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:

<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 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 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

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.

Modulation Factor = 1+V(d)

- **V(d)**
- **0**
- **d (along trace)**
- **Period**
- **Lx**
- **Ly**
- **Resonance due to periodicity**
Causal model for dielectric with changing properties – Option 1

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

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

Multi-pole Debye model:

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

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

Wideband Debye model (aka Djordjevic-Sarkar):

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

\[ \phi = 1 \] 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):

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

Wiener lower boundary model (comb-like dielectric):

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

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

<table>
<thead>
<tr>
<th>Lyr</th>
<th>Type</th>
<th>Cu weight (oz)</th>
<th>Construction</th>
<th>Thickness after lam (mil)</th>
<th>DK/DF</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Top prepreg</td>
<td>0.5 plating</td>
<td>Gigasync 2116 - RC 60%</td>
<td>2.1</td>
<td>4.13/0.067</td>
</tr>
<tr>
<td>2</td>
<td>GND</td>
<td>0.5</td>
<td>Gigasync 2116</td>
<td>4.5</td>
<td>4.13/0.066</td>
</tr>
<tr>
<td>3</td>
<td>core</td>
<td>0.5</td>
<td>Gigasync 2116 - RC 60%</td>
<td>4.4</td>
<td>4.13/0.067</td>
</tr>
<tr>
<td>4</td>
<td>GND prepreg</td>
<td>0.5 plating</td>
<td>I-SPEED 3X1652</td>
<td>19.0</td>
<td>3.72/0.007</td>
</tr>
<tr>
<td>5</td>
<td>GND</td>
<td>0.5</td>
<td>I-SPEED 3313 - RC 61.5%</td>
<td>4.4</td>
<td>3.50/0.007</td>
</tr>
<tr>
<td>6</td>
<td>S6</td>
<td>0.5</td>
<td>I-SPEED 3313</td>
<td>4.0</td>
<td>3.65/0.007</td>
</tr>
<tr>
<td>7</td>
<td>GND prepreg</td>
<td>0.5 plating</td>
<td>I-SPEED 3313 - RC 61.5%</td>
<td>4.8</td>
<td>3.50/0.007</td>
</tr>
<tr>
<td>8</td>
<td>Bot</td>
<td>0.5 + plating</td>
<td></td>
<td></td>
<td>2.1</td>
</tr>
</tbody>
</table>

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)

Vertical bundle-to-bundle pitch:
\[ G_v = \frac{(39.1 + 38.4)}{4} = 19.4 \]

Center-to-center:
\[ D_s = 9.7 \]

\[ D_v = 0.25 \times G_v / (N-1) + k \times G_v \text{ (offset)} \]

5 samples with offset
\[ D_v = 1.2 + k \times 19.4 \text{ mil} \]

Worst case

Best case

Gv/2 ~ 9.7 (center-to-center)

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

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

\(K_v\) 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)

6-inch segment of t-line with inhomogeneous dielectric – non-uniform t-line model
Model identification for worst case skew (numerical example)


<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>
</tr>
</thead>
<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>
</tr>
<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;

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**

- Strip with 10% more resin
- Strip with 10% less resin
- No imbalance (homogeneous mixture)

**Single-ended transmission phase delay**

- Strip with 10% more resin
- Strip with 10% less resin

_graphs_
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;

**Graph:**
- Balanced IL
- IL, imbalance +- 10% resin
- Near and far end mode transformation with imbalance +- 10%
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)

- 38.3 ps
- 0.78 V

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

- 35.43 ps
- 0.47 V

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

Launches are different for all 4 traces or calibration problem?

Impedance changes along the traces

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…