Modelling jitter induced by fibre weave effect in PCB dielectrics

Yuriy Shlepnev [#1], Chudy Nwachukwu [*2]

[#] *Simberian Inc.*
3030 S Torrey Pines Dr., Las Vegas, NV, 89146, USA
[1] `shlepnev@simberian.com`

[*] *Isola Group USA*
165 S Price Rd., Chandler, AZ 85224, USA
[2] `Chudy.Nwachukwu@isola-group.com`

Abstract — **Dielectric properties of Printed Circuit Board (PCB) glass weave re-enforcement can differ greatly from the properties of the resin matrix due to processes inherent in the engineering of dielectric substrates. This inhomogeneity can contribute to increases in skew and deterministic jitter at data rates of 10 Gbps and higher for paired transmission lines routed on typical PCB materials. This paper proposes a new model for accurately characterizing the glass weave-induced skew and jitter in PCB substrates. This new model will be used to predict the package-level performance of existing and next-generation skew mitigating laminate materials. The model provides guidance for PCB material selection on the basis of skew/jitter estimates for the corner cases.**

I. Introduction

Data links running at bitrates of 10-50 Gbps and beyond are becoming mainstream in communication and other electronic systems. The design of Printed Circuit Board (PCB) packages and interconnects for such systems remains a challenging problem that requires electromagnetic analysis over broad frequency bandwidths from DC to 50 GHz. An accurate prediction of interconnect behaviour over such extreme frequency bandwidths requires the use of causal broadband dielectric models of PCB composite materials. Woven fabric composites are typically used as insulators to manufacture PCBs; however both the fabric fibre and resin are composite materials with typically different dielectric constant (Dk) and loss tangent (LT) properties. A layer of fabric fibres with one dielectric form a 2D lattice with a pitch of 10-30 mils filled with epoxy resin of a different dielectric property, and conductor traces are routed over or between such layers with changing dielectric properties as shown in Fig. 1.

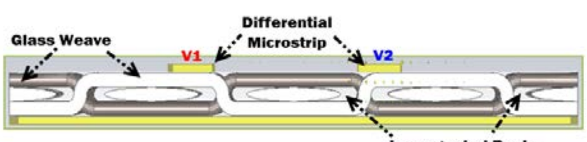


Fig. 1. Differential traces on glass weave-resin composite.

At lower GHz frequency range the composite mixture can be simply homogenized and an effective broad-band dielectric multi-pole or wide-band Debye (Djordjevic-Sarkar) model can be identified and used for the analysis of signal propagation [1], [2].

As data rates increase, two problems arise: first, the fibre-resin dielectric inhomogeneity in differential interconnect cross-section creates asymmetry (imbalance) in differential traces as reported in [3], [6-10]. This can cause either skew in un-coupled pairs or differential to common mode transformation in coupled pairs. This imbalance can also lead to additional losses and change in differential impedance, and an increase of deterministic jitter even at lower Gbps data rates. Second, the fibre-resin dielectric inhomogeneity along the interconnect causes additional signal degradation due to variations in propagation constant and characteristic impedance along the line. This is also related to the resonant-type increase in insertion and reflection loss due to possible periodicity or quasi-periodicity observed in [4], [5], [11-14]. Ultimately, this inhomogeneity can contribute to an increase in deterministic jitter at tens of Gbps for typical PCB materials.

The fibre-weave effects can be accurately modelled directly with 3D electromagnetic analysis by using a detailed description of weave geometry and resin filling as demonstrated in [4], [5], [10], [12]. This approach is accurate when the geometry and composite material properties are properly defined. Although the process of geometry description is laborious and analysis time is relatively long, direct 3D EM analysis is suitable for research projects and may be for analysis of corner cases for a particular material micro-structure. However, it is not a practical approach and cannot be used for statistical analysis of interconnects running at different locations and at angles with respect to the fibre lattice. To simulate skew in a differential line, quasi-static field solver can be used for extraction of transmission line (T-line) parameters with dielectric inhomogeneity across the line cross-section [9], [14]. Although this approach is simple and fast, it may only be accurate in cases where interconnect traces are running along weft or fill fibres and trace imbalance does not change along the line. The periodic changes in dielectric properties along the line can be accounted for with concatenation of T-line segments with different parameters as suggested in [11] or by periodic loading of the transmission line model as done in [13]. However, such models do not reflect gradual changes in the material properties and are

Published in Proc. of the 2014 IEEE International Symposium on Electromagnetic Compatibility, Raleigh, NC, USA, August, 2014, p.

developed to predict only weave-induced resonances. Therefore, a practical model has to account for dielectric inhomogeneity across the cross-section of a differential pair and along single ended and differential transmission lines. This model would also be applicable for investigating both corner cases and statistical analysis of interconnects running at different board locations at different angles, which is especially important for optimal PCB material selection.

A new non-uniform transmission line model for practical prediction of the fibre weave effect (FWE) on signal propagation in PCB interconnects is introduced in this paper. The model is causal and allows analysis of non-uniformity of dielectric properties along the line to simulate resonances due to periodic changes of properties, as well as in the cross-section for each dielectric layer to simulate mode transformation (skew and jitter) due to dielectric asymmetry in differential traces.

II. Non-Uniform Transmission Line Model

A non-uniform transmission line model is constructed here to describe the variations in dielectric properties along and across the transmission line. Two parameters are introduced to describe this dielectric inhomogeneity. The variation of the dielectric properties across differential t-line is described with a parameter called the **imbalance factor**. Variations along the t-line are described with a functional parameter called the **modulation factor**. A unit factor corresponds to volume average resin percentage defined for the given PCB material globally (typically defined for a large volume). Any variations of the imbalance and modulation factors upwards correspond to higher volumetric content of glass (higher dielectric constant and smaller polarization losses). Any variation of the factors downward will correspond to higher volumetric content of the resin (smaller dielectric constant and larger polarization losses).

A step-like function $\varphi(x/y)$ defined with the imbalance factor is used to describe differential pair asymmetry as illustrated in Fig. 2.

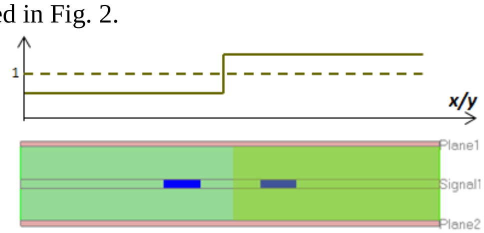


Fig. 2. Model for non-uniform dielectric filling in cross-section.

If the PCB material cross-section contains multiple layers of dielectric, the imbalance factor is applied separately to each layer. A similar model was first used for the analysis of skew in differential pairs in [9] and [15].

In addition to the imbalance in the cross-section, a modulation factor function $\xi(z)$ is used here to describe the variations of dielectric properties along the line as illustrated for the harmonic modulation in Fig. 3.

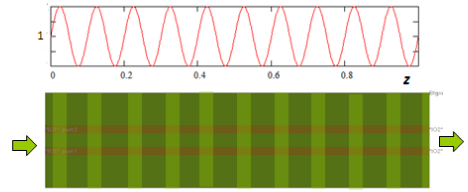


Fig. 3. Model for non-uniform dielectric filling along traces.

A Quasi-static field solver is used to extract the transmission line parameters with the imbalance in the cross-section. Non-uniformity along the transmission line is modelled with a stair case approximation with electrically short T-line segments. The segment length is automatically selected as either a small fraction of the wave-length at the maximal frequency or using threshold on changes in dielectric properties between the segments. The dielectric model of each segment is adjusted as described by the modulation factor function and imbalance factor. Technically, this solution is reduced to multiple extractions of T-line parameters with a quasi-static field solver and the analysis of a circuit with concatenated transmission line segments - this can be considered a combination of techniques used in [9] and [11]. It is important to note that **the key in this approach is how to use the imbalance and modulation factors for adjustment of dielectric properties, to ensure the entire model is causal and physical.** Assignment of different dielectric models for each line segment or each half of differential pair is a possibility but not practical approach.

Two models are proposed here for the description of variations in the dielectric properties. **The first model can be used for homogenized dielectric models described with closed-form expressions such as multi-pole or wideband Debye.** The imbalance and modulation factors are lumped into a common factor $\phi = \varphi(x/y)\cdot\xi(z)$ and simply applied to the dielectric constant of a broadband dielectric model at infinity $\varepsilon(\infty)$. The Multi-pole Debye model is modified as follows:

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

Here fr_n is frequency of n-th pole and $\Delta\varepsilon_n$ is n-th pole residue. Similarly, the wideband Debye or Djordjevic-Sarkar model is modified as follows:

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

$$F_d(f) = \frac{1}{(m_2-m_1)\cdot\ln(10)}\cdot\ln\left[\frac{10^{m2}+if}{10^{m1}+if}\right] \qquad (2)$$

m_1 and m_2 define the model low and high poles (usually fixed). $\varepsilon(\infty)$ ε_{rd} are model parameters that can be defined with values of Dk and LT at one frequency [1],[2]. $\phi = 1$ corresponds to the original "homogenized" model; $\phi > 1$ increases the dielectric constant at infinity and at all frequencies and automatically decreases the loss tangent; $\phi < 1$ decreases the dielectric constant at infinity and at all frequencies and automatically increases the loss tangent. This behaviour is expected in the glass-resin mixtures. A similar adjustment of $\varepsilon(\infty)$ can be introduced for other broadband causal dielectric models.

The second modulation model is based on models for the dielectric mixtures and is closer to reality. It can be effectively used if broadband models for the glass and resin composites are known and dielectric can be described with a mixing formula such as Wiener, Hashin-Shtrikman, or Maxwell-Garnett [16]. The volume fraction in the mixing formulas can be used as the parameter to define the inhomogeneity across and along the line. Similar to the previous case, the imbalance and modulation factors are lumped into ϕ factor and used to adjust the volume fraction parameter in the mixing formulas found in [16] along and across the t-line. For instance, the Wiener upper boundary formula is modified as follows (suitable for layered dielectric structure):

$$\varepsilon_{eff,\max} = \phi \cdot f \cdot \varepsilon_2 + \left(1 - \phi \cdot f\right) \cdot \varepsilon_1 \quad (3)$$

The Wiener lower boundary formula is modified as follows (suitable for comb-like dielectric structure):

$$\varepsilon_{eff,\min} = \frac{\varepsilon_1 \cdot \varepsilon_2}{\phi \cdot f \cdot \varepsilon_1 + \left(1 - \phi \cdot f\right) \cdot \varepsilon_2} \quad (4)$$

Dielectric with permittivity ε_2 is mixed into a dielectric with permittivity ε_1 and occupies a volume fraction f. Both dielectrics in the mixture can be described with either multi-pole or wideband Debye formulas. All other mixture formulas can be modified in the same way. If the volume fraction in the mixing formula f defines content of the glass in the resin-glass mixture, $\phi = 1$ corresponds to the "homogenized" case. Then $\phi > 1$ corresponds to areas with a larger content of glass (larger Dk and smaller LT), and $\phi < 1$ corresponds to dielectric areas with a smaller content of glass (smaller Dk and larger LT).

III. Identification of Dielectric Imbalance and Modulation Factors

Two approaches are suggested here to define the imbalance and modulation factors. First, the factors can be simply adjusted to fit the model to the measured S-parameter data. The reflection-less generalized modal scattering parameters (GMS-parameters) can be used to derive the direct imbalance and modulation factor identification procedure [1], [2]. However, this approach is only useful for the model validation. The final model can then be applied specifically to the position and angle with the fibre lattice used in the experiment. Although this approach can be used to identify the imbalance and modulation factors for the worst case scenarios, a number of samples with a specific offset described in [6] should be placed on the test board for the identification in order to capture the worst case scenario

A more general approach is to map a physical description of the fibre into the electrical model. Glass cloth manufacturers provide the parameters needed to describe the geometry of fabrics used in the manufacture of PCBs [17]. If some parameters are missing (such as vertical bundle size for instance), they can be either physically measured or identified with the measured data. This process begins with the global average resin content (RC) for a given laminate. The RC locally around each trace is computed and used to define the imbalance and modulation factors as the difference of the global resin content with the local resin content. This approach works naturally with the mixing formulas (3)-(4). The factors may be additionally calibrated with the measurements to account for specificity of all models (1)-(4) and mapping uncertainties. **This approach can be called the localized homogenization.**

IV. Test Board Design

Our test board was designed to estimate worst case skew and resonances for two dielectric materials: Isola GigaSync with 2116 glass fabric and Isola I-SPEED with 3313 glass fabric. The hybrid PCB stackup is designed to have both micro-strip and strip-line configurations in both materials as shown in Fig. 4. Homogenized dielectric constants and loss tangents as well as global resin content for each material are also specified in Fig. 4.

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					

Fig. 4. Test board material stackup.

Both materials use spread glass style such as 3313 glass shown as an example in Fig. 5.

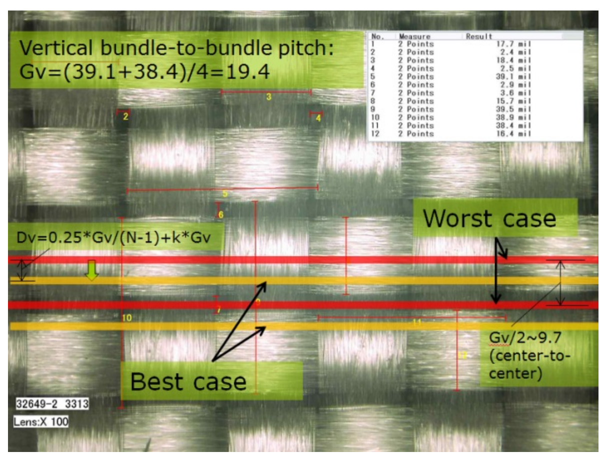


Fig. 5. Micro-photograph of 3313 glass fabric with the best and worst cases for skew in differential pairs.

Per the manufacturer, the I-SPEED material is composed of regular glass with Dk close to 5 and resin with lower Dk close

Published in Proc. of the 2014 IEEE International Symposium on Electromagnetic Compatibility, Raleigh, NC, USA, August, 2014, p.

to 2.8, and the GigaSync material shows no measurable difference between its glass and resin properties.

Multiple 6-inch differential line segments and calibration structures were routed on the test board to find worst case due to fiber weave effect as shown in Fig. 6.

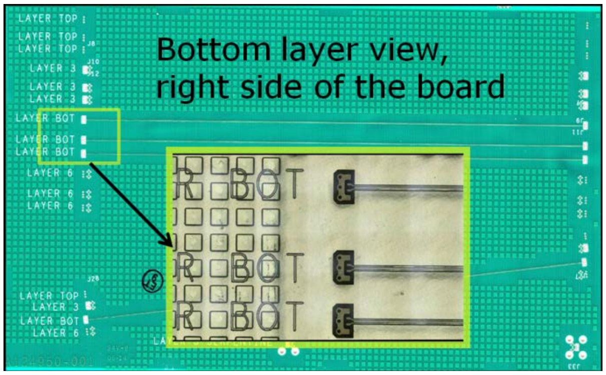


Fig. 6. Bottom view of the test board right side with 3 6-inch segments aligned with the fiber (2 additional segments are on the left side).

In reality the board cannot be manufactured with the exact positioning of the strips over the fabric fiber bundles, therefore to get close to the best and worst skew cases we used 5 segments of differential T-lines running horizontally with vertical offset computed as illustrated in Fig 5. If two strips are arranged symmetrically around valleys or hills formed by the glass fabric for the best case as illustrated in Fig. 5, the worst case positioning of the differential strips would be achieved if the strips are separated by a distance 0.25 of the vertical fabric pitch. Thus, we placed 5 identical horizontal differential links with vertical offset $Dv=1.2+k*19.4$ for the 3313 fabric and $Dv=1.1+k*17.6$ for the 2116 fabric. Additional differential links were also placed at 7 and 15 degrees to the weave to estimate the resonances caused by the periodic variation of dielectric properties.

V. Numerical Analysis

As a model for I-SPEED composite material with previously identified Dk=3.5 and LT=0.007 at 1 GHz, we use Wiener average mixture of glass with known Dk=5 and LT=0.001 at 1 GHz and 61.5% of resin with Dk adjusted to 2.8 and LT=0.011 (to have Dk and LT of the mixture equal to the identified). Our simulation study begins with the board geometry import and decomposition of a microstrip configuration of a 6-inch differential link, corresponding to the I-SPEED material, as shown in Fig. 7.

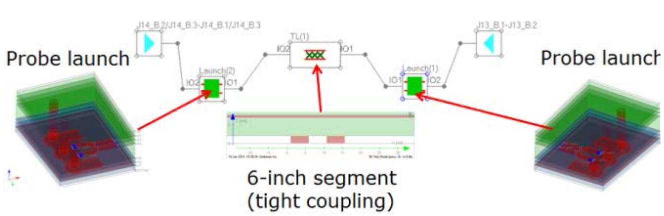
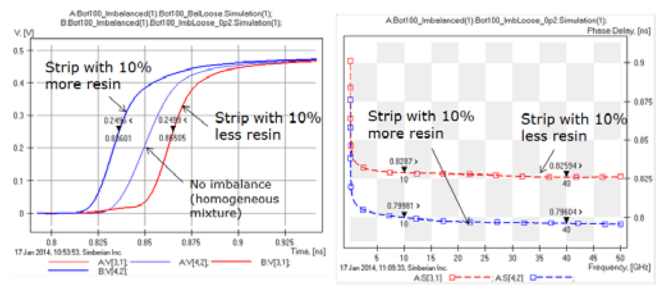


Fig. 7. De-compositional model of 6 inch differential microstrip link path.

Two links are used to generate our simulation models: with a tightly coupled differential pair of 4.9 mil wide traces separated by 4.8 mils (9.7 mils center to center, voltage coupling coefficient 0.21), and with a loosely coupled pair of 9 mil wide traces separated by 39.5 mils (voltage coupling coefficient 0.012). Measured worst case skew for the identical glass weave-resin composite was equal to 59 ps or 4.2 ps/inch as recorded in [17]. Hence, we begin our numerical analysis here using slightly larger 5 ps/inch skew value as the maximal possible skew due to FWE of the I-SPEED 3313 composite, and adjust the imbalance factor for loosely couple lines in order to obtain the same skew. Next we estimate the jitter due to skew in loosely coupled lines and then use the same imbalance factor to determine worst possible skew in tightly coupled lines and also estimate jitter. Finally we define the modulation of the material properties along the T-line with the same amplitude as predicted by the imbalance and simulate the effect on jitter. For the analysis we will use Simbeor software [18]. As shown in Fig. 8, an imbalance factors 0.9 and 1.1 (imbalance coefficient 0.2 in Simbeor software) corresponding to an imbalance in resin content of ±10% produced 5 ps/inch skew in the loosely coupled differential pair.



Figs. 8a (left). Single-ended TDT with 20 ps Gaussian step;
8b (right). Single-ended transmission phase delay
on loosely coupled traces.

Ideally, the differential to common mode transformation in a differential pair is equal to zero if there is no imbalance. Our analysis shown in Fig. 9 using the same ±10% resin content imbalance shows very large far end mode transformation (orange line), and this mode transformation degrades differential insertion loss (IL, blue line).

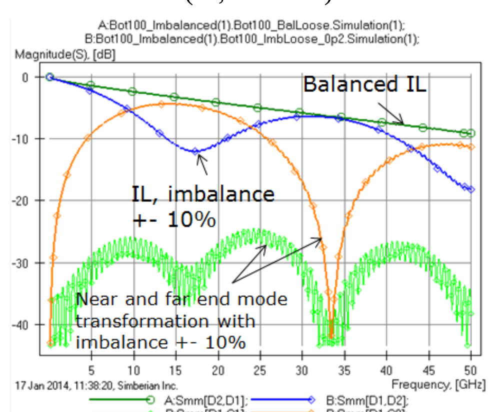
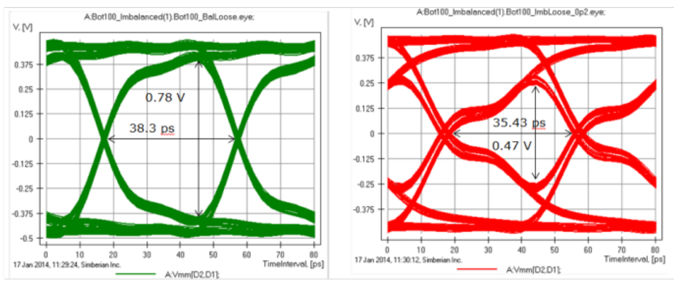
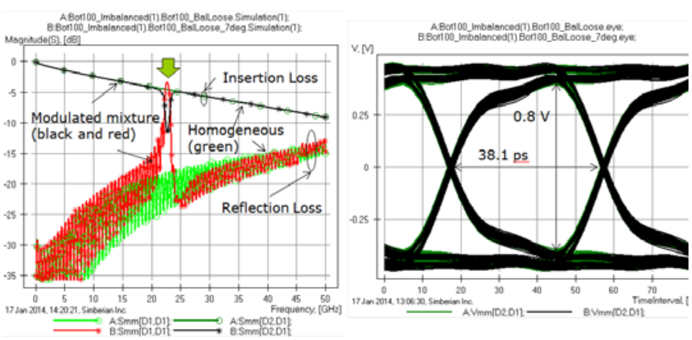


Fig. 9. Impact of differential to common mode transformation on IL for loosely coupled differential link.

Simulation of eye diagram for differential signal using a 25 Gbps PRBS-7 sequence with a 10 ps rise and fall time shows severe eye degradation caused by the imbalance in our link with loosely coupled pair as shown in Fig. 10b. **The mode transformation in loosely coupled differential interconnect induced by the FWE increases the inter-symbol interference and substantially reduces both eye width (timing jitter) and eye height.** Note that for T-lines running at 7 degrees to the horizontal fibre, there is no significant change in the differential eye diagram (Fig 11b). However, the resonance effect on insertion and reflection loss parameters due to periodic loading [5] is clearly visible on differential S-parameters show in Fig 11a. We have used sinusoidal modulation function with amplitude 0.2 identified from the worst skew. The resonance is close to the second harmonic of the 25 Gbps signal, but too narrow to introduce considerable jitter.

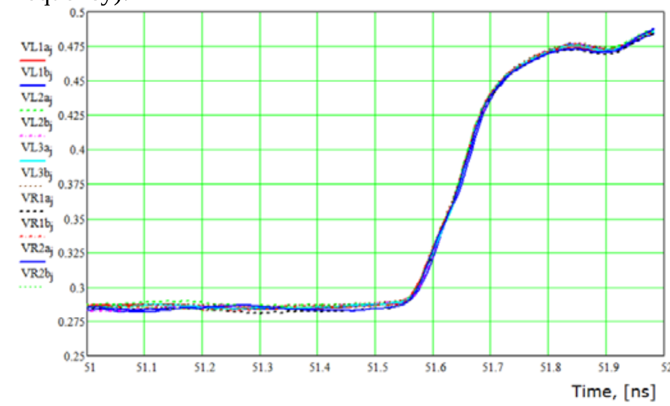


Figs. 10a (left). Eye diagram for dielectric mixture with no imbalance;
10b (right). Effect of ±10% resin content imbalance on link with loosely coupled traces.

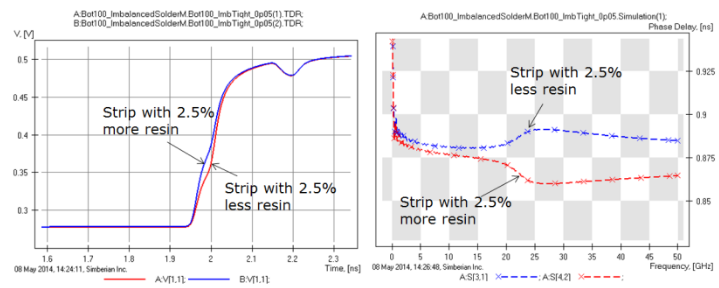


Figs. 11a (left). Resonance due to periodic changes of dielectric properties for traces at 7 degrees to horizontal fibre;
11b (right) Corresponding 25 Gbps eye diagram showing no significant changes on link with loosely coupled traces.

Next, we analysed the imbalance effect on the link with tightly coupled traces. Board with tightly coupled traces have been manufactured and TDR responses for 5 differential traces aligned with the fiber bundles on I-SPEED side of the board are measured by Introbotix (http://www.introbotix.com/, courtesy Brian Butler). All TDR responses were very close as shown in Fig. 12. The delay was measured at the voltage level 0.388 V (in the middle of the rise ramp). The worst possible skew between traces of differential pair was about 6 ps or about 1 ps/inch. This is less than expected on the base of measurements for loosely coupled traces. To have the same 6 ps skew, the imbalance of resin content in the models was adjusted to ±2.5% (imbalance coefficient 0.05 in Simbeor software). Note, that it is difficult to clearly identify a number for skew with the single-ended S-parameters in this case as illustrated in Fig. 13 (the signals on different traces have different shape of the rise and phase delay changes with the frequency).



Figs. 12. Single-ended TDRs measured for all tightly coupled traces;



Figs. 13a (left). Single-ended TDT computed with 20 ps Gaussian step for tightly coupled traces with ±2.5% resin content imbalance;
13b (right). Single-ended transmission phase delay.

Though, there is little far and/or near mode transformation and no impact of mode transformation on the differential insertion of this tightly coupled pair as shown in Fig. 14. The impact of worst case skew on jitter is practically not visible as shown in Fig. 15.

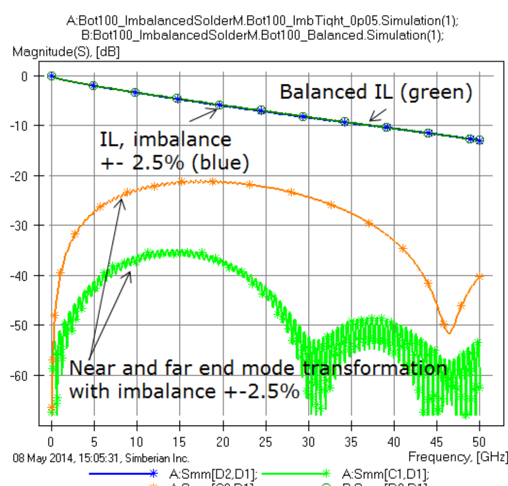
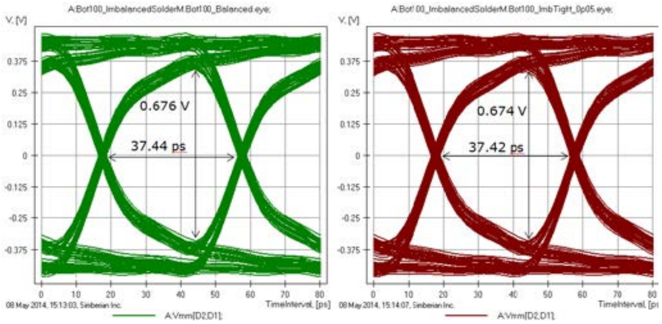


Fig. 14. No Impact of differential to common mode transformation on IL for the link with tightly coupled traces with ±2.5% resin content imbalance.



Figs. 15a (left). Eye diagram for dielectric mixture with no imbalance; 15b (right). Little to no effect of ±2.5% resin content imbalance on link with tightly coupled traces.

VI. Conclusion

A new causal non-uniform imbalanced transmission line model for practical prediction of the fibre weave effect (FWE) on signal propagation in PCB interconnects has been introduced in this paper. The usability of the model has been illustrated with example of practical investigation of the corner cases for I-SPEED dielectric with 3313 glass. It has been shown that the composite I-SPEED dielectric with 3313 glass weave can be modelled as a Weiner average mixture of glass and the appropriate resin percentage (61% in this case). The dielectric constant of the S-type glass material was used to approximate the dielectric constant and loss tangent of the resin, using previously identified Dk and LT of the composite. The proposed model parameters of the fibre-weave effect have been defined from experimentally observed maximal skew for I-SPEED dielectric with 3313 glass. Using the identified imbalance and modulation factors, we have simulated the effect of FWE on loosely and tightly coupled differential links. The FWE impact on jitter and eye height for 25 Gbps signal was evaluated for both configurations. The takeaways from this paper include the following:

- Significant effect of imbalance on jitter for loosely coupled microstrip pairs has been observed and quantified;
- There is no significant effect of imbalance on tightly coupled microstrip traces;
- Finally, the effect of periodicity on jitter for loosely coupled pairs is observed and quantified.

Note that 3313 fabric with spread fiber bundles is used in this investigation, but the proposed models are not limited to just this glass style. The non-uniform imbalanced transmission line models can be also constructed following the same procedure for not spread glass style fabrics such as 1080 for instance.

The follow-up investigations include experimental verification of little to no FWE effect in the homogenous GigaSync material, more rigorous comparison of measured and modelled S-parameters of tightly and loosely coupled differential pairs, and the effect of imbalance on jitter for differential pairs routed in a stripline configuration.

References

[1] Y. Shlepnev, A. Neves, T. Dagostino, S. McMorrow, Practical identification of dispersive dielectric models with generalized modal S-parameters for analysis of interconnects in 6-100 Gb/s applications. DesignCon 2010.

[2] Y. Shlepnev, System and method for identification of complex permittivity of transmission line dielectric, US Patent #8577632, Nov. 5, 2013, Provisional App. #61/296237 filed on Jan. 19, 2010.

[3] S. McMorrow, C. Heard, The Impact of PCB Laminate Weave on the Electrical Performance of Differential Signaling at Multi-Gigabit Data Rates, DesignCon 2005.

[4] J. R. Miller, G. J. Blando, I. Novak, Additional Trace Losses due to Glass-Weave Periodic Loading, DesignCon 2010.

[5] G. Romo, C. Nwachukwu, R. Torres-Torres, S.-W. Baek, M. Schauer, Stack-up and routing optimization by understanding micro-scale PCB effects, DesignCon 2011.

[6] G. Brist, B. Horine, G. Long, Woven glass reinforcement patterns, Printed Circuit Design & Manufacture, Nov. 2004, p. 28-33.

[7] H. Heck, S. Hall, B. Horine, T. Liang, Modeling and mitigating AC common mode conversion in multi-Gb/s differential printed circuit boards, in Proc. of 13th IEEE Meeting on Electrical Performance of Electronic Packaging (EPEP), Portland, OR, Oct. 25-27, 2004, p. 29-32.

[8] J. Loyer, R. Kunze, X. Ye, Fiber weave effect: Practical impact analysis and mitigation strategies, DesignCon 2007.

[9] G. Blando, J. R. Miller, I. Novak, Losses induced by asymmetry in differential transmission lines, DesignCon 2007.

[10] C. Herrick, T. Buck, R. Ding, Bounding the effect of glass weave through simulation, DesignCon 2009.

[11] P. Pathmanathan, C. M. Jones, S. G. Pytel, D. L. Edgar, P. G. Huray, Power loss due to periodic structures in high-speed packages and printed circuit boards, in Proc. of 18th European Microelectronics Packaging Conf., 2011.

[12] M. Schauer, G. Romo Luevano, R. Torres-Torres, C. Nwachukwu, S.-W. Baek, Understanding and mitigation of fiber weave effects in striplines, DesignCon 2012.

[13] R. Torres-Torres, G. Romo, M. Schauer, C. Nwachukwu, S.-W. Baek, Modeling resonances in transmission lines fabricated over woven fiber substrates, IEEE Trans. on MTT, v. 61, N 7, 2013, p. 2558-2565.

[14] P. Pathmanathan, P. G. Huray, S. G. Pytel, Analytic solutions for periodically loaded transmission line modeling, DesignCon 2013.

[15] S. H. Hall, H. L. Heck, Advanced signal integrity for high-speed digital designs, John Wiley & Sons, 2009.

[16] A. Sihvola, Electromagnetic mixing formulas and applications, IET, 1998.

[17] L. Ritchey, J. Zsio, R. Pangier, G. Partida, High speed signal path losses as related to PCB laminate type and copper roughness, DesignCon 2013.

[18] Simbeor Electromagnetic Signal Integrity Software, www.simberian.com

Published in Proc. of the 2014 IEEE International Symposium on Electromagnetic Compatibility, Raleigh, NC, USA, August, 2014, p.