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Opening Eyes on Fiber Weave and CAF

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Abstract

The signal channels that link high speed processors to memory and various other peripherals, are limited by the inherent characteristics of the printed circuit board. These are what ultimately connect information to the outside world. One limiting factor is the effect of non-uniformity of the glass fiber distribution in the printed circuit substrate material, also known as fiber weave effect (FWE). FWE introduces signal skew and timing errors which place an upper limit on bit rate and trace length.

Using unique fabrication techniques and a proprietary low dielectric constant glass composition, a revolutionary glass fabric is presented that is essentially free of fiber weave effect while demonstrating inherently improved resistance to conductive anodic filament (CAF) formation. Improved laminate performance is demonstrated with finite element modeling and HyperLynx simulations, and corroborated with dielectric property measurements on prototype substrates.

A printed circuit board using this material demonstrates superior signal integrity performance over the traditional glass-based solution. By uniformly distributing glass fibers the maximum surface area becomes available to bond with the resin, which is enhanced by direct application of a finish to provide a high quality interface between glass and resin. Two high profile performance issues, fiber weave effect and CAF, are addressed by a unique laminate reinforcement.

Introduction to Fiber Weave Effect

Fiber weave effect (FWE) is a performance-limiting factor due to a non-homogeneous spatial distribution of dielectric constant (Dk) of the PCB substrate. It becomes significant in 3 Gbps signaling design and beyond. Except under special circumstances, this discontinuous distribution is inherent to all glass fiber-reinforced laminate systems.

In the glass fabric, the warp and weft yarns form a weave pattern where the glass bundles are at 0, 1, and 2 yarn thicknesses (see Figure 1). The cross points have 2 yarn thicknesses and are often referred to as "knuckles"; the gaps between yarns have 0 yarn thickness. Each of these weave pattern features determines a localized Dk**,** and the boundary between each feature defines a spatial Dk discontinuity. The localized discontinuity is proportional to the difference in Dk (ΔDk) between the reinforcing glass fabric and the resin system.

Consider the localized contribution of each weave pattern feature where the glass fabric style defines the dimension and magnitude of each localized Dk in a laminate system. The respective displacements of resin at 0, 1, and 2 glass yarn thicknesses define the Dk of each feature. These features in each of the three cases induce a signal propagation delay along their associated conductor lengths.

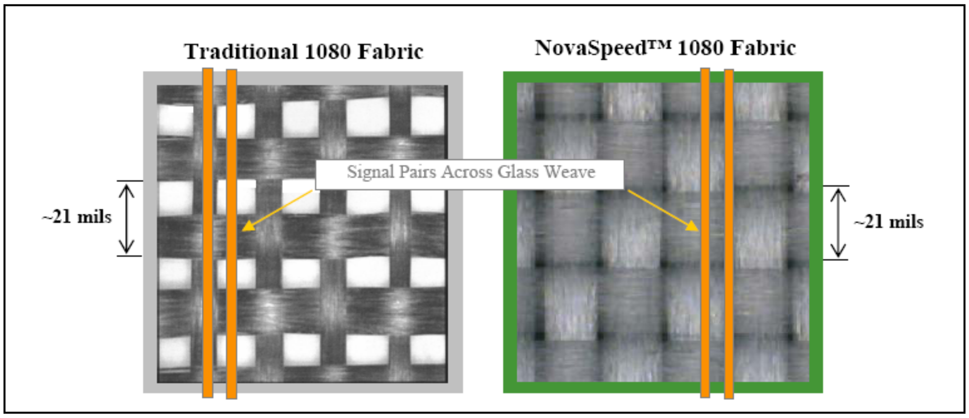


Figure 1 – Comparison of traditional and spread fiber low Dk fabric weaves, with 3-mil signal traces superimposed.

A spread fiber fabric has an exceptionally uniform distribution of glass fibers, when compared to a traditional glass fabric as shown in Figure 1. This allows it to overcome a major contributor to FWE, which is the weave pattern itself. Note that both fabrics shown are Style 1080 with equal amounts of glass. Optimization of the entire glass fabric manufacturing process with respect to these considerations results in a superior signal integrity solution at the laminate level.

A proprietary low Dk glass composition overcomes a second contributor to FWE, which is the difference in Dk between the glass and resin. There is an underlying phenomenon at play when considering the implication of FWE. Not only is it a result of areas of differential glass and resin content, but also the difference of glass versus resin Dk. A novel spread fiber low Dk glass fabric addresses both of these factors. It offers a unique reinforcement with superior glass fiber distribution for PCB laminates.[1]

As a signal propagates along a trace conductor in a typical glass fabric-reinforced laminate system, the localized composite Dk determines the signal propagation velocity and incremental propagation delay. Differences in propagation delay between signal pairs result in signal skew. Skew is defined (in EIA JEDEC Standard JESD65B) as *"The magnitude of the time difference between two events that ideally would occur simultaneously."*[2] The variations in signal skew**,** such as occur in differential signaling, determine the maximum bit rate obtainable on such a system. A variation in the accumulated propagation delay between conductor pairs is the total skew for a differential signal. Each signal trace has its own unique response, resulting in FWE-induced signal integrity limitations to high-speed system performance.

Performance Modeling and Verification

To assess system performance and predict the benefit of laminate materials, an internal tool was developed using finite element modeling (FEM) which predicts the ΔDk of the worst case scenario across a differential signal on any laminate system. Starting with glass and resin dielectric properties, an array of elements was modeled based on a standard fabric construction, as shown in Figure 1. By modeling copper traces aligned with the weave pattern and by maximizing intra-pair ΔDk, in a worst case scenario of intra-pair propagation delay will result. At a given conductor length, the difference of intra-pair propagation delays is calculated from the velocity equation as used by Loyer et al[3] (see page 6); this difference in propagation delays is skew. The FEM model gives a statistically worst-case scenario and corroborates with an Intel study of nearly 60,000 data points analyzing skew.[3,4] The model predicts a significant difference between the spread fiber low Dk and traditional E-Glass fabrics if all other parasitic effects are held constant. The prediction is for nearly an order of magnitude reduction in signal skew related to fiber weave effect.

To confirm the validity of this prediction, test panels were fabricated using traditional E-glass (as shown in Figure 1) and two versions of spread fiber fabric, one using E-glass and the other using low Dk glass. The test pattern included an array of traces overlaid on the woven glass structure. By measuring trace impedance, laminate Dk is calculated as a function of location. The max-to-min range of laminate Dk was measured at three frequencies for each of the three different test panel constructions as shown in Figure 2. These same ranges of laminate Dk values were calculated using the finite element model, with the model results and averages from Figure 2 given in Table I. For the two cases of a spread fiber configuration, the modeling is nearly identical to the measured values. The measured ΔDk values were produced from a laminate built up from several layers of glass fabric. The model predictions are based on a single layer of fabric and give a more likely worst case range of values, independent of sample size.

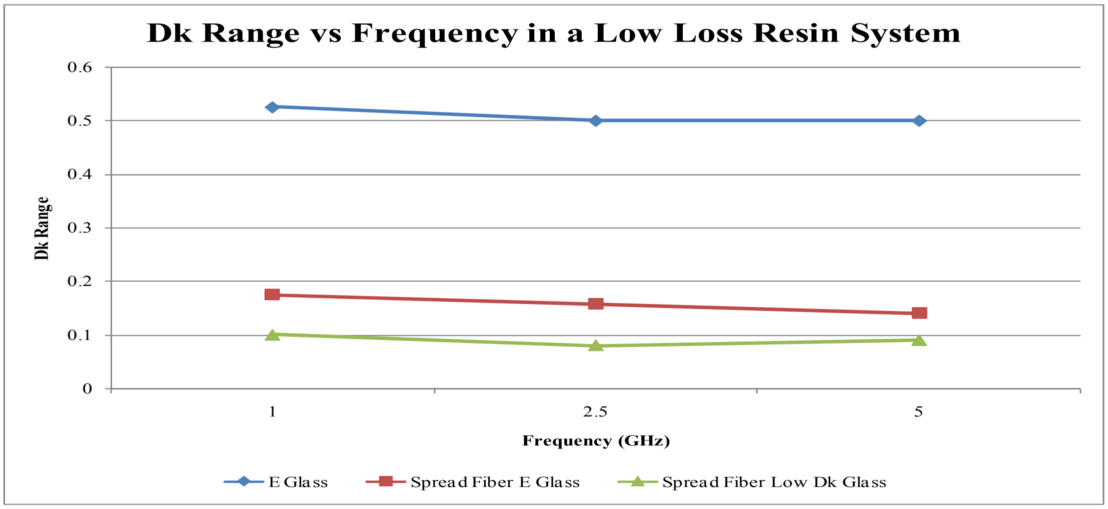


Figure 2 – Measured laminate Dk variation for traces overlaid on woven fabric reinforcement.

In comparing the predicted values of Dk to the measured values from test panels, it is confirmed that the finite element model gives accurate performance estimates. Validation of ΔDk prediction, with real samples, allowed for further extrapolation (FR-4). More importantly, the spread fiber glass configuration demonstrates a significant reduction in Dk variation and therefore a corresponding decrease in signal skew due to fiber weave effect.

Table I – Measured and Predicted Laminate Dk Range

Fabric Type	Resin Type	Average Dk	Measured ΔDk	Predicted ΔDk
E Glass	Low Loss	3.80	0.50	0.62
E Glass	FR-4	4.25	---	0.47
Spread Fiber (E Glass)	Low Loss	3.80	0.14	0.12
Spread Fiber (Low Dk)	Low Loss	3.65	0.09	0.08

HyperLynx Simulation

Fiber weave effect was simulated using Mentor Graphics' HyperLynx GHz software. This allows an assessment of the impact on signal integrity and further corroboration of the performance predictions. Pairs of microstrip traces were specified with different (max or min) laminate dielectric constants, as calculated from the average and ΔDk values given in Table I. These corresponded to whether each trace in a pair was located over a glass strand (longer signal propagation delay) or between glass strands (shorter propagation delay). The HyperLynx LineSim model for a 100 ohm, 24 inch microstrip using spread fiber low Dk glass is shown in Figure 3.

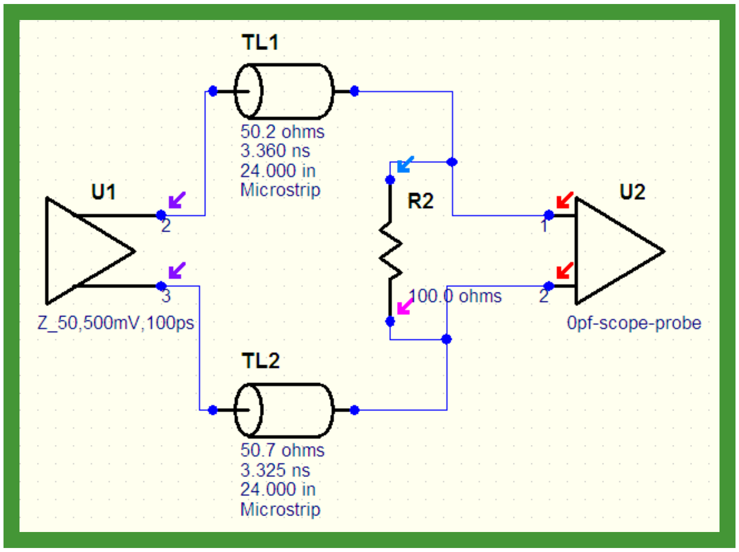


Figure 3 – Example of HyperLynx LineSim model used for simulating fiber weave effect.

To simulate fiber weave effect on a differential pair requires a ΔDk across the respective traces. This is achieved in HyperLynx by modeling two microstrips with substrate dielectric constants of average Dk plus ΔDk/2 and average Dk minus ΔDk/2, respectively. HyperLynx generates eye diagrams and bit error rate (BER) plots (also called bathtub plots). An illustrative pictorial of an eye diagram is shown in Figure 4. Eye opening is defined as the width of the eye as a proportion of the unit interval (T_B). The accepted standard[5] for system performance is a BER of less than 1 in 10^{12}. This is the metric used for determining the bit rate at a given trace length that is achievable on various laminate systems. In the region of interest, it can be shown that signal skew is proportional to ΔDk. As bit rate increases for a given skew, the skew portion of a bit interval increases and eye opening is decreased.

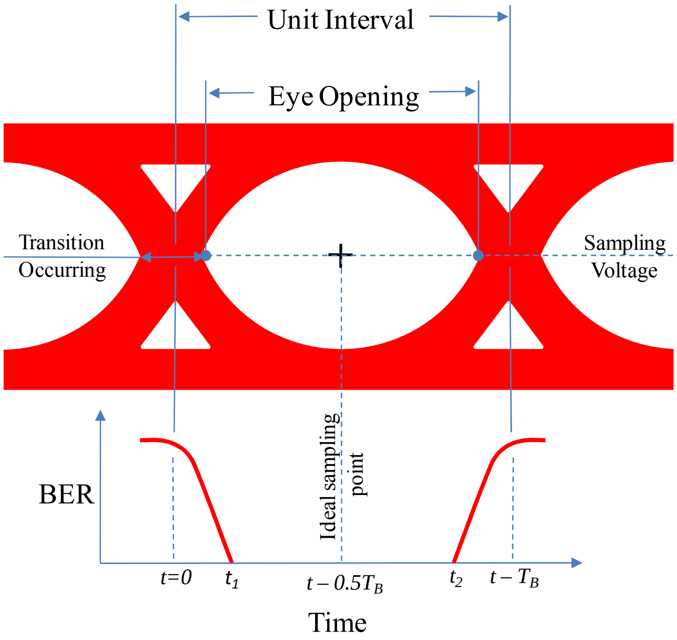
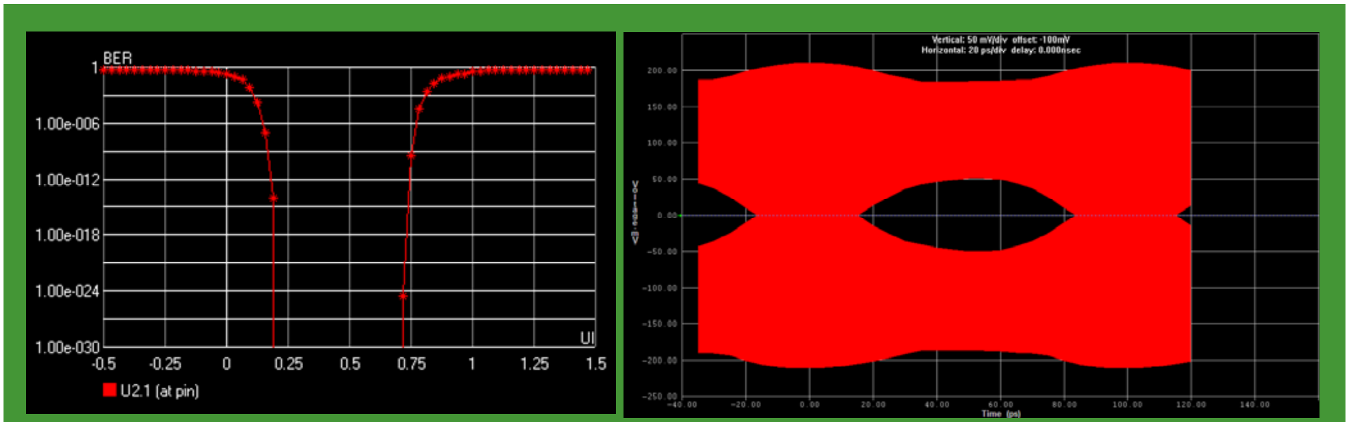
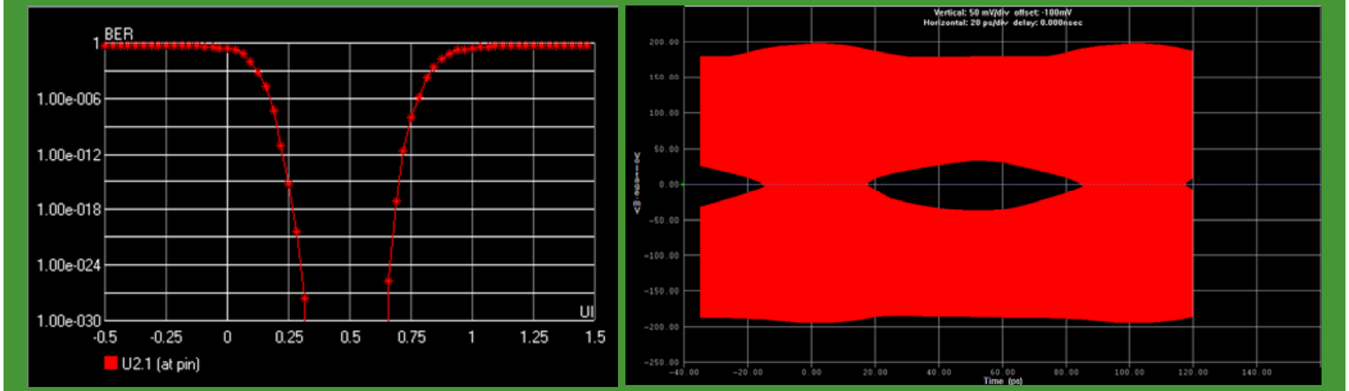


Figure 4 – Eye diagram showing eye opening relation to a bathtub plot. According to IEEE 802.3 a bit error rate (BER) of $1x10^{-12}$ at the receiver is specified.

The simulation was run with a 10 bit pseudo random binary sequence (PRBS) at increasing bit rates and trace lengths while monitoring bit error rate and reduction of eye opening. As an example, Figure 5 shows bit error rates and eye diagrams for spread fiber low Dk glass at 10 Gbps and trace lengths of 18, 21 and 24 inches. At 24 inches the eye opening shrinks to 0.2 T_B.



NS, 10Gpbs, 18in



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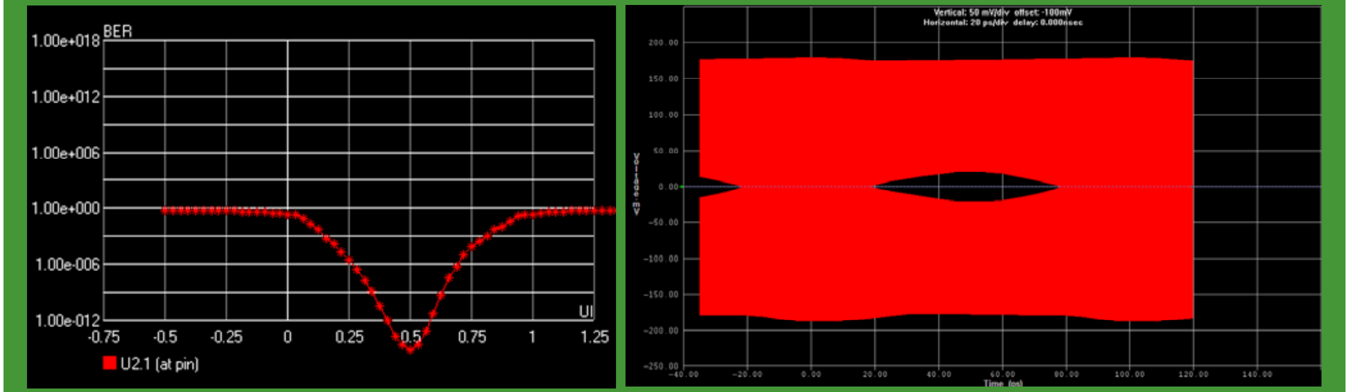

NS, 10Gpbs, 24in

Figure 5 – Bath tub plots and their respective eye diagrams for spread fiber low Dk glass at 10 Gbps and trace lengths of 18, 21 and 24 inches.

The HyperLynx simulations also report propagation delays from which signal skew can be calculated. These are compared to the signal skews predicted by the FEM model and further corroborate the calculations as shown in Table II. The HyperLynx simulation used actual laminate and copper designs which take into account trace and laminate geometry and dielectric properties.

Table II –Predicted and Simulated Skew of 100 ohm Differential Pair

Fabric Type	Resin Type	HyperLynx Simulation (ps/in.)	FEM Predicted (ps/in.)
E Glass	Low Loss	9.87	13.8
E Glass	FR-4	7.26	9.71
Spread Fiber (E Glass)	Low Loss	2.23	2.52
Spread Fiber (Low Dk Glass)	Low Loss	1.46	1.83

Simulations were run at 2.5, 5.0, 7.5 and 10 Gbps and increasing trace lengths to determine the maximum bit rate and length at which an eye opening of 0.32 T_B and BER of $1x10^{-12}$ is achieved. The results are shown in Figure 6 for four different laminate systems. The simulations at 10 Gbps showed moderate signal degradation at the driver. It is expected that all of the laminate systems tested would perform marginally better at 10 Gbps than in the simulations.

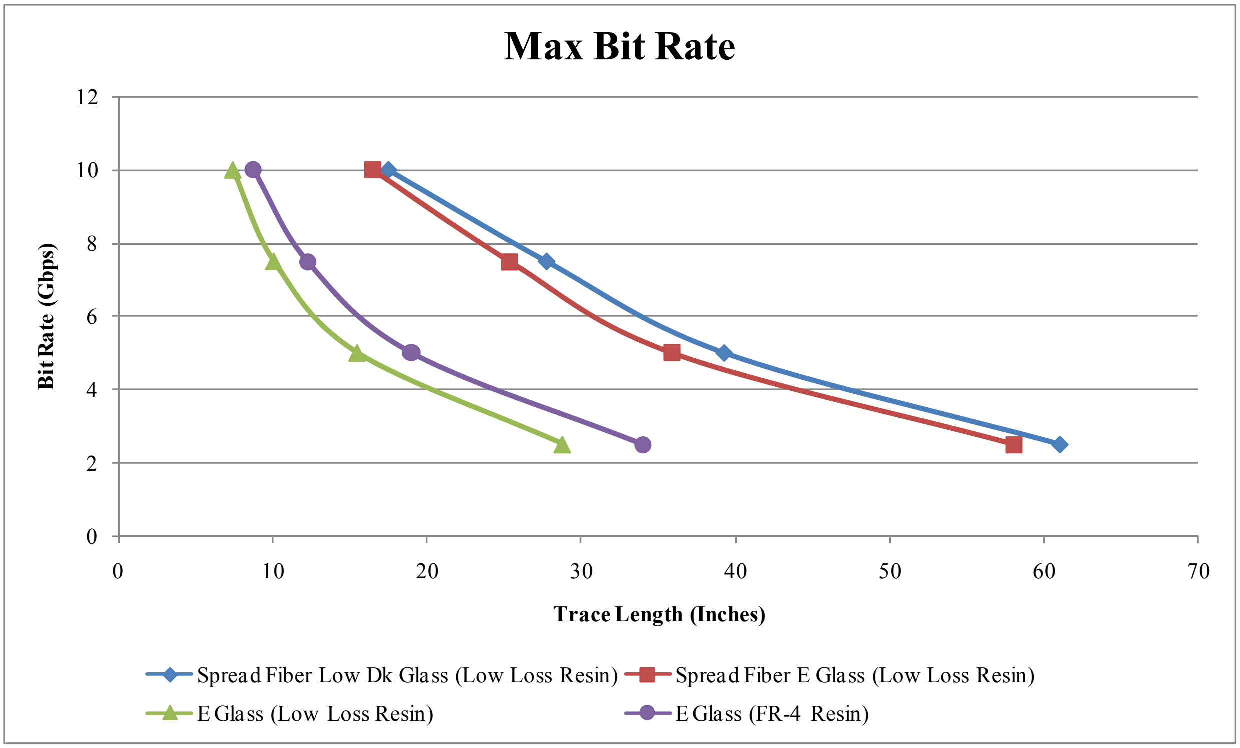

Figure 6 – Max bit rate achievable as a function of skew for varying trace lengths. Eye width simulated at $\Delta t_{1,2} = 0.32T_B$ and a bit error rate of $1x10^{-12}$.

As seen in Figure 6, the traditional fabric is limited to about 8-inch trace length at 10 GHz compared to over 16 inches for either of the spread fiber fabrics. It is an interesting point that the simulation indicates slightly better performance for the standard FR-4 resin than for a high end low loss resin regarding fiber weave effect. This is because fiber weave effect is driven by the difference in dielectric constant between the resin and the glass reinforcement. FR4 has a higher dielectric constant than the low loss resin and is closer in value to E glass. As expected, the spread fiber low Dk fabric has better performance than spread fiber E glass and demonstrates the best performance of the four systems simulated. Overall, the spread fiber fabrics allow either a doubling of trace length or a doubling of bit rate, as compared to traditional fabric in the range of 2.5 to 10 Gbps.

CAF Resistance

Spread fiber glass fabrics with a direct finish were expected to offer improved resistance to conductive anodic filament (CAF) formation and this is now demonstrated. By spreading the glass fibers the maximum surface area becomes available to bond with the resin, while direct application of a finish (no heat cleaning) provides a high quality interface between glass and resin. This results in a very robust laminate with excellent hydrolysis resistance and improved immunity to electrochemical migration (ECM) failures. CAF is a type of ECM failure that typically occurs at the glass fiber-to-resin interface.

To assess the benefit of both spread fiber low Dk glass fabric and spread fiber E glass fabric as compared to traditional technology, an aggressive testing regimen was performed. Three sets of test boards were fabricated. A commercially available high Tg CAF-resistant laminate system (made with traditional E glass) was used for the control. Laminates and prepreg were then made using the same commercial high Tg resin system with the spread fiber low Dk glass and spread fiber E glass fabrics. The boards were baked and subjected to four consecutive reflow cycles at either 245°C or 260°C, as might be experienced using lead free assembly processes allowing for rework. Then a typical CAF resistance test was performed similar to IPC-TM-650 2.6.25.[6] The purpose of the reflow cycles was to force measurable failure rates while staying within ranges of temperature and humidity that could be experienced in fabrication and operation.

Test results from this aggressive regimen, shown in Table III, demonstrate that a common high end CAF-resistant system exhibited ECM/CAF failures in every instance. In both versions of spread fiber fabric, a significant proportion of the boards passed the test. Curves representing average Log resistance are shown in Figure 7 for the passing test boards. There was insufficient data to generate a curve for the test boards which used traditional E glass fabric. It should be noted that both of the spread fiber fabrics were manufactured using a proprietary direct finish technology for an improved glass-to-resin interface.[1] Furthermore, an analysis of actual failures suggests that an effective approach to improving CAF resistance is to treat the substrate as a high performance composite and design for superior hydrolysis resistance.

Table III – CAF Test Results

Glass Fabric	% Pass
Traditional 1080 E Glass	0%
Proprietary Spread Fiber E Glass	31%
Proprietary Spread Fiber Low Dk Glass	56%

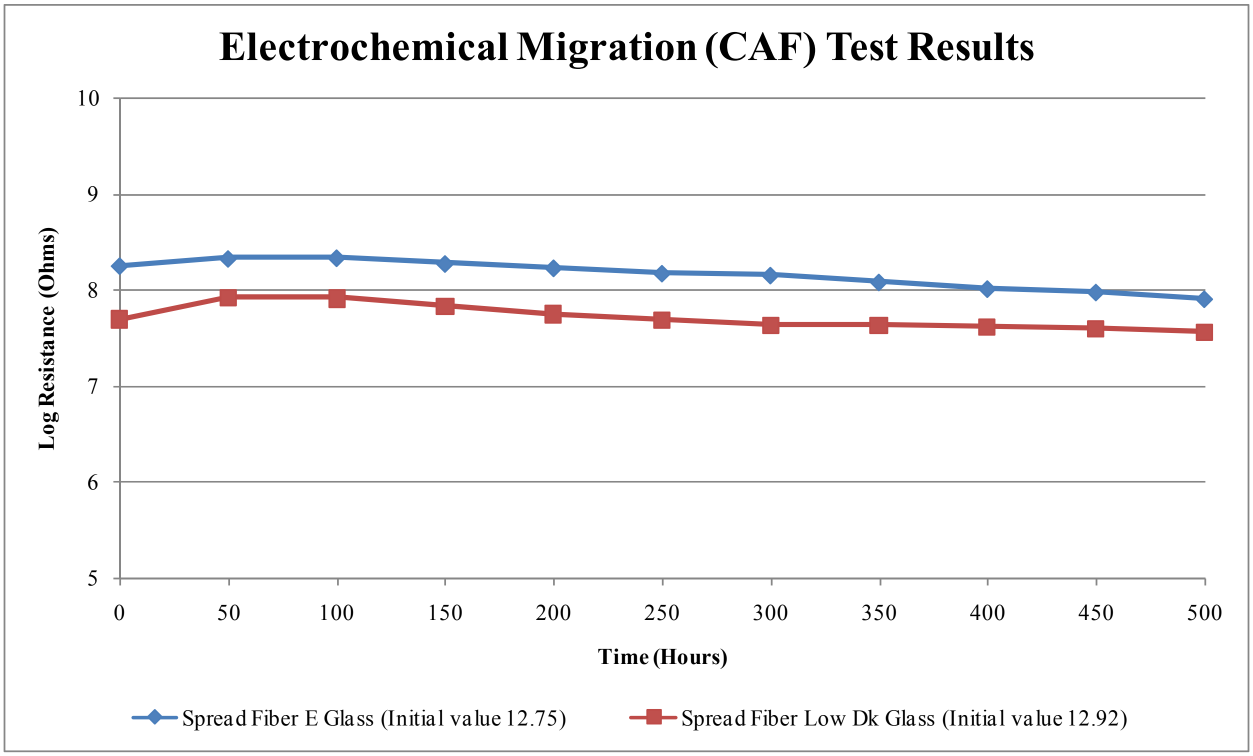

Figure 7 – Log resistance measurements of boards during CAF test.

Hollow Fibers

ECM/CAF failures are known to have occurred due to hollow fibers in the glass reinforcement. While the appearance of hollow fibers is relatively infrequent today with traditional E glass, commercial low Dk glass yarn faces unique manufacturing challenges associated with high temperature glass melting. The proprietary spread fiber low Dk glass fabric used for these tests is certified to be hollow fiber free and fully wets when impregnated with resin.

Additional Considerations

Homogeneous glass fabric allows for an even distribution of energy during the laser ablation process. Consequently, laser drilled microvias are processed faster and cleaner with fewer failures. Mechanically drilled holes are also more uniform and minimize damage and separation between the resin and glass fibers. This was amply demonstrated in the CAF testing results which show a much more robust composite than that produced using traditional substrate materials.

Conclusions

The question has been asked for the industry to provide a solution to Fiber Weave Effect. Many solutions have been proposed to *mitigate* FWE.[3,7] However, we propose that to *eliminate* FWE it must be addressed at the earliest stages of manufacture, at glass fabric manufacture. By solving the two contributing factors to FWE, ΔDk and homogeneous fiber distribution, this new technology is the complete and unique solution to FWE. Based on finite element modeling, HyperLynx simulations and subsequent verification by measurement, a new level of high-speed design is anticipated using existing FR-4 processable resin systems. Bogatin[8] alluded to increasing difficulties meeting tighter skew specifications in systems over 3 Gbps, due to glass weave / signal line interactions. The use of new spread fiber glass fabrics with low loss resins have demonstrated the capability to reduce skew by nearly an order of magnitude and permit designs up to 10 Gbps and beyond.

The proposed solution of a spread fiber glass fabric using direct finish technology has also demonstrated significant performance advantages beyond elimination of FWE. It appears that, with spread fiber technology, elimination of FWE and CAF resistance are integrally connected. The use of advanced composite technology offers an improved resin-glass interface and demonstrates superior CAF resistance. Two performance issues are addressed with one unique product.

Test results to date have verified the modeling and prediction of FWE elimination, as well as material characteristics such as CAF resistance, laser drilling, and other requisites of a performance material solution. Further work is in progress to empirically define performance capability, particularly in the area beyond 10 Gbps.

Acknowledgements

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