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

- Improved Accuracy vs. Model Complexity/Solve Time

  - Brute Force Fiber Weave Model
  - Unit Cell Cascaded in System Tool

  System Model with Simplified Dielectric Periodicity

  - Simple Channel Model with “Practical” Insertion Phase

  - Probe launch (3D EM model)

  - Probe launch (3D EM model)

  Model Complexity/Solve Time
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:

<table>
<thead>
<tr>
<th>Typical Dielectric Material Property</th>
<th>DK</th>
<th>DF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass Weave</td>
<td>4.4 - 6.1</td>
<td>0.002 - 0.007</td>
</tr>
<tr>
<td>Resin</td>
<td>3.2</td>
<td>0.003 - 0.027</td>
</tr>
</tbody>
</table>

- 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
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.

\[
\text{Imbalance Factor} = 1 \pm 0.5 \times \text{Imbalance}
\]
**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.
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:

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

Wideband Debye model (aka Djordjevic-Sarkar):

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

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

\[
\phi = \text{ImbalanceFactor} \cdot \text{ModulationFactor}
\]

\[
\phi = 1 \quad \text{corresponds to the original “homogenized” model;}
\]

\[
\phi > 1 \quad \text{increases the dielectric constant at infinity and automatically decreases the loss tangent;}
\]

\[
\phi < 1 \quad \text{decreases the dielectric constant at infinity and automatically increases the loss tangent;}
\]

Other causal models can be adjusted similarly.
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):

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

Wiener lower boundary model (comb-like dielectric):

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

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

$\phi = 1$ 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 Stackup to investigate 2 materials from Isola

<table>
<thead>
<tr>
<th>Lyr</th>
<th>Type</th>
<th>Structure (Stack up)</th>
<th>Cu weight (oz)</th>
<th>Construction</th>
<th>Thickness after laminate (mil)</th>
<th>DK/DF</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>TOP prepreg</td>
<td></td>
<td>0.5 + plating</td>
<td>Gigasync 2116 - RC 60%</td>
<td>2.1</td>
<td>4.13/0.0067</td>
</tr>
<tr>
<td>2</td>
<td>GND</td>
<td></td>
<td>0.5</td>
<td>Gigasync 2116</td>
<td>0.6</td>
<td>4.13/0.0066</td>
</tr>
<tr>
<td>3</td>
<td>S6</td>
<td></td>
<td>0.5</td>
<td>Gigasync 2116 - RC 60%</td>
<td>0.6</td>
<td>4.13/0.0067</td>
</tr>
<tr>
<td>4</td>
<td>GND core</td>
<td></td>
<td>0.5</td>
<td>I-SPEED 3X1652</td>
<td>0.5</td>
<td>3.72/0.007</td>
</tr>
<tr>
<td>5</td>
<td>GND prepreg</td>
<td></td>
<td>0.5</td>
<td>I-SPEED 3313 - RC 61.5%</td>
<td>0.6</td>
<td>3.50/0.007</td>
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<tr>
<td>6</td>
<td>S6 core</td>
<td></td>
<td>0.5</td>
<td>I-SPEED 3313</td>
<td>0.6</td>
<td>3.65/0.007</td>
</tr>
<tr>
<td>7</td>
<td>GND</td>
<td></td>
<td>0.5</td>
<td>I-SPEED 3313 - RC 61.5%</td>
<td>0.6</td>
<td>3.50/0.007</td>
</tr>
<tr>
<td>8</td>
<td>BOT LiAg Finish</td>
<td></td>
<td>0.5 + plating</td>
<td>2.1</td>
<td>55.9</td>
<td></td>
</tr>
</tbody>
</table>

**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;
Two Cases Considered

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

Vertical bundle-to-bundle pitch:
$G_v=(39.1+38.4)/4=19.4$

Worst case

Best case

$D_v=0.25*G_v/(N-1)+k*G_v$

$G_v/2\sim9.7$ (center-to-center)
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)

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

<table>
<thead>
<tr>
<th>MATERIAL</th>
<th>WEAVE</th>
<th>MINIMUM</th>
<th>MAXIMUM</th>
<th>AVERAGE</th>
<th>MINIMUM</th>
<th>MAXIMUM</th>
<th>AVERAGE</th>
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<tbody>
<tr>
<td>IS415</td>
<td>3313</td>
<td>0</td>
<td>8</td>
<td>5</td>
<td>30</td>
<td>123</td>
<td>88</td>
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<tr>
<td>FR408HR</td>
<td>3313</td>
<td>1</td>
<td>8</td>
<td>5</td>
<td>3</td>
<td>43</td>
<td>20</td>
</tr>
<tr>
<td>FR408HRIS</td>
<td>8313</td>
<td>0</td>
<td>7</td>
<td>4.6</td>
<td>6</td>
<td>20</td>
<td>11.8</td>
</tr>
<tr>
<td>I-SPEED</td>
<td>3313</td>
<td>3</td>
<td>10</td>
<td>4.5</td>
<td>1</td>
<td>59</td>
<td>18</td>
</tr>
<tr>
<td>I-SPEED LOW DK</td>
<td>8313</td>
<td>1</td>
<td>4</td>
<td>2.3</td>
<td>5</td>
<td>12</td>
<td>7.5</td>
</tr>
<tr>
<td>I-TERA</td>
<td>3313</td>
<td>1</td>
<td>12</td>
<td>6</td>
<td>1</td>
<td>13</td>
<td>9.5</td>
</tr>
<tr>
<td>I-TERA LOW DK</td>
<td>8313</td>
<td>1</td>
<td>4</td>
<td>2.5</td>
<td>4</td>
<td>59</td>
<td>24.6</td>
</tr>
</tbody>
</table>

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;
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

Graphs showing voltage over time and phase delay for different resin contents.
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
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)

```
0.78 V
38.3 ps
```

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

```
35.43 ps
0.47 V
```

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 $\pm 10\%$ 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)
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;

Bottom layer view I-SPEED, 3313, right side of the board (two additional structures on the left side)
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
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
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

Launches are different for all 4 traces or calibration problem?

Impedance changes along the traces (manufacturing induced tolerances)

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
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

<table>
<thead>
<tr>
<th>Layer #</th>
<th>Material Type</th>
<th>Material Construction</th>
<th>Copper Type S = RTF, X = HVLP</th>
<th>Material Pressed Er (at ~2 GHz)</th>
<th>Material Unpressed Thickness (mils)</th>
<th>Material Pressed Thickness (mils)</th>
<th>Picture</th>
<th>Copper Thickness (mils)</th>
<th>Copper Thickness (oz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Prepreg</td>
<td>1 x 3313 RC = 57%</td>
<td>X</td>
<td>3.68</td>
<td>4.3</td>
<td>4.1</td>
<td>Prepreg</td>
<td>2.2</td>
<td>1.5</td>
</tr>
<tr>
<td>2</td>
<td>Core</td>
<td>1 x 3313 RC = 55%</td>
<td>core</td>
<td>3.72</td>
<td>4</td>
<td></td>
<td>Core</td>
<td>0.6</td>
<td>0.5</td>
</tr>
<tr>
<td>3</td>
<td>Prepreg</td>
<td>2 x 3313 RC = 57%</td>
<td>X</td>
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<td></td>
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<td>7</td>
<td>Prepreg</td>
<td>2 x 3313 RC = 57%</td>
<td>X</td>
<td>3.68</td>
<td>8.6</td>
<td>8.3</td>
<td>Prepreg</td>
<td>0.6</td>
<td>0.5</td>
</tr>
<tr>
<td>8</td>
<td>Core</td>
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<td>4</td>
<td></td>
<td>Core</td>
<td>0.6</td>
<td>0.5</td>
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<td>3.68</td>
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<td>Prepreg</td>
<td>0.6</td>
<td>0.5</td>
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<td>3.72</td>
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<td>Core</td>
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<td>4.3</td>
<td>4.1</td>
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<td>2.2</td>
<td>1.5</td>
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<td>16</td>
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<td>0.7</td>
<td></td>
<td></td>
<td>Solder Mask</td>
<td></td>
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<table>
<thead>
<tr>
<th>Material Thickness</th>
<th>Total Thickness</th>
<th>Copper Thickness</th>
</tr>
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<tbody>
<tr>
<td>97.3</td>
<td>110.1</td>
<td>12.8</td>
</tr>
</tbody>
</table>
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
Isola HSD Versus Competition Insertion Loss (dB/in.)
Lee Ritchey 16 Layer TV (8" Line)
## Insertion Loss Data

<table>
<thead>
<tr>
<th>GHz</th>
<th>Tachyon (VLP2)</th>
<th>Teragreen (VLP2)</th>
<th>I-Tera (VLP2)</th>
<th>Meg6 (HVLP)</th>
<th>Chronon (VLP2)</th>
<th>I-Speed (VLP2)</th>
<th>Gigasync (VLP2)</th>
<th>Meg4 (RTF)</th>
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<tbody>
<tr>
<td>1.25</td>
<td>-0.165</td>
<td>-0.175</td>
<td>-0.169</td>
<td>-0.173</td>
<td>-0.185</td>
<td>-0.179</td>
<td>-0.183</td>
<td>-0.196</td>
</tr>
<tr>
<td>2.00</td>
<td>-0.219</td>
<td>-0.231</td>
<td>-0.224</td>
<td>-0.228</td>
<td>-0.245</td>
<td>-0.251</td>
<td>-0.256</td>
<td>-0.278</td>
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<td>-0.286</td>
<td>-0.293</td>
<td>-0.304</td>
<td>-0.324</td>
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## Skew Data Product Comparison

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*Courtesy of Speeding Edge*
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

Thank You!