PTFE based Solutions for the Future of High Speed Digital

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Abstract
A growing need is developing in the high-speed digital arena (backpanels, motherboards, line cards etc) for materials offering sufficient signal integrity for applications up to 10 Gbps. One solution is a PTFE/ fiberglass/thermosetting resin composite[1] that can be processed at conventional PCB pressures and temperatures. Because the PTFE can be applied in a high volume process by a PTFE processor and the thermosetting resin can be applied in a large scale manufacturing process using commercial treaters, the volume manufacture of PTFE based laminates can be achieved in a cost effective fashion. The prepregs and laminates are based on a PTFE/fiberglass/BT-epoxy composite that is treated with 10-40 wt% of a thermosetting resin. The resulting composite has demonstrated signal integrity in a 20 layer backplane that is very competitive relative to a pure PTFE/fiberglass construction[2]. The hybrid has a very low dissipation factor when 15-40 wt% thermosetting adhesive is used (0.004-0.005 at 14.5 GHz). The PTFE/fiberglass/BT-epoxy composite provides good bonding to substrates at conventional processing temperatures, gap filling of 2 oz circuitry, very high thermal stability, and predictable movement. Preliminary results suggest that the materials drill better than standard PTFE boards.

Introduction

The challenges posed by future high-speed digital applications has pushed designers to look for materials with increasingly lower signal loss at high frequency. To meet this challenge, material suppliers are offering a variety of different chemistries. Although there will always be a market for FR4 operating at the conventional 2.5 Gbps, the challenge of the future is to offer improved signal integrity over 20-50 inch trace lengths at higher data rates. The marketplace has seen a transition from FR4 like materials to PPO resin systems. In short, the marketplace is slowly moving toward the performance domain primarily occupied by PTFE based products and other substitute materials. Substitute materials currently being considered for high data rate applications are not necessarily cheap and have the following drawbacks: expensive glass styles, thermoplastic resin systems that present real challenges with regard to flow, materials with excessive movement, and elastomeric/ceramic resin systems that are challenged by poor drill hit counts and low copper bond strengths.

Polytetrafluoroethylene (PTFE) has a long history of meeting the needs in microwave applications up to 77 GHz. PTFE based materials reinforced with woven glass fabric have traditionally offered the advantage of very low loss (0.001-0.003 @ 10 GHz) depending on the PTFE resin content of the composite. A general adoption of PTFE based laminates has been slowed by the perception that PTFE based solutions are expensive and must be processed differently. Surprisingly, PTFE based composites have become competitively priced as they have been adopted by larger OEMs for the telecommunications infrastructure. This has occurred despite the fact that the volume limitations of PTFE manufacturing have not been overcome. In other words, certain PTFE based composites have reached attractive cost/performance levels despite the long press cycles-higher costs, required to manufacture PTFE laminates. PTFE/fiberglass/BT-epoxy laminates, however, overcome the volume manufacture limitations posed by standard PTFE laminates, enabling their manufacture using conventional FR4 cycles and infrastructure.

The PTFE/fiberglass/BT-epoxy approach uses the infrastructure of known materials and combines their performance and benefits. The PTFE/fiberglass is used to offer the low loss characteristics necessary for future signal integrity (SI) demands. The thermosetting resin is used uniquely as an adhesive and is used only as needed. The thermosetting resin of choice is BT-epoxy that is known to be a low risk, reliable, high flowing resin that has seen used in packaging applications. The following characteristics of such a material design will be described with respect to the high speed digital marketplace: (1) the composition of the product (2) processing of the composite (3) various physical aspects of the composite (4) dielectric properties (5) and SI measurements obtained from a test vehicle.

Discussion

The material in its simplest form is a fiberglass reinforced PTFE system that contains a thermosetting resin adhesive. The composite can be used as a **prepreg** or as a **core** material by laminating copper onto its surface. An unclad laminate of the product can be seen in Figure 1. Figure 1 contains a ceramic filled PTFE giving it a white appearance, fiberglass, and a layer of filled BT-epoxy. The approach offers the following levels of flexibility:

- the amount of thermosetting resin can be varied depending on the gap filling required
- the balance between the PTFE/fiberglass can be varied depending on the level of signal integrity desired. An increasing weight of PTFE will lead to a correspondingly lower dielectric constant and loss
- the material can be optimized as a **core** material using low levels of adhesive or a **prepreg** using higher levels of epoxy. For core materials, a lowered BT-epoxy level lowers the loss at 10 GHz to ~ 0.0040.
- the amount of flow of the prepreg is directly related to the level of thermoset used. It is anticipated that varying levels of thermosetting resin will be offered depending on whether demand requires the filling of 0.5, 1.0 oz, or 2.0 oz circuitry. Prepreg materials containing high levels of BT-epoxy to fill 2 oz trace will increase the loss at 10 GHz to ~ 0.0050
- any woven or non-woven reinforcement can be readily used.

The fiberglass reinforcement helps to offer the hybrid good dimensional stability whereas non-reinforced PTFE/thermosetting resin/ceramic composites have been challenged at the higher layer counts due to excessive movement. Figure 2 is a laminate based on non-filled PTFE, 1080 fiberglass, and ceramic filled BT-epoxy. PTFE appears as an almost clear but opaque layer. The ceramic filled BT-epoxy layer is observed in Figure 2 as a flat white layer. The design of the product allows one to add ceramic to any portion of the composite, and potentially to add reinforcement to any portion of the composite. Figure 2 is shown for demonstrative purposes only as this design is not currently being manufactured. The demands of the high speed digital marketplace do not require this level of performance. However, Figure 2 supports the notion that one advantage of this approach is that a substrate can be used having very high loadings of PTFE.

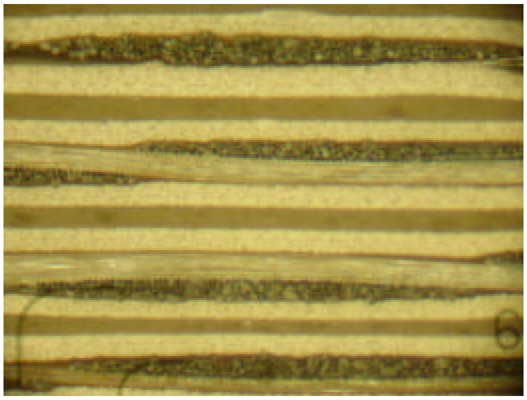


Figure 1 - Photomicrograph of Ceramic Filled PTFE/Fiberglass/BT-Epoxy Laminate

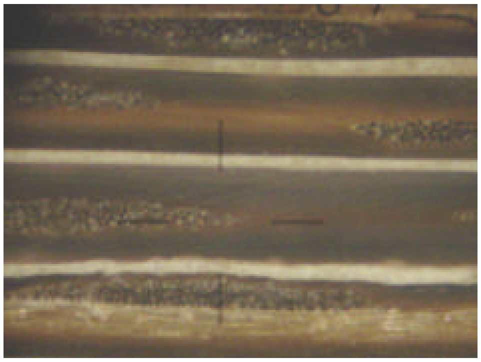


Figure 2 - Photomicrograph of PTFE/Fiberglass/BT-Epoxy Laminate (1080 Fiberglass)

The dependence of the dielectric constant and dissipation factor on frequency is shown in Figure 3 (Bereskin method-stripline resonator).[4] As shown in Figure 3, the dissipation factor up to the 10 GHz range is less than 0.003. The dielectric constant is flat over this frequency at 2.58. This low dielectric constant should be particularly attractive to designers. Low dielectric constant enables the use of thinner dielectric spacings in thick multilayers. Figure 3 also supports the notion that this PTFE approach has the legs to provide designers with enough signal integrity extending well out into the future.

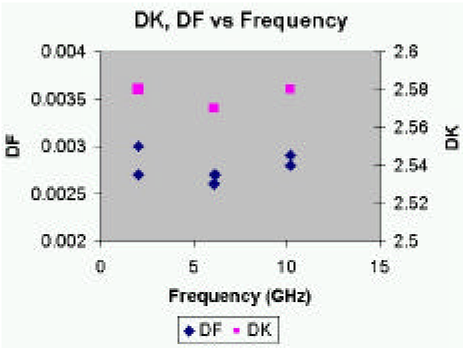


Figure 3 - Dielectric Constant and Dissipation Factor for a PTFE/Fiberglass/BT-Epoxy Laminate having a High PTFE Content[4]

The following lamination conditions are recommended when using this PTFE/fiberglass/BT/ceramic hybrid: heat rise of 10°F(5°C)/minute to 392°F/200°C. The critical flow window is from 140°F (60°C) to 302°F (150°C). The recommended hold time is 60 to 90 minutes. Cooling should be less than <6°F (3°C)/minute. A previously published paper suggests that the minimum viscosity is reached around 150°C with the onset of the viscosity decrease occurring at 130°C.[5] The data was obtained from a PTFE/fiberglass/BT-epoxy/ceramic hybrid containing only 15 wt% BT-epoxy. With 15 wt% BT-epoxy, 1.0 wt% resin flow was observed. This preliminary result suggested that the product behaved like a no flow prepreg. However, the degree of flow can be readily varied and optimized by those experienced in the art. As high as 14 wt% resin flow is observed in optimized prepreg having 35 wt% BT epoxy.

Figure 4 shows the conformance of the PTFE/fiberglass/BT-epoxy (15 wt% BT-epoxy) to 0.5 oz circuitry.

Figure 5 shows the conformance of the PTFE/fiberglass/BT-epoxy (22 wt% resin) to 1 oz circuitry. It has been observed that the PTFE/fiberglass/BT-epoxy hybrids having high levels of resin, 35 wt% for example, fill 2 oz traces over a much wider processing window.

Figures 6 and 7 show the gap filling ability of a 35 wt% BT-epoxy hybrid at 4°F and 10°F/minute heating rates, at 350 psi (200°C). An analogous result was observed for a rate of heat rise of 20°F/minute. This suggests that the higher flowing 35 wt% BT-epoxy/PTFE/fiberglass prepreg can be processed at FR4 like conditions. The high levels of BT-epoxy seem to fill gaps with a much lower level of PTFE/fiberglass conformation to the outline of the copper circuitry. The PTFE/fiberglass/BT-epoxy is compatible with standard oxide innerlayer treatments. One further advantage of this approach is that costs can be taken out of the multilayers at the board fabrication level by using foil lamination.

Figure 4 - PTFE/Fiberglass/BT-Epoxy Prepreg (15 wt% BT-Epoxy) Filling 0.5 oz Circuitry

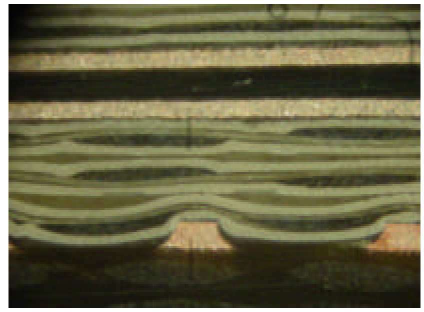


Figure 5 - PTFE/Fiberglass/BT-Epoxy Prepreg Filling 2 oz Circuitry (22 wt% BT-Epoxy)

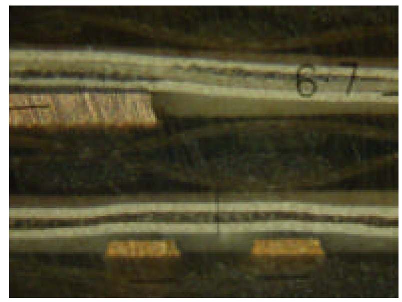


Figure 6 - PTFE/Fiberglass/BT-Epoxy Prepreg Filling 1& 2 oz Circuitry [35 wt% BT Resin, 4°F(2°C)/min Heat Rise].

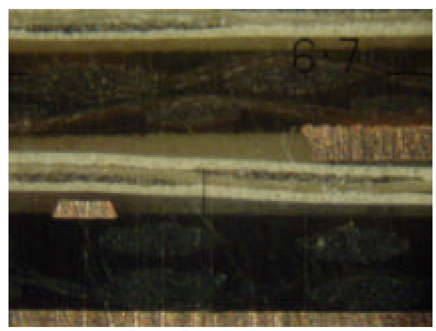


Figure 7 - PTFE/Fiberglass/BT-Epoxy Prepreg Filling 1&2 oz Circuitry (35 wt% BT Resin, 10°F(5°C)/min Heat Rise

The dependence of glass transition temperature on the rate of heat rise during lamination and the length of the hold time at temperature (392°F/200°C, 450 psi) was evaluated. The results are described in Table 1. The glass transition temperature does not seem to be dependent on the ramp rate in the press, nor the hold time. This result is confirmed by both the DSC derived glass transitions and the TMA derived glass transitions. However, the glass transitions determined by the two methods should be treated somewhat skeptically. PTFE has a constant rate of expansion between room temperature and the 340°C gel state, such that only a relatively weak transition for the BT-epoxy is observed. Because the bulk of the polymer composition is PTFE, the glass transition of the BT-epoxy is not as well pronounced compared to an all epoxy system. Very weak transitions as indicated by a slope change is observed by DSC for all samples between 140-150°C. The TMA scans for the materials are complex suggesting that there are two or more relaxations taking place. Although a TMA derived glass transition is reported in Table 1 for what looks to be the dominant change in slope, it should be acknowledged that there are multiple slope changes occurring in the samples suggesting a much more complicated combination of relaxations that occur during heating. This is confirmed by the dynamic mechanical analysis scans that were used to analyze the materials with different rates of heat rise/hold times during lamination (see Table 1). DMA suggested two relaxations, one between 120-130°C and a second from 150-160°C. DMA was conducted in duplicate. In a limited number of cases a single transition was observed at the midpoint between 120 and 160°C, while a second scan would show the two transitions. The low temperature peak from 120-130°C is generally a weak peak, a shoulder, or non detectable. In any event, the results suggest that with regard to **glass transition**, equivalent results are obtained whether laminates are held in the press for one or two hours, or the ramp rate is 4°F(2°C) or 10°F(5°C)/minute. This is confirmed by CTE measurements that appear independent of the rate of rise or a 60 to120 minute hold time. CTE measurements will be described in more detail in a follow-up publication. The overall data suggest that the following processing window will yield the best results:

- 60-90 minute hold time at 392°F/200°C
- Heat rise 10°F(5°C)/min (flow window 176°F/80°C–302°F/150°C)
- Cool-down under pressure @<6°F(3°C)/minute

Preliminary data suggests that the hybrid can be processed using drill parameters typical for a related PTFE/fiberglass product.[3] New carbide FR-4 drill bits should be used. Resharpened bits should not be used. Entry materials should be 0.012-0.020 inch paper phenolic and the exit material should be 0.090-0.125 inch phenolic fiberboard. Initial results suggest that 10 mil holes can be drilled with 10-1 aspect ratios, details of which will be described in a later publication. Drilling parameters for PTFE/fibreglass and PTFE/fibreglass/BT-epoxy composites differ slightly from those made from all thermoset plastic multilayers. This is entirely attributed to the relatively softer nature of PTFE. Similarly however, the objective of drilling is to remove material in a manner that minimises mechanical distortion while preventing the softening and possible smearing of resin over exposed inner layers. A study by German tool manufacturer HPTec showed that a combination of relatively fast parameters and suitable tooling could help to achieve this aim. The fast feeds and speeds prevent the PTFE from heating up and smearing.

Mechanical distortion can be minimised with slower drilling parameters. The downside can be the creation of smear, even on high-melt PTFE materials. On the other hand minimising smear can be realised with more aggressive parameters. This discrepancy can be satisfied with the correct combination of feeds/speeds and drill-bits that are specially designed for such conditions. A spade-type geometry for small diameters (< 0.5 mm) is ideal for this application. Additionally a higher helix angle of 40° allows higher flute capacity and enables faster parameters.

HPTec drill bit types 210 (for ∅ <0.55 mm) and 540 (for ∅ >0.50 mm) were used to drill 10 layer PTFE/fibreglass / PTFE/fibreglass/BT-epoxy multiplayer pwbs.[6] These drill types were developed for complex multilayer boards that require the highest hole-wall-quality. An example of drilling parameters[4] and PTH quality is shown in Figure 8. Of equal importance is the drill-stack composition. The use of a relatively thick entry material like a 1.5 mm phenolic paper laminate offers the best stability and prevents damage to panel surfaces while melamine coated wood-based board offers the best back-up material.

Table 1 – Glass Transition Temperatures of PTFE/Fiberglass/BT-Epoxy Laminate by DSC, TMA, and DMA

Sample	Wt% BT-Epoxy	Heat Rate (°C/min)	Hours (392°F)	Tg/°C (DSC)	Tg/°C (TMA)	Tg/°C (DMA)
1-1	22	8	2	142	155	126/150
1-2	35	8	2	-	152	124/162
2-1	22	8	1.5	142	160	125/148
2-2	35	8	1.5	146	162	123/158
3-1	22	8	1.0	145	156	127/155
3-2	35	8	1.0	143	156	123/158
4-1	22	4.2	2	142	160	126/154
4-2	35	4.2	2	148	160	124/160
5-1	22	5.7	2	149	152	132/152
5-2	35	5.7	2	147	156	123/165

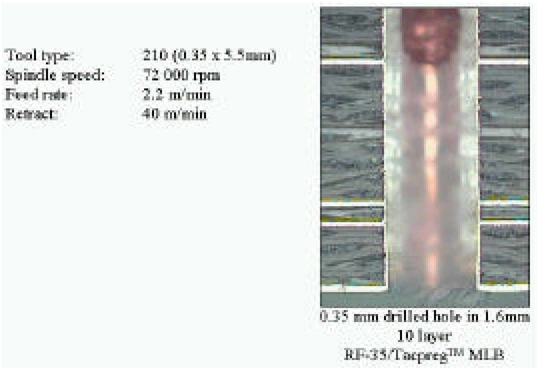


Figure 8 - 10 Layer Multilayer made using PTFE/Fiberglass[2] Laminate Cores and PTFE/Fiberglass/BT-Epoxy[3,4] Prepreg

A fluorescing aid is readily compatible with the resin system and has been deployed to help overcome issues related to automated optical inspection. 6X solder floats on 0.171" 20 layer backplanes suggest that plated through hole reliability is robust, the results of which have been published earlier[2]. IST and CAF testing are in progress and will be reported at a later date. Preliminary scaling factors that have been used successfully for backplanes are –350 ppm in the fill yarn direction and + 350 ppm in the warp yarn direction.

Some of the physical properties of the PTFE/fiberglass/BT-epoxy hybrid properties are listed in Table 2. The electrical properties will be addressed in a later section. The BT-epoxy was chosen because it is a highly reliable resin system with good peel strengths. Essentially it is the BT-epoxy adhesive that is directly responsible for copper bond adhesion. Therefore, a low risk approach was taken utilizing a robust varnish system. An internal requirement was satisfactory adhesion to 0.5 oz reverse treated foil that poses the most difficult condition to obtain copper adhesion. Five to six lbs of adhesion are typically obtained. 24 hour immersion/23°C in water yields a moisture uptake of typically 0.1 wt%. The product is thermally very stable. TMA time to delamination tests shows a value of >30 minutes at 300°C. Again, resin flow can be readily modified with the degree of b-staging and other factors. The hybrid material currently has a 105°C V0 rating and work is in progress to raise the relative thermal index (RT). Based on screening work by UL Laboratories and initial data, a final RTI from 140-150°C is anticipated.

The dissipation factor and dielectric constant are relatively flat over frequency when experimental error is taken into consideration. Figures 9 and 10 show the dependence of the dielectric constant and dissipation factor on frequency. The dielectric constant seems quite constant using 15 or 35 wt% thermosetting resin. For both the 15 and 35 wt% BT-epoxy samples the deviation from 1-15 GHz seems to be from 3.20 to 3.18-3.19, a measurement that challenges the accuracy of the method due to the little variation that is observed. The dissipation factor over frequency is largely flat for both the 15 and 35 wt% BT-epoxy hybrids. Surprisingly, the difference in loss is relatively low. At 14.5 GHz the loss is 0.0043 for the 15% resin content hybrid vs 0.005[1] for the 35 wt% BT-epoxy hybrid. This surprisingly low degree of variation suggests that the amount of adhesive, the BT-epoxy, can be varied over quite a large range to obtain the optimal balance between gap filling and electrical performance. For **core material**, where the major requirement is only to bond copper to the hybrid, a relatively low loading of adhesive can be used. For applications requiring a significant amount of gap filling, a high adhesive content can be used without a significant compromise in the dissipation factor or a change to the dielectric constant.

Table 2 - Physical Properties of the PTFE/Fiberglass/BT-Epoxy Laminate

Property	**Units**	**Typical Value**	**Method**
Dielectric Constant (1 MHz, 15-35% resin)		3.20	IPC-TM 650 2.5.5
Dielectric Constant (10 GHz, 15-35% resin)		3.19	Bereskin[4]
Dissipation Factor (1 MHz, 15% resin)		0.0022	IPC-TM 650 2.5.5.5
Dissipation Factor (14.5 GHz, 15% resin)		0.0043	Bereskin[4]
Dissipation Factor (14.5 GHz, 35% resin)		0.0050	Bereskin[4]
Peel Strength (warp) 0.5 oz reverse treated foil	lbs	5.6	IPC-TM 2.4.8
Peel Strength (fill) 0.5 oz reverse treated foil	lbs	6.4	IPC-TM 2.4.8
Moisture Absorption	(%)	0.1	IPC-TM 650 2.6.2.1
T260/T288/T300	min	>600/>60/>30	
Glass Transition	(°C)	Non-detectable 128, 177 150-160	(DSC) (DMA) (TMA)
Resin Flow	(%)	1-14	IPC – TM 650 2.3.17

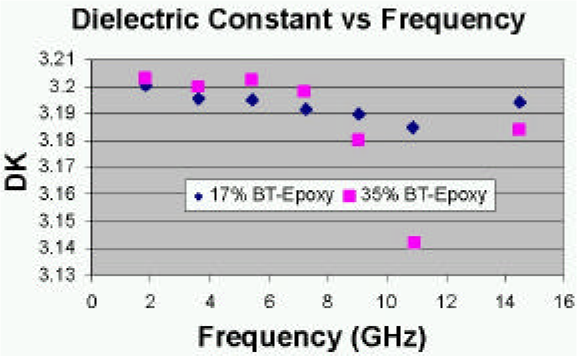


Figure 9 - Dielectric Constant vs Frequency for PTFE/Fiberglass/BT-Epoxy Laminates of Varying Resin Content (Bereskin[1]).

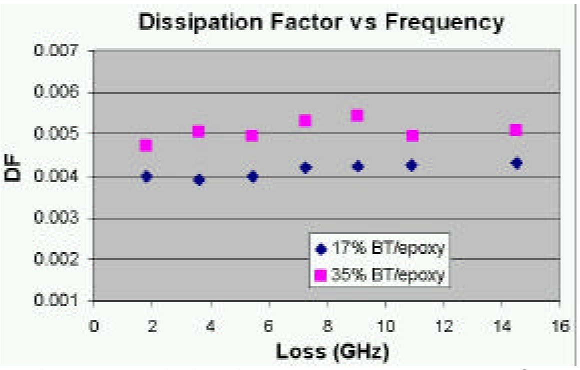


Figure 10. Dissipation Factor vs Frequency for PTFE/Fiberglass/BT-Epoxy Laminates of Varying Resin Content (Bereskin[1])

A 20-layer test vehicle designed especially for SI measurements was prepared by Teradyne Connection Systems. The 20-layer test vehicle can be seen in Figure 11. The 20-layer test vehicle consists of alternating signal and ground planes (foil lamination). The SI vehicle is designed as follows: 18 x 24", 1 oz copper, 8 mil innerlayer cores of a PTFE/fiberglass composite, bonded together by 3 plies of the PTFE/fiberglass/BT-epoxy hybrid, trace widths of approximately 8 mil, an impedance close to 100 ohms, using a differential stripline configuration/edge coupled differential (two parallel traces spaced at roughly 9 mils apart, the traces having a ground plane above and below the traces to yield the stripline configuration), and copper traces of 10 and 20 inches in length. The multilayer was pressed together using processing conditions similar to those recommended above. The hole walls were treated with plasma.

SI measurements were made by attaching two FR4 daughter cards to the backplane using Teradyne's GBX™ connectors. The random sequence of bits are generated by a HP70340A Signal Generator (HP70004A display, 1-20 GHz) connected to a daughter card by cable and SMA connector. The signal then exits the daughter card through a GBX™ connector into the backplane under test. After conduction along a 10" or 20" copper trace, the signal exits via a GBX™ connector to another daughter card. Half the signal is routed to a BERT (bit error rate detector, Agilent 70843B 0.1-12 Gbps Error Performance Analyzer) and the other half to an Agilent Oscilloscope (Agilent 86100A Wide-Bandwidth O-scope) where the signal is sampled and displayed in real time.

It should be understood that the signal integrity is a function of the entire system, not just the backplane. The 5 layer FR4 daughter cards, for example, will impart appreciable loss to the system. Recognizing that there is a system loss independent of the laminate under test, the configuration is good for comparing different laminate materials used to make the backplanes.

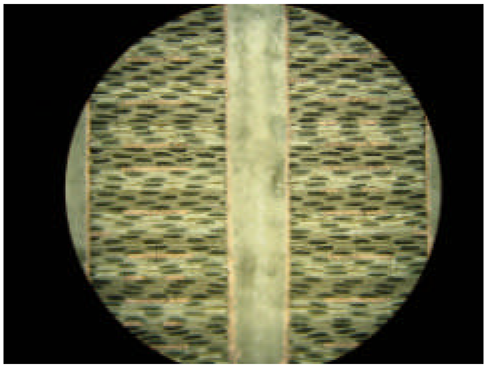


Figure 11 - 20 Layer Multilayer containing PTFE/Fiberglass Laminate Cores[2] and Prepregs of PTFE/Fiberglass/BT-Epoxy

Figure 12 shows the eye pattern of the multilayer described above using 20" traces at 7.5 Gbps. Critical to eye pattern measurements are the shape of the eye, the eye height (the separation of the level 1 and level 0 states that is a value in millivolts) and the width of the crossover from the level 1 state to the level 0 state (the jitter). If there were no loss in the system and no loss associated with the switching frequency, there would be an instantaneous rise time. In other words, the transition from the level 0 state to the level 1 state would be straight up and the waveform would look like the conventional square wave as bits are normally depicted. However, the eye pattern appears more like a sine wave than a square wave because of the following factors. The transition from the different states occurs in an analog fashion according to a switching rate. Because the 1s and 0s are switching back and forth at a certain frequency and the system has loss, the square wave is extended out to look like a sine wave because of a rise time that is not instantaneous. The width of the crossover point is known as jitter and is measured in the time domain, picoseconds. The larger the rise time, in picoseconds, the smaller the bandwidth, as they are directly related. Therefore, it is the jitter and eye height that are particularly important to designers.

Figure 13 compares the eye height of the PTFE/fiberglass/BT-epoxy hybrid vs a competitive ceramic filled elastomer. Over a 20” trace, at 7.5 Gbps, the BT hybrid has 2x the eye height.

Figure 14 shows the ceramic filled elastomer to have a higher amount of jitter for the ceramic filled epoxy, thus leading to a smaller bandwidth. Further measurements were made at 10 Gbps for the BT-hybrid, while none could be measured for the ceramic filled elastomer. This will be the subject of a future publication.

In the absence of techniques to improve signal integrity such as equalizers, the PTFE/fiberglass/BT-epoxy is capable of delivering signal integrity at the 10Gbs level and has the legs to extend out to higher frequencies. However, it must be acknowledged that the ceramic filled elastomer and the PTFE/fiberglass/BT-epoxy test vehicles were manufactured at different points in time. While poor impedance matching to 100 ohms, for example, can lead to poor results, the materials were evaluated under similar conditions, with the only variable being the material under test. Other random losses could be the discontinuity caused by a poor SMA stub (the launch), and poorly routed differential pairs. With all things being considered, the results should probably not be considered absolute. A future test vehicle will eliminate the use of the FR4 daughtercard and the losses associated with the daughter card and a proprietarily optimized launch developed by Teradyne (patent pending). Future measurements will measure Db of loss over increasingly longer trace lengths as a function of frequency. While the absolute millivolt level of eye opening should not be considered absolute due to the many losses associated with the system, the test vehicle used should be sufficient to compare somewhat different materials under test.

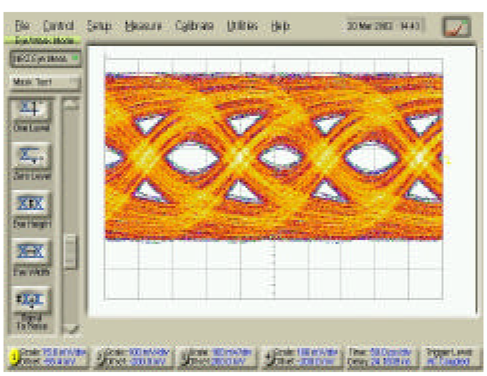
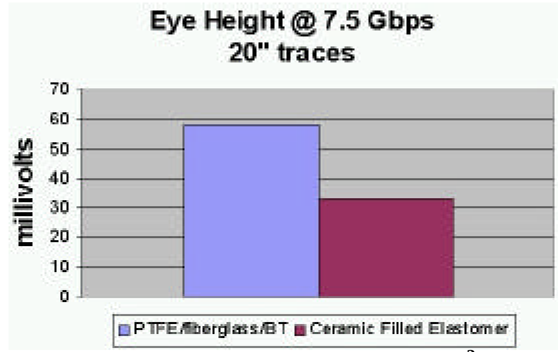


Figure 12 - Signal Integrity of 20 Layer Test Vehicle Containing PTFE/Fiberglass Laminate Cores[2] and Prepregs of PTFE/Fiberglass/Bt-Epoxy (7.5 Gbps, 20” trace)



PTFE/Fiberglass Laminate Cores[2]- PTFE/Fiberglass/Bt-Epoxy Prepreg Based Multilayer vs a Ceramic Filled Elastomer Based Multilayer using the 20 Layer Test Vehicle Design

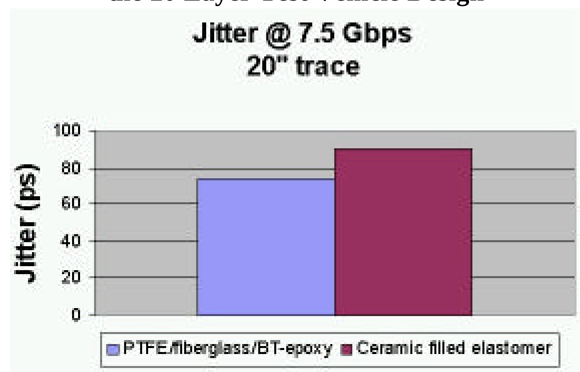


Figure 14 - Signal Integrity Comparison of PTFE/Fiberglass Laminate Cores[2]- PTFE/Fiberglass/Bt-Epoxy Prepreg Based Multilayer vs a Ceramic Filled Elastomer Based Multilayer using the 20 Layer Test Vehicle Design

Conclusions

The PTFE/fiberglass/BT-epoxy approach overcomes the issues related to the volume manufacture of PTFE based products. The joint efforts of a PTFE processor and a major laminate supplier ensures that the supply and value chain is in place. Early data suggest that very low loss can be maintained up to 14.5 GHz even when high loadings of a thermosetting resin are used. Signal integrity measurements further suggest that the typical properties of interest, eye height and jitter, are quite promising when compared to some other materials. The use of a robust BT-epoxy resin system fills 2 oz circuitry, has good adhesive properties, and allows a much wider fabrication window.

1. TacPreg™ TP-32/IS 630 (jointly manufactured product between Taconic and Isola AG)
2. Taconic’s RF35, RF35P
3. RF35, RF35P drilling parameters
4. Bereskin, A., US Patents 5,083,088 and 5,187,443.
5. McCarthy et al., ”PTFE-based Composites for High-Speed Digital Designs”, PC FAB, in press
6. PWBs processed by Varioprint (www.varioprint.ch)
7. Preliminary drill study carried out by Lothar Halder at HPTec (www.hptec.de)