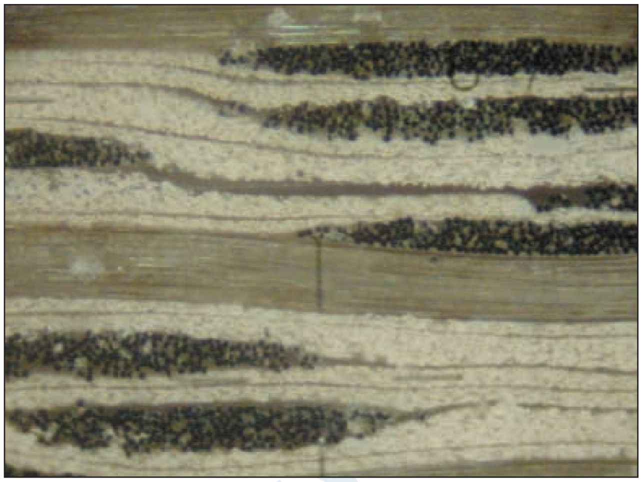

FIGURE 1. A microsection of a 1080-based PTFE/fiberglass/ceramic laminate.

PTFE-Based Composites for HIGH-SPEED DIGITAL DESIGNS

A new composite serves as a prepreg and processes at FR-4 temperatures, simplifying fabrication – and trimming cost.

by THOMAS F. MCCARTHY, DAVID L. WYNANTS, SETH J. NORMYLE, JAMES E. REVEAL, ROBERT B. NURMI, KEVIN RAFFERTY, and JOE TRIPI

In the race to win future high-speed digital designs, several materials have been developed to meet more demanding dielectric loss requirements. As data rates increase from 2.5 Gbps to more than 10 Gbps, few materials meet the dielectric loss requirements. PTFE-based materials have long been favored for microwave frequencies, with applications extending into the 77 GHz range in collision avoidance systems, for example.[1] PTFE can extend well into the high-speed digital space but acceptance has been limited due to the differences associated with PTFE versus FR-4. These include 1) chemistries for PCB fabrication, 2) material cost, 3) mechanical properties, and 4) high temperature lamination (close to 700°F).

A recent study compared a PTFE/fiberglass/BT epoxy hybrid composite* with a conventional PTFE/fiberglass-based laminate** to demonstrate that the barriers to broad acceptance of pure PTFE-based laminates can be overcome by the use of more advanced composites.

There are differences in the processing of PTFE-based laminates but none that suggests that PTFE boards are difficult to process. The biggest difference is hole wall treatment. PTFE laminates should be treated with plasma before electroless copper or direct plating to chemically activate the surface. Plasma is used to treat many types of materials, and is used successfully as a desmear process step for epoxies. Preliminary data suggest that the novel composite is drillable using conventional peck drilling for thick multilayers (≅0.170″), although it is not known at this time whether peck drilling is required for any given thickness. This is a key step because PTFE-based materials are not readily desmeared. Indeed, drilling must take place without PTFE smear. Reason: PTFE is not attacked by potassium permanganate. Plasma will activate the surface of PTFE, but it has difficulty dissolving it.

Drill bits should be new, not resharpened. Early drilling information from the field for the novel composite suggests that the sharpest bits will eliminate smear in small holes (<0.010″). The novel composite does not need to be interleafed for handling, as do some prepregs that are very tacky in the B-staged state.

The conventional material is a ceramic-filled PTFE/fiberglass composite based on 1080 fiberglass and used in microwave applications (Figure 1). Generally, PTFE-based laminates are layered using varying chemistries to provide the desired performance. Therefore, their cross-sections are not homogeneous. Areas that might appear as voids are actually various types of chemistries that might be used to design the composite. PTFE/fiberglass/ceramic composites are characterized by dielectric losses from 0.002 to 0.0035 in the 10 GHz range.

The hybrid is a 1080-based PTFE/fiberglass/ceramic/BT epoxy composite (Figure 2). The distinguishing feature between the figures is the proprietary layer of thermosetting resin that is used as an adhesive layer. In Figure 2, the ther-

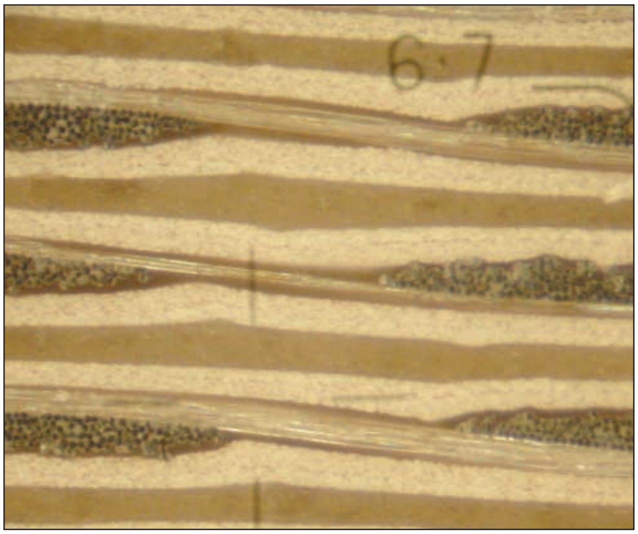

FIGURE 2. A 1080-based PTFE/fiberglass/ceramic/BT epoxy composite prepared at BT epoxy conditions.

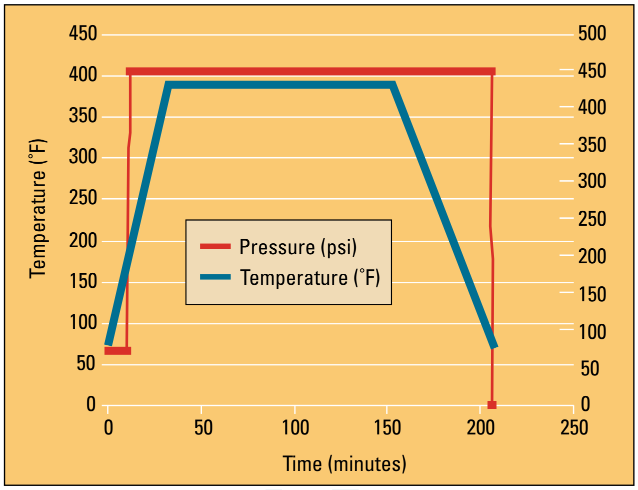

FIGURE 3. Preliminary press cycle recommendations for pressing the novel composite.

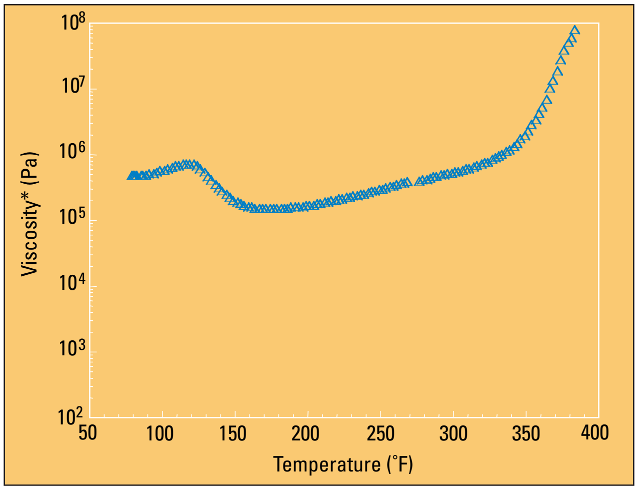

FIGURE 4. Viscosity versus temperature results.

mosetting resin appears as a uniform flat layer because there is no circuitry to be filled. The BT epoxy component permits the material to serve as a prepreg, enables lamination at fabrication temperatures similar to those of FR-4, and reduces the cost because the laminates can be manufactured in volume. This is a key point. While woven glass and PTFE raw material costs are significant, the addition of lower-cost ceramics into the material matrix stretches the low-loss capability of the base polymer at a lower unit cost than a pure polymer alternative.

To wit, PTFE laminates have historically cost five to nine times more than FR-4, although the highest performing PTFE-based composites could cost 30 times that of FR-4.[2] The novel laminate materials range between three to four times that of FR-4. Moreover, as telecommunications has adopted PTFE the cost and manufacturing infrastructure has changed considerably.

One major drawback of PTFE has been the high temperature processing required to build pure PTFE/fiberglass multilayers. The conventional material, for example, must be pressed at temperatures of 680 to 700°F in an eight to 10 hr. press cycle. The PTFE/epoxy hybrid can be pressed under conditions close to those of FR-4. The suggested press cycle is preliminary and is shown in Figure 3. Current recommendations call for somewhat higher temperatures and pressures to be used, but it is anticipated that a press cycle similar to that of BT epoxy can be used. The minimum viscosity is achieved with a heating rate of approximately 10°F/min.

The thermosetting resin used in the hybrid begins melting at about 120°F, and the minimum viscosity is reached around 160°F (Figure 4). For best gap filling and the highest peel strength, higher pressures are recommended. Foil laminations can be performed with the novel composite. Peel strength will increase with increasing pressure, with the benefit starting to level at around 500 psi. Because the hybrid is BT epoxy-based, the prepreg is compatible with standard innerlayer treatments such as oxides.

A standard PTFE/fiberglass material cannot be used as a prepreg unless fusion bonding is performed at 720°F and 1,000 psi. The novel composite is suitable both as a prepreg and as a core laminate material. Figure 1 shows the hybrid being used to prepare a laminate and Figure 5 shows the hybrid being used as a prepreg bonding layer. When used as a prepreg, apply conventional rules of resin-coated foil. For resin-coated foil, 35 µm of B-staged epoxy will fill 1 oz. circuitry, 50 µm will fill 2 oz. circuitry.

The novel composite is 1080-based and has sufficient BT epoxy necessary for filling 1 oz. circuitry. Surprisingly, the PTFE/fiberglass component of the hybrid also conforms to the copper topography. A test showed the ability of the novel hybrid to fill 2 oz. innerlayers (Figure 5). It was observed to conform fairly well to 2 oz. circuitry, although a certain level of voiding was acknowledged (Figures 6 and 7). Under these conditions, the BT epoxy flows to the areas where it is needed. Therefore, the novel hybrid should not require the levels of thermosetting resin necessary to fill copper traces that RCFs require. (A 2 oz. filling novel composite with 35% thermosetting resin content is expected to overcome the minor voids observed in this test.)

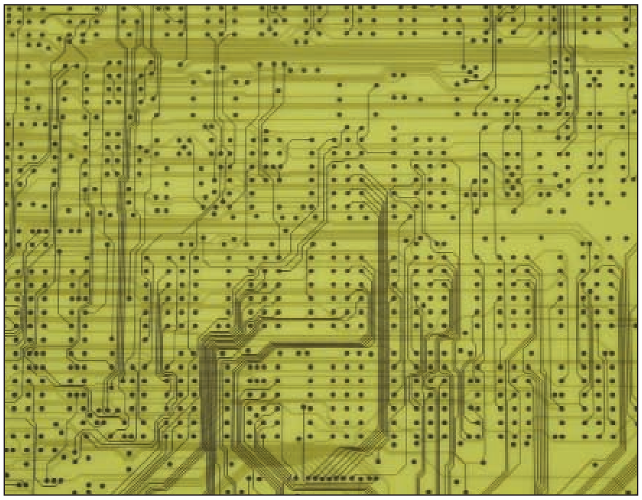

FIGURE 5. Innerlayers with 2 oz. copper (Source: Merix Corp.)

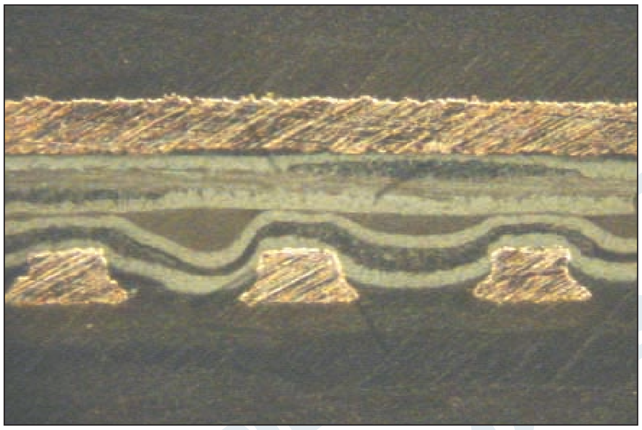

FIGURE 6. In testing, three plies of the novel composite filled gaps in copper circuitry on an FR-4 innerlayer …

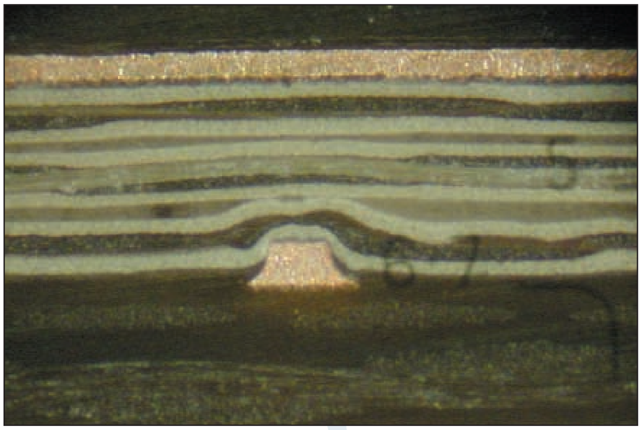

FIGURE 7. … with 2 oz. circuitry. The hybrid is draping over the circuitry.

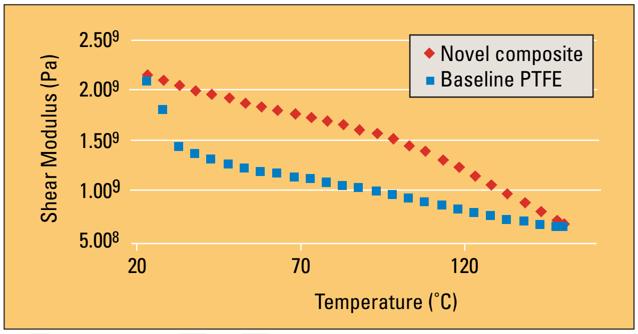

FIGURE 8. Dynamic mechanical analysis of a PTFE/fiberglass laminate and the novel composite under shear.

The BT epoxy used as an adhesive in the novel hybrid unexpectedly influences the mechanical properties of the resulting composite. PTFE-based composites are perceived to have certain limitations: too flexible for some applications; may creep under some circumstances; may need frame support during fabrication.

Conversely, some thermoset resin system laminates are very brittle. The novel composite approach could pose an interesting compromise in mechanical properties to rigid FR-4 materials. Table 1 lists various mechanical and electrical properties of laminate prepared from the novel composite. Table 1 shows a yield stress (shear) of 4750 psi for the BT epoxy hybrid, versus 1300 psi for the PTFE/fiberglass/ceramic composite, an increase of 365%. Basically, the epoxy hybrid fails in a fracture-like mechanism. This result is also reflected in the shear strength. The PTFE/fiberglass only creeps under the same conditions.

The two materials were also measured by dynamic mechanical analysis (DMA) under shear. The room temperature transition of PTFE can be observed in Figure 8. The shear modulus G' (ASTMs D5279/D4065, Rheometric RDAIII) of the conventional material drops significantly over room temperature with mild heating corresponding to the crystal morphology change that occurs in PTFE. The novel material maintains a significantly higher shear modulus until the glass transition temperature (Tg) of the BT epoxy is reached, at which point the benefit of the stiffer BT epoxy component disappears. Therefore, the epoxy hybrid should be more robust for drilling or routing, which could otherwise cause intraply delamination of a PTFE/glass laminate.

Surprisingly, the Shore hardness is practically the same for the two materials. We anticipated that the epoxy hybrid would show a higher surface stiffness because the BT epoxy resides primarily at the surface of the laminate. The flexural modulus and the Young's modulus are roughly equivalent for the two materials. The Young's modulus is measured in tensile and is most indicative of the fiberglass reinforcement. Thus, it is not surprising that the materials are roughly equivalent.

The flexural moduli are roughly equivalent. This finding suggests that the flex modulus in the novel composite is more dependent on the bulk properties of the fiberglass/PTFE backbone. Because of the novel composite's BT epoxy content, its bulk properties are dominated by the PTFE/fiberglass.

The z-axis coefficient of thermal expansion for both the conventional material and novel composite is reasonably low and consistent (Table 1). Fiberglass reinforces both products in the x and y directions such that most expansion occurs in the z direction. Because PTFE is a thermoplastic, not a thermoset, it has a relatively higher volume expansion than BT

TABLE 1. Comparison of Baseline PTFE to Novel Composite

PROPERTY	UNITS	BASELINE PTFE (PTFE/ FIBERGLASS)	NOVEL COMPOSITE (BT EPOXY HYBRID)	METHOD
Shore Hardness	D Scale	79	75	ASTM D 2240
Yield Stress (shear)	PSI	1300	4750	ASTM D5379 V-Notched Beam
Shear strength (MD/CD	PSI	NA	5010 / 4840	ASTM D5379 V-Notched Beam
Dielectric Constant		3.48	3.19	IPC-TM-650 2.5.5.3
Dielectric Constant		3.5	3.13	Bereskin (US 5,083,088)
Dissipation Factor	1.0 MHz	0.0025	0.0022	IPC-TM-650 2.5.5.3
Dissipation Factor	10 GHz	0.0038	0.0045	Bereskin (US 5,083,088)
Glass Transition	°C	RT	non-detectable	DSC
Glass Transition	°C		128, 177	DMA
Moisture Absorption	%	0.03	0.1 to 0.2	IPC-TM-650 2.6.2.1
Dielectric Breakdown	kV	38.8	38.5	IPC-TM-650 2.5.6 (0.008˝)
Strain at Break (MD)	%	1.4	1.2	ASTM D 790
Strain at Break (CD)	%	1.4	1.1	ASTM D 790
Flexural Modulus (MD)	kpsi	2,094	1,667	ASTM D 790
Flexural Modulus (CD)	kpsi	1,551	1,686	ASTM D 790
Flexural Strength (MD)	psi	25,000	19,000	ASTM D 790
Flexural Strength (CD)	psi	15,000	16,000	ASTM D 790
Tensile Strength (MD)	psi	47,600		ASTM D 882
Tensile Strength (CD)	psi	26,400		ASTM D 882
Tensile Strength (MD)	psi		19,800	ASTM D 3039
Tensile Strength (CD)	psi		18,000	ASTM D 3039
Tensile 0.2% Offset Yield Strength (MD)	psi		17,300	ASTM D 3039
Tensile 0.2% Offset Yield Strength (CD)	psi		17,000	ASTM D 3039
Young's Modulus (MD)	psi	2.26 X 106	1.77 X 106	ASTM D 3039
Young's Modulus (CD)	psi		1.76 X 106	ASTM D 3039
Poisson's Ratio (MD)		0.042	0.131	ASTM D 3039
Poisson's Ratio (CD)			0.136	ASTM D 3039
T300	minutes	–	15	IPC 2.4.24.1
Peel Strength (1 oz ED)		10.0	7.0	IPC-TM-650 2.4.8 Sec. 5.2.2 (Thermal Stress)
Peel Strength (0.5 oz RTF)	lbs./linear in.	–	5 to 6	IPC-TM-650 2.4.8 Sec. 5.2.2 (Thermal Stress)
CTE (Z axis)	ppm/°C [0-100°C]	152	155	IPC-TM-650 2.4.41 / ASTM D 3386
CTE (Z axis)	ppm/°C [0-<RT°C]	107	144	IPC-TM-650 2.4.41 / ASTM D 3386
CTE (Z axis)	ppm/°C [>RT-110°C]	116	133	IPC-TM-650 2.4.41 / ASTM D 3386
CTE (Z axis)	ppm/°C [160-260°C]	116	297	IPC-TM-650 2.4.41 / ASTM D 3386

epoxy in the unreinforced state. The conventional material has a high fiberglass content and, therefore, a lower z-axis CTE than the novel composite. The data from Table 1 suggest that the z-axis expansion for the novel composite is dominated by the PTFE component. However, above the Tg of the BT epoxy, as suggested by TMA, the z-axis CTE (297 ppm/°C) appears more indicative of a thermosetting resin because PTFE is otherwise normally flat (116 ppm/°C) up to its gel point (>340°C). The z-axis coefficient of thermal expansion is most relevant to thermal excursions and the associated stresses that might result. Typical failures might include barrel cracking, land separation on the innerlayer contact to the barrel hole wall, and land lifting at the top and bottom of a plated through-hole.

The microsections shown in Figure 9 are of a 20-layer board using the novel composite as the fill layers in a foil lamination. No evidence of land separation, barrel cracking, or copper lifting was detected.

Because PTFE's very low loss characteristics are somewhat diluted by a thermosetting adhesive layer, a resulting increase in dielectric loss would be anticipated. Figure 10 shows the dielectric loss of the pure PTFE/fiberglass compos-

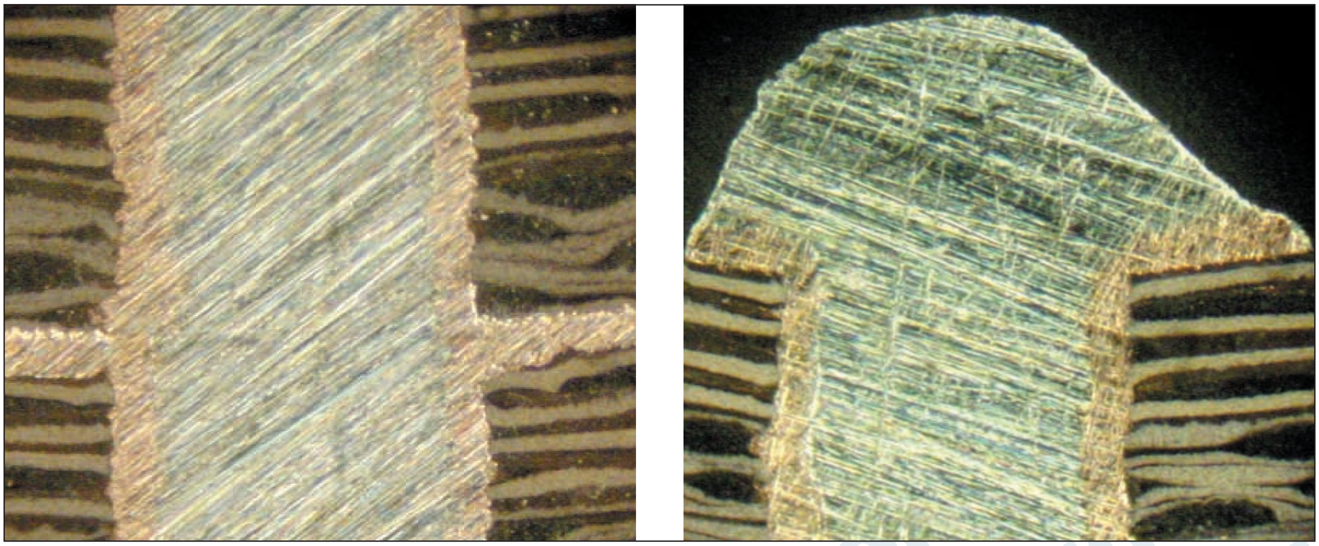

FIGURE 9. Plated through-hole reliability after 6X solder float of the tested materials stackup.

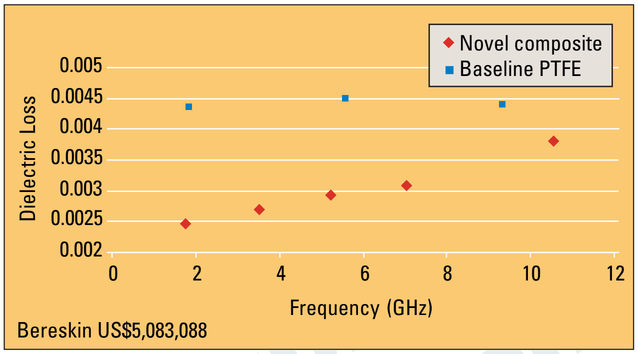

FIGURE 10. Preliminary data comparing dielectric loss between a PTFE/fiberglass laminate and the novel composite containing BT epoxy.

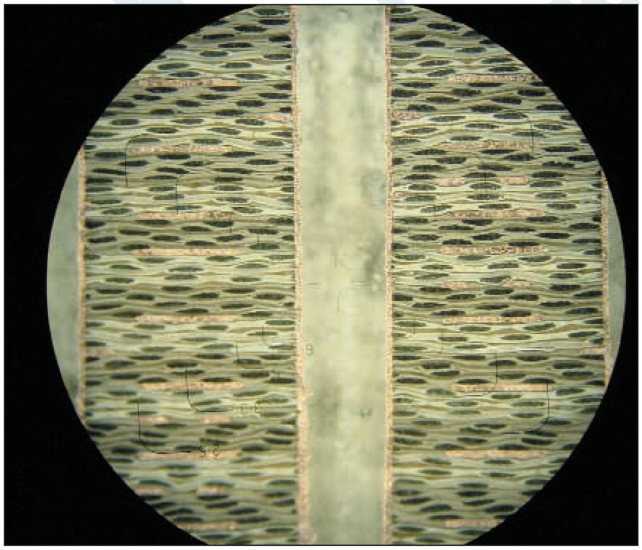

FIGURE 11. Twenty-layer board based on the novel composite bonding plies and conventional material cores fabricated at 392°F and 450 psi.

ite versus the analogous composite containing the BT epoxy resin. The conventional material has a lower loss through the 1 to 10 GHz range. However, the loss climbs upon reaching the 1 to 10 GHz range. The novel laminate has a higher initial dielectric loss but is very flat over frequency. The PTFE/fiberglass composite probably has the steeper slope because it contains a relatively higher glass content that is the highest loss component. The BT epoxy hybrid has a significantly lower glass content, although the absolute data should be considered preliminary as the product is in the process of commercialization.

A 20-layer test board designed especially for signal integrity measurements was made by Teradyne Connection Systems (Figure 11). The test board is a foil lamination using alternating signal and ground planes. The board is 18 x 24″, with 1 oz. copper and 0.008″ core innerlayers using PTFE/fiberglass bonded by three plies of the novel composite. It has trace widths of approximately 0.008″, an impedance close to 100Ω, uses a differential stripline configuration/edge coupled differential (two parallel traces spaced at roughly 0.009″ apart, the traces having a ground plane above and below the traces to yield the stripline configuration), and has copper traces of 10 and 20″ in length. The multilayer was pressed using processing conditions similar to those recommended in Figure 3. The hole walls were treated with plasma.

Signal integrity measurements are shown in Figure 12. Signal integrity was measured by attaching two FR-4 daughtercards to the backplane using Teradyne "GBX" connectors. The random sequence of bits was generated by an "HP70340A Signal Generator 1-20 GHz" with "HP70004A" display, and connected to a daughtercard at one end of the backplane by an SMA connector. Signals exit the daughtercard through the connector and are fed into the backplane, after which the signal exits via a connector to another daughtercard, with half the signal routed to a BERT (bit error rate detector, Agilent model "70843B 0.1-12 Gbps Error Performance Analyzer") and half to an Agilent oscilloscope (Agilent "86100A Wide-Bandwidth O-scope"), which samples the signal and displays it in real time.

The signal integrity is a function of the entire system, not just the backplane. For example, the five-layer FR-4 daughter-

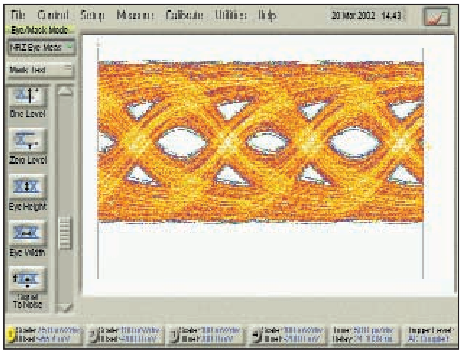

FIGURE 12. Signal integrity measurement of 20″ lines at 7.5 Gbps using the novel composite to bond the PTFE/fiberglass laminate cores. (Source: Teradyne)

cards will yield appreciable loss to the system. In any event, the configuration is good for comparing different laminate materials used to make the backplanes.

As a point of reference, the eye heights were measured for three materials, the construction shown in Figure 11, FR-4, and a ceramic-filled elastomer product. The eye height is a measure of a minimum separation between the level 0 and level 1 states. Generally, the signal is generated having a 250 to 500 mV separation between the level 0 and level 1 states. In an ideal world with no signal degradation, the oscilloscope should be able to see this separation.

The following eye heights were obtained on the 20″ lines at 7.5 Gbps:

- Novel composite: 70 mV.
- FR-4 non-measurable, ceramic-filled elastomer: 30 mV.

The composite approach should be able to deliver signal integrity in the 10 Gbps frequency range. Because there is design flexibility to the loading of PTFE used in the composite, PTFE should have the “legs” to extend its use without major OEM redesigns. ○

*“TacPreg TP-32” (Taconic)/“IS630” (Isola).
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