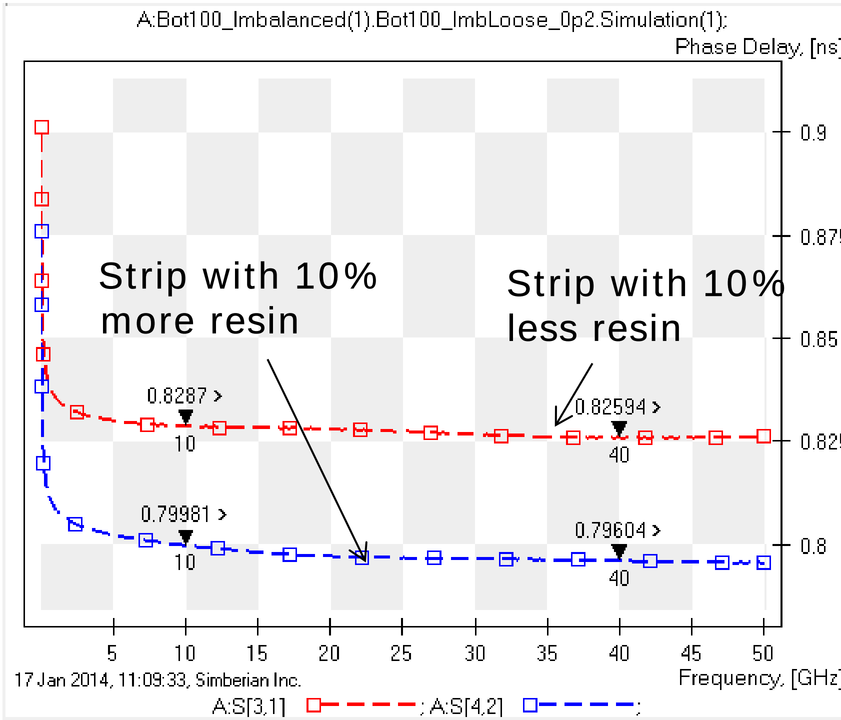
# Identification of imbalance with the worst case skew

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



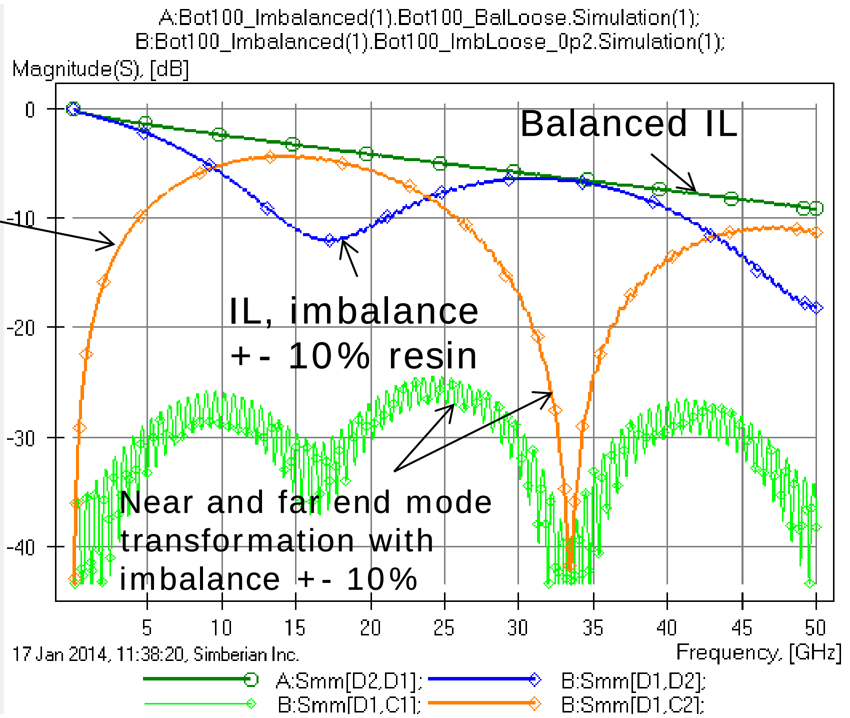

Single-ended transmission phase delay



# 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);

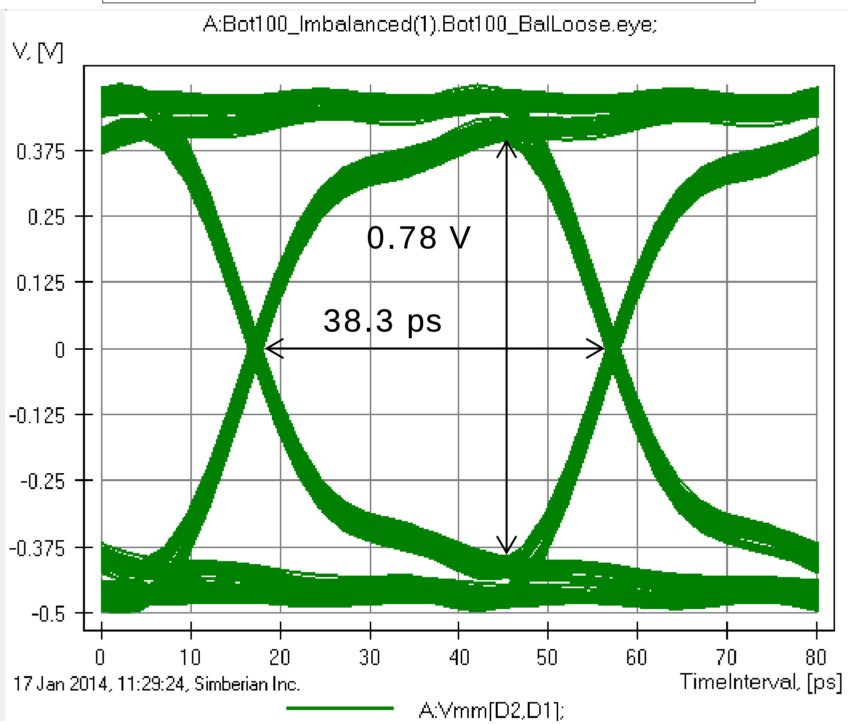
Optionally, far end mode transformation parameter can be used to evaluate the imbalance – it is zero for symmetric traces;



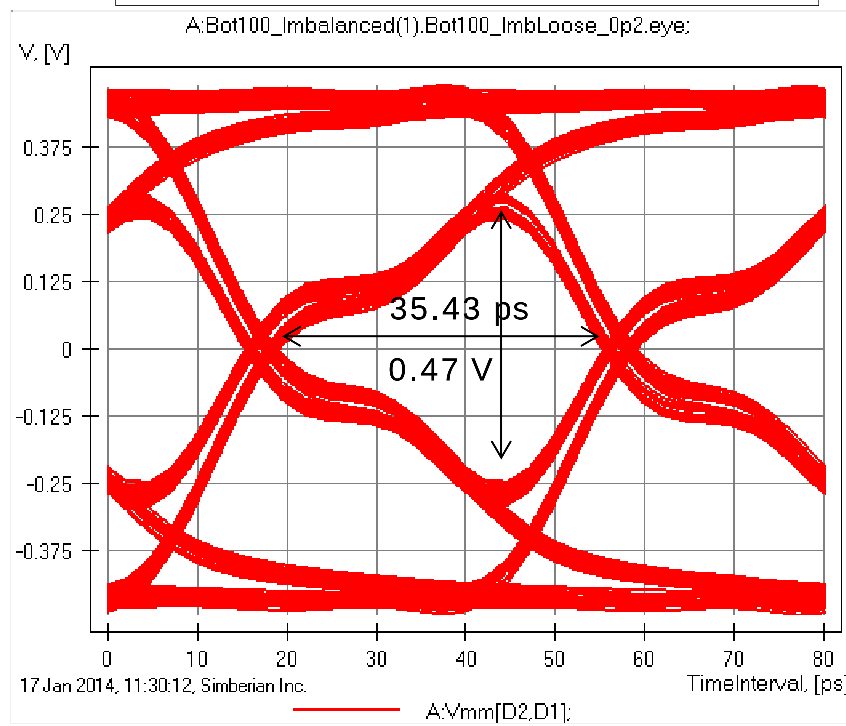
# Impact of worst case skew on jitter (loosely coupled traces)

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

No Imbalance
(homogeneous mixture)




Imbalance = 0.2
(+/- 10% of resin content)

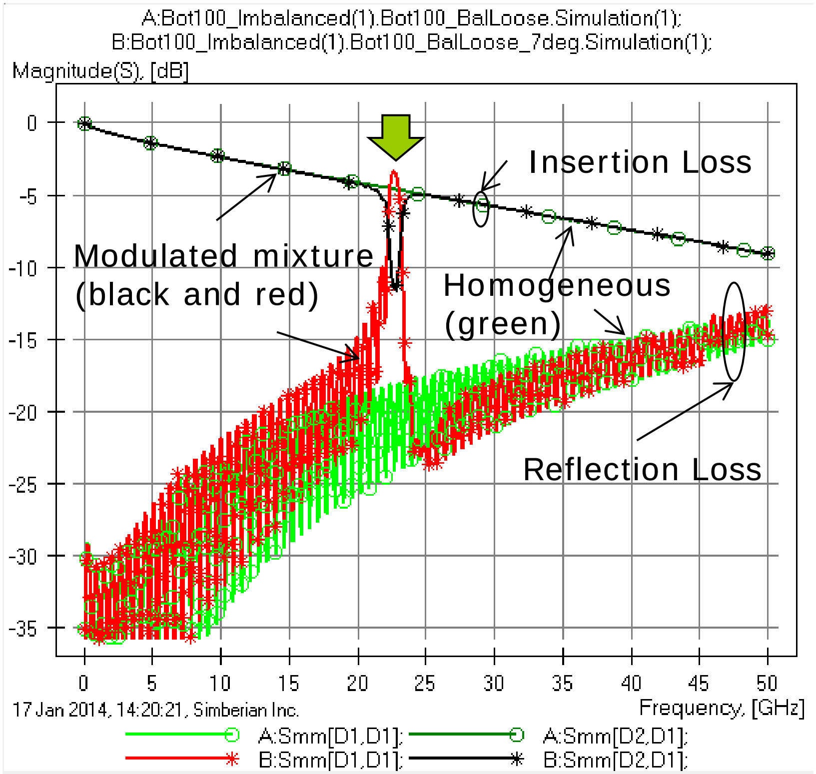


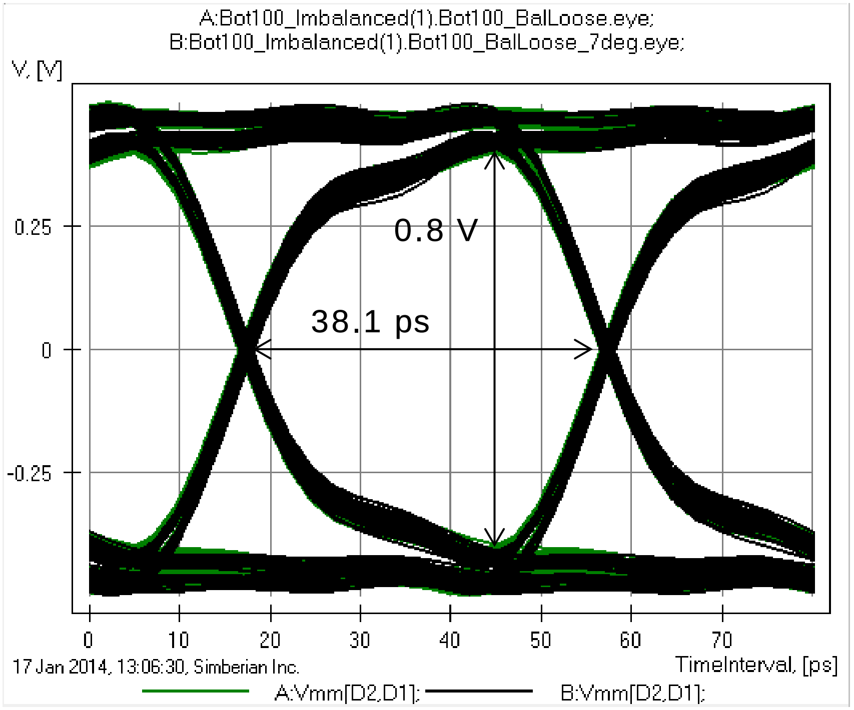

Substantial reduction of eye width (timing jitter) and eye height is expected

# 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

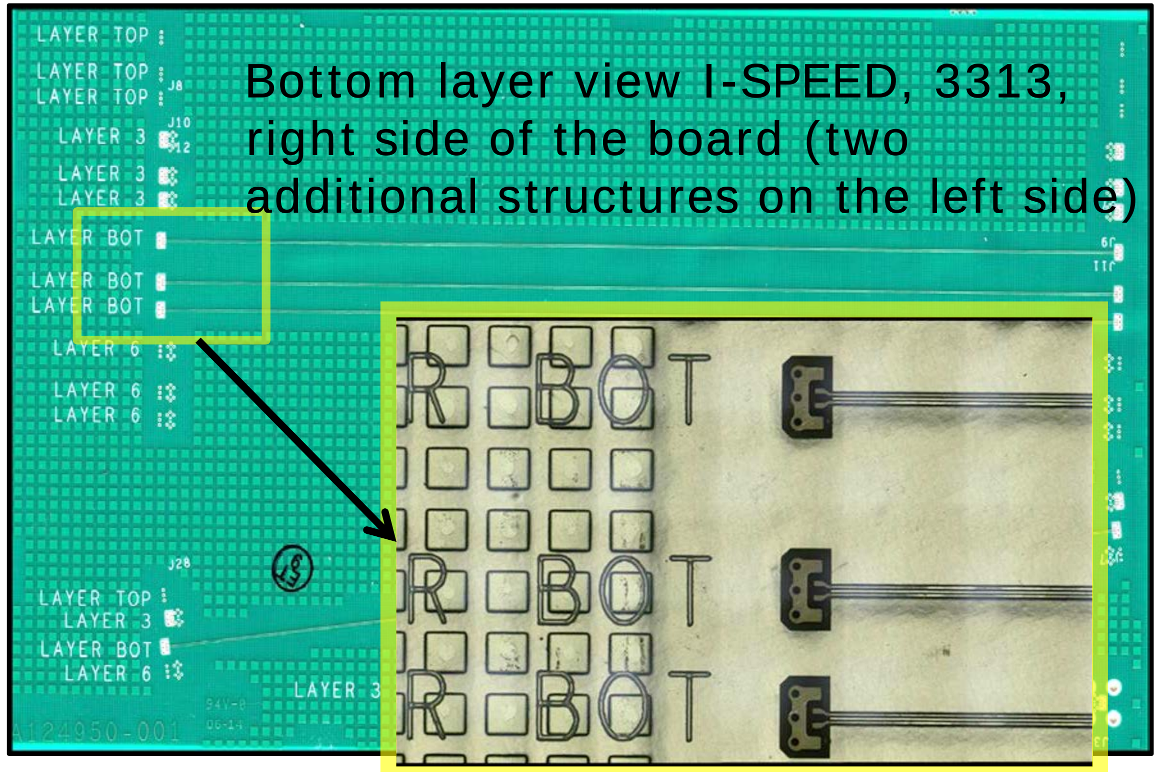
5 microstrip structures with offset for I-SPEED/3313 on the bottom side;

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**;

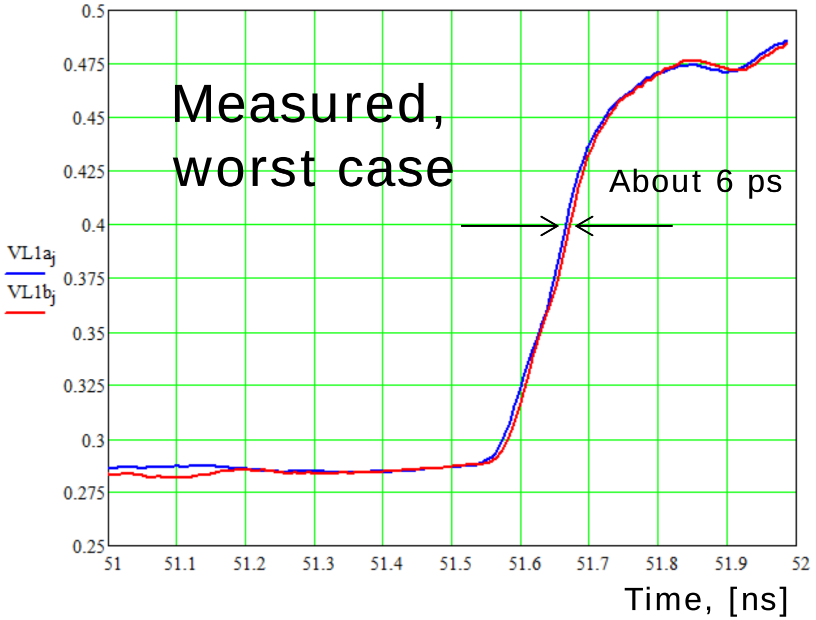
Analysis with **Simbeor software**;

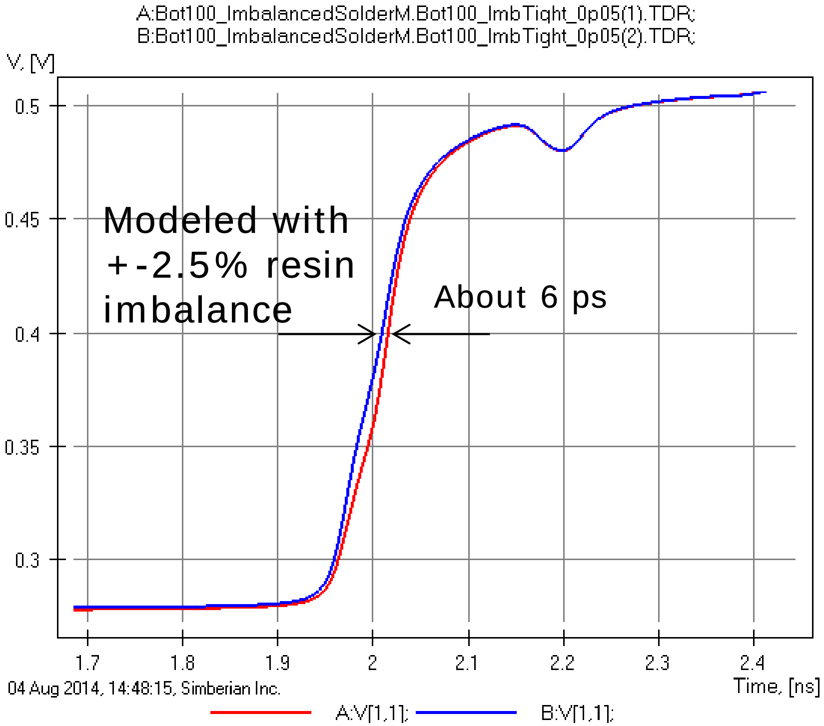



All simulations for tightly coupled traces are done with 2.2 mil conformal solder mask with DK=3.8, LT=0.01 at 1 GHz and conductor roughness (Modified Hammerstad model with SR=0.35 and RF=3.7)

# 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)

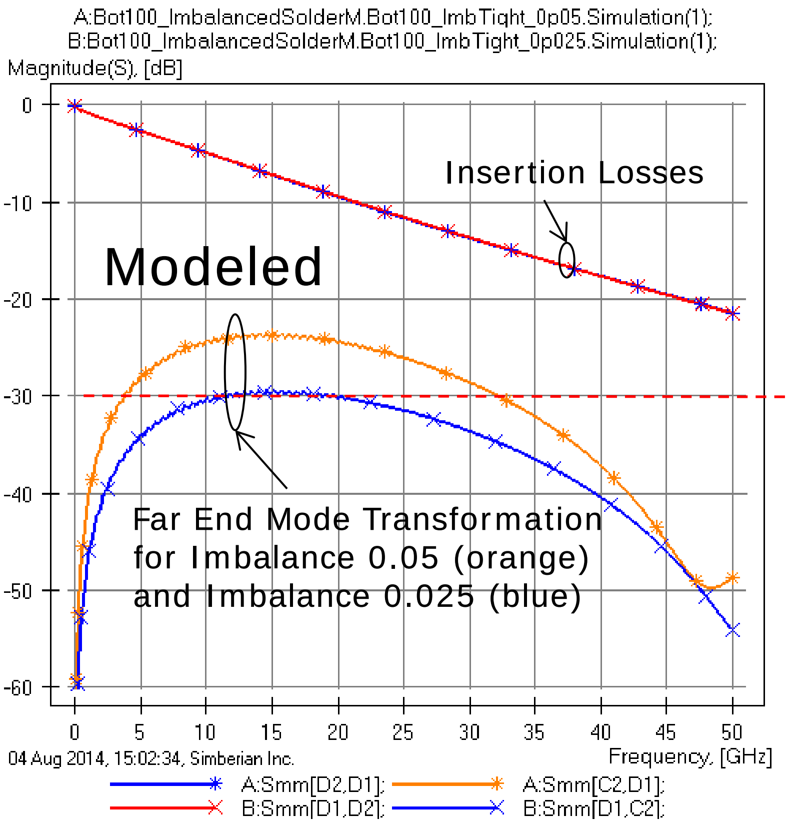


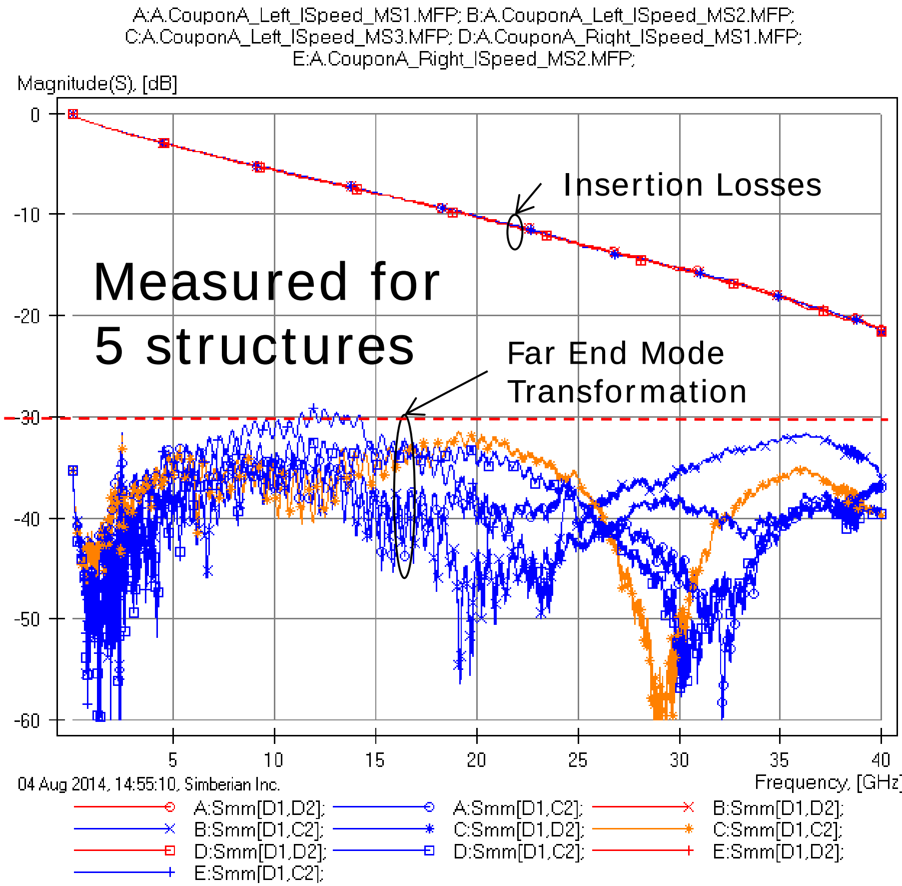




TDR measurements and simulation are done with all ports open;

# S-parameters, tightly coupled traces

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



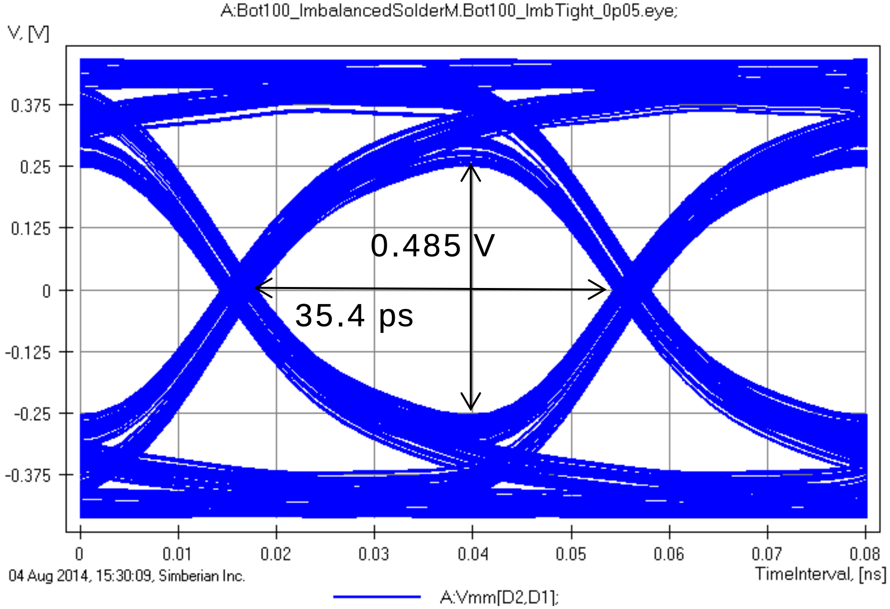

Mode transformation is smaller than expected from the TDR measurements – the imbalance is closer to 0.025

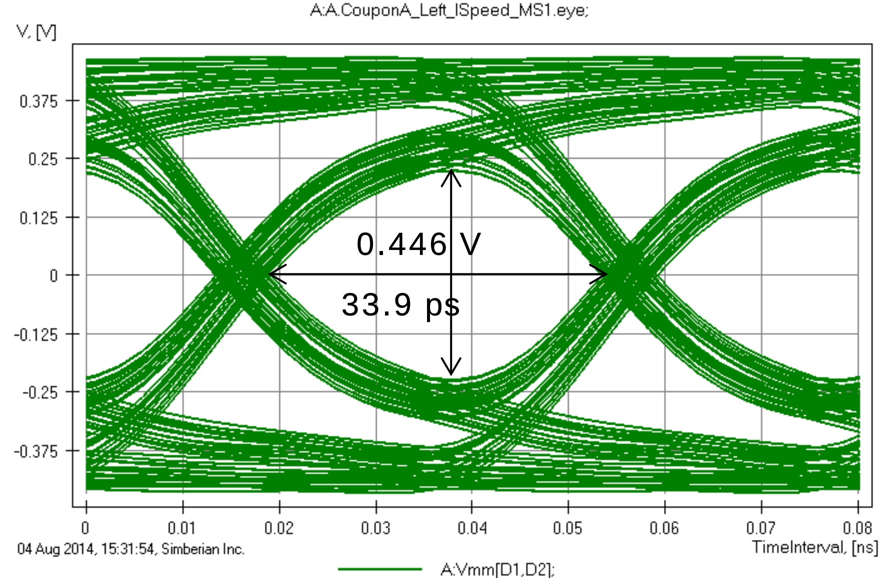
# Imbalance impact on eye diagram

- 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)

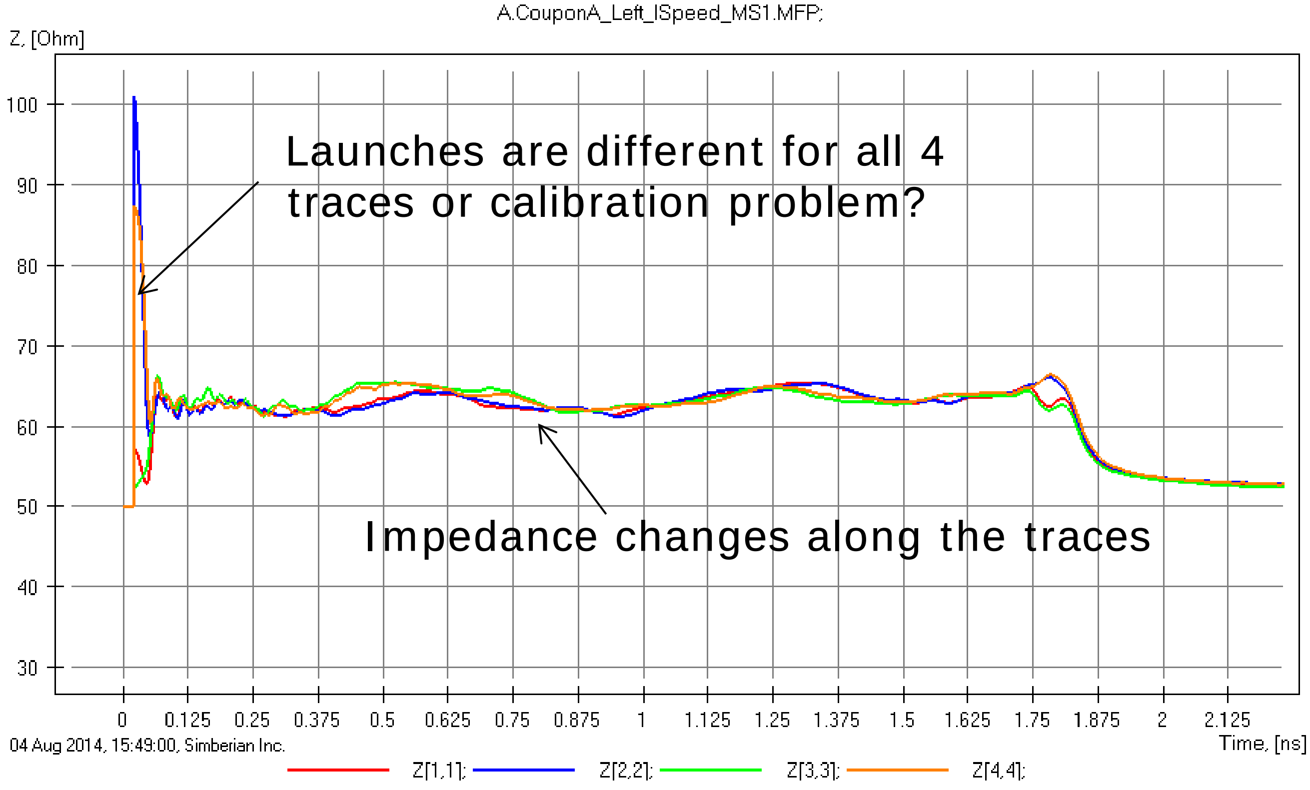



Analysis with Balanced strips produce practically the same eye (no visible difference);
Why simulated and measured eyes are slightly different? – see next slide...

# 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



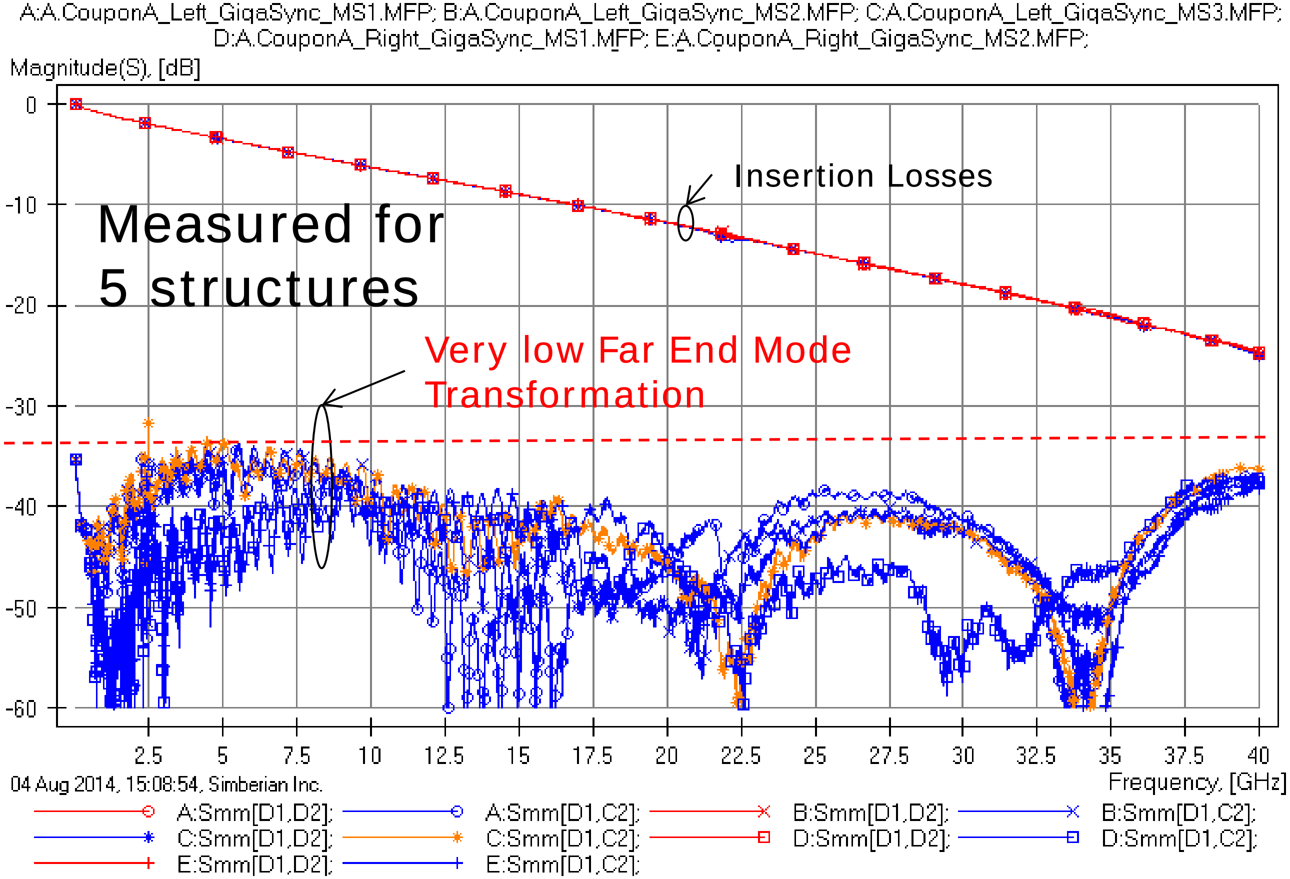

These effects are more considerable then investigated imbalance?

# 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…