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Cost-Effective Laminate Materials Made by Continuous Lamination Using Thermosetting Polymer Alloys (TPA) for Microwave and High Speed Applications

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Abstract
Utilizing continuous lamination techniques, new materials are being developed to meet demanding market requirements. Laminates produced using Thermosetting Polymer Alloys (TPA) are cost effective products that can be employed in RF and microwave applications. A family of unique products has been developed that provide various solutions for microwave applications with electrical, mechanical, thermal and processing characteristics that surpasses competitive products.

Today's high-speed electronic products also require cost-effective materials to enable timely market penetration and sustained growth through subsequent cost reductions. The technical demands for these products have seen operating frequency increase or data transmission rates increase to a point that high performance circuit laminate must be employed to create reliable performance for the consumer. Until very recently, those applications requiring high performance laminate materials had few options. Even with some of these existing material options, laminate premium could be as high as 3-10 times and fabrication techniques required could multiply the costs even further.

Introduction
Today's high volume electronic products require cost-effective materials to enable swift initial market penetration and sustained growth through subsequent cost reductions. The technical demands for these products have seen operating frequency increase or data transmission rates increase to a point that high performance circuit laminate must be employed to create reliable performance for the consumer. Until very recently, those applications requiring high performance laminate materials had few options over traditional PTFE based materials. Even with some of these new material options laminate premium could be as high as 3-10 times and fabrication techniques required for the new material systems could multiply the costs even further.

Laminates can be provided that have grown out of materials and manufacturing technologies associated with high volume, low cost, consumer applications, yet meet the demanding requirements of microwave applications. The characteristics of a new product developed from earlier work with UPE resins were superior control of Dk (range) and excellent high voltage performance. The product competed against FR-4, CEM-1 and other inexpensive laminates. Used primarily in the television industry it allowed the combination of tuners and high voltage circuitry on a single board. Additionally the material significantly decreased their tuning labor due to superior control of the Dk tolerance.

Having both FR-4 and CEM-1 as competitive products and having a very large volume target market demands a manufacturing environment driven to create a cost model that can produce technically superior products at the lowest possible cost. Unlike PTFE manufacturers that started with high priced, low volume, military applications and utilized presses to manufacture small panels, a process was created that combines copper and glass roll stock with resin, then laminates and cures continuously in a wide web. The thin-core product thus produced can be shipped in rolls and panel products can be produced in whatever length required for the application. This process can produce 3-5 million square meters of laminate per machine, depending on product thickness. The economies of scale and efficiencies of this production technology allow the ability to compete globally against several products, whether commercial or microwave, in their price/performance arenas. This manufacturing technology also offers technological advantages as well as cost advantages. Thickness tolerances are typically tighter than press technology. Copper is handled in roll stock allowing copper weights of as low as 9 microns (unsupported) and 5 microns (supported) to be applied without yield loss. Warp can be controlled by material tensioning in the continuous web. This continuous lamination process maintains a world-class cost model, provides superior quality and yield, and enables benefits such as roll-to-roll fabrication, thin copper for fine-line product and tight thickness tolerances for controlled impedance/microwave application.

Having created a unique product and leveraging it into very high volume production, work began which focused on the electrical performance attributes of their resins to be utilized. Previously, the focus was not on Df or the stability and pre-selection of Dk for application types. Products such as low-noise block down converters, cellular base station antennas and power amplifiers all have application needs that cannot be adequately satisfied by FR-4 type laminates.

To respond to these market needs, a line of TPAs (Thermosetting Polymer Alloys) (7 US patents, 4 Japanese patents) was created. These chemical tools are used to create products that are optimized for the needs of the microwave market and can replicate the Dk's of other material systems. Most observers would assume that there is a great deal of trial and error in the process of developing the right resin and reinforcement combinations to optimize a product design. While there is always some fine-tuning, the process is actually very precise and well understood. The company's technologists utilize computer based product design tools that can take the target application's electrical, thermal and mechanical performance requirements and create a TPA recipe that offers a precise solution for the application, within the limits of the TPAs capabilities. The ability to replicate Dk allows dual sourcing for fabricators.

Once the electrical, mechanical and thermal properties are created, there are certain basic properties that are believed to be needed in every platform created. Flammability of UL94 V-0 is standard in every product platform. Moisture absorption is very low. Conventional fabrication and assembly processing must be acceptable to process the company's materials. High performance laminates such as PTFE and its ceramic filled competitors have poor histories with fabricators. Special processes, such as Tetra-etch, are used with PTFE to get acceptable plating in through holes. The material systems being discussed use standard FR-4 desmear and PTH chemistries. Ceramic filled materials sharply diminish drill life and remove drill temper, increasing processing costs. The materials in this discussion use FR-4 speeds and feeds for drilling and routing and see comparable drill wear to FR-4 products. Optimization of electrical, thermal, mechanical, processing and cost-effective laminate manufacturing has created platform technologies as outlined in Table 1.

Table 1 - Platform Technologies

Platform	Application	Alternative to:	Features
TPA #1 (GML 1000)	Power Amp, Antennas, Radios, Feedlines, LNAs Filters	PTFE, Hydrocarbon Resins, PPE, PPO	Low Loss, Low and Stable Dk
TPA #2 (GML 2000)	LNBs, LNAs, mm Wave, Antennas, Power Amp, Filters	PTFE, Hydrocarbon Resins	Low Loss, Low and Stable Dk, High Tg
TPA #3 (GML 3000)	High Speed Digital, RF Modules, Chip Packages (CSPs, MCMs, etc)	BT, PI, PPO, PPE	Thin Core, Low Loss, Low and Stable Dk

TPA #1 Product Family

This product is a low loss rigid laminate for LNB's, antennas and RF/Microwave circuits and is an industry leader in cost/performance ratio. Characteristic dielectric stability through temperature (-55°C to 125°C), frequency and humidity make it a material of choice for antennas, power amps, base station components, LNAs, LNBs, radios, feedlines and filters. Material A is a controlled PIM (passive innermodulation) material.

Table 2 - TPA #1 Product Family (Materials A, B and C)

GML Product	Material B	Material A	Material C
Dk (10 GHz)	Varies with thickness (±0.05)	3.20 ± 0.05	3.38 ± 0.05
Df (10 GHz)	0.005		
Peel (lb/in on 34 micron ED foil)	4.5		
Water Absorption	0.11%		
Thermal Stress (288°C)	>20 seconds		
Tg (DMA)	140°C		
PIM (dBc)	-110	-135	N/A

TPA #2 Product Family

This new addition to the TPA platform technologies has lower loss and very stable Dk when compared to the other platforms. TPA #2 is a rigid laminate using a custom modified PPO blended with thermoset resins. Its key characteristic of stable Dk, rivals high end ceramic products, and very low loss help it provide solutions in demanding antenna, LNB, LNA, opto-electronic, mm wave, power amp, radio, feedline and filter applications. TPA #2 Dks are comparable to competitive products allowing a "drop in" product for existing designs and dual sourcing capability.

Table 3 - TPA #2 Product Family

Product	Material R	Material S
Dk (10 GHz)	3.20 ± 0.05	3.38 ± 0.05
Df (10 GHz)	0.0029	0.0035
Peel (lb/in on 34 micron ED foil)	4.5	
Water Absorption	0.10%	
Thermal Stress (288°C)	>40 Seconds	
Tg (DMA)	180°C	
PIM (dBc)	-150	

The TCk' (thermal coefficient of Dk) is critical to the performance of an antenna and many other microwave devices. Material R of the TPA family #2 performs better than competitive organic materials as shown in Figure 1 and Figure 2.

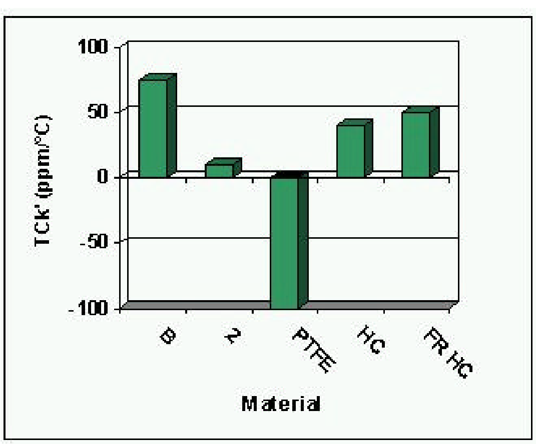

Figure 1 - TCk' Values of Several Laminates

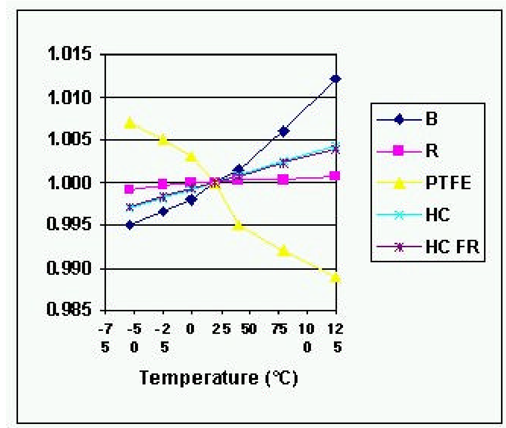

Figure 2 – Apparent Dk Change vs. Temperature

To see the effects of this stability through temperature, let's compare the shift of the center frequency of a microstrip antenna using a laminate with a -100 ppm/°C TCk and a laminate with a +10 ppm/°C (assume Dk = 3.2 and ΔT = 100°C).

If TCk' = -100 ppm/ºC, then the shift in Dk = -0.032. This translates into a frequency shift of 9 MHz at 1.8 GHz and 140 MHz at 28 GHz (0.5% shift).

If TCk' = +10 ppm/ºC, then the Dk shift is 0.0032. This translates to a frequency shift of –0.9 MHz at 1.8 GHz and –14 MHz at 28 GHz (0.05% shift).

According to:

$$\frac{df}{f_0} = -\frac{1}{2}\frac{de_r}{e_r}$$

Clearly this unique benefit affords the designer improved performance and reliability in his design of microstrip antennas.

TPA #3 Product Family-Development

This material is a woven glass thin core material with a high performance, stable dielectric for use in hybrid multi-layer or thin RF/microwave circuits. It performs well in mixed dielectric applications. To be available in roll or panels, it has an industry leading cost/performance ratio. This laminate would be typically used in high-speed multilayer designs, chip packaging, RF modules and mm wave designs. Typical properties of a 0.0024-inch (60 µm) thick laminate are shown in Table 4.

Again, the stability of Dk, Df and low moisture absorption in this TPA platform provides design solutions other materials can't match. Figures 3 and 4 show TPA #3 materials change in Dk and Df over frequency. Figure 5 shows the TPA #3 water absorption as compared to other laminate types.

Table 4 - Typical Properties of TPA #3 Materials

Laminate Property	0.06 mm (0.0024 inch)	Units
Peel Strength (18µm ED Cu foil 90° Peel) Standard profile copper foil A. As Received B. After Thermal Stress	 0.88 (5.0) 0.88 (5.0)	N/mm (lb/inch)
Volume Resistivity A. C-96/35/90	8×10^7	MΩ-cm
Surface Resistivity A. C-96/35/90	3×10^7	MΩ
Moisture Absorption	0.04	%
Permittivity @ 10^{10} Hz (10 GHz)	3.10	—
Loss Tangent @ 10^{10} Hz (10 GHz)	0.004	—
Tensile Strength A. Length direction B. Cross direction	155 (22.5) 115 (16.8)	N/mm^2 ($lb/inch^2 \times 10^3$)
Tensile Modulus A. Length direction B. Cross direction	10340 (1.50) 9300 (1.35)	N/mm^2 ($lb/inch^2 \times 10^6$)
Elongation A. Length direction B. Cross direction	 1.9 1.6	%
Initiation Tear Strength A. Length direction B. Cross direction	 2200 1440	grams
Propagation Tear Strength A. Length direction B. Cross direction	 30 >40	grams
Thermal Stress @288°C (550°F) A. Unetched	40+	s
Limiting Oxygen Index	32	-
CTE, average maximum X,Y axes (grain, cross) Z axis (<Tg, >Tg)	 21/19 TBD	ppm/°C
Glass Transition (Tg) by DMA	165	°C
Thermal Conductivity (@99°C)	TBD	W/m/°K
Dimensional Stability (E-4/105 + E-2/150) Length direction Cross direction	-0.0019 -0.0024	mm/mm or inch/inch

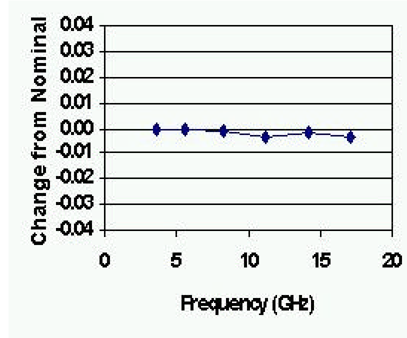

Figure 3 - TPA #3 Dk Change over Frequency

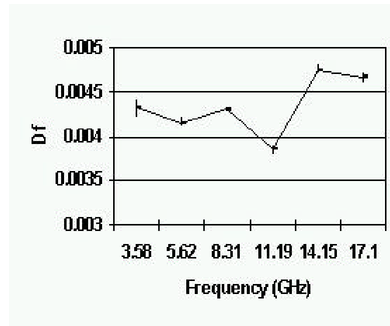

Figure 4 - TPA #3 Df Change Over Frequency

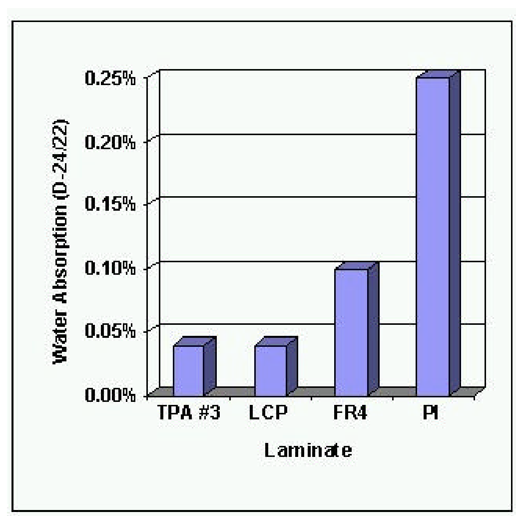

Figure 5 - Water Absorption Comparison

TPA #3 Products are available in 0.0024 inch (60 µm), 0.0031 inch (79 µm), 0.0062 (157 µm) and 0.0093-inch (236 µm) dielectric thickness. Copper weights of ½ oz (H), 1 oz and 2 oz are standard. Copper weights of ¼ oz (Q) and δ oz (T) are also available. Coppers greater than 9 micron can be supplied unsupported, less than 9 micron are supported. 5-micron copper has been proven feasible. It is possible that copper foils as thin as 1-3 microns may be reached.

The major factors in controlled impedance designs are conductor thickness, conductor width, dielectric thickness and dielectric constant tolerance. Conductor thickness is controlled by the copper foil manufacturers and usually is held within a tight tolerance. The imaging and etching processes at the PWB manufacturer control the conductor width. Either the PWB manufacturer (in a multi-layer PWB) or the laminate (core) manufacturer controls the dielectric thickness. The laminate manufacturer controls the dielectric constant tolerance. Of the three factors controlling the line impedance, the dielectric thickness has the most impact on the design.

In a microstrip design, assume a dielectric thickness of 0.0024 inch (60 µm), 50-ohm impedance, ½ oz copper foil. If the dielectric thickness is controlled to within ±25%, the resulting impedance values will vary ±17%. If the thickness tolerance is controlled to within ±10%, the resulting impedance varies ±6.4%.

Thickness control is also critical in stripline controlled impedance applications. Additionally, dielectric constant tolerance and the ability to predict the effect of mixed dielectrics with prepreg layers need to be accurate. Figure 6 shows the basic stripline design using two different dielectric layers.

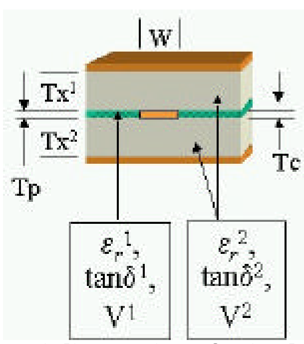

Figure 6 - Stripline Design of Mixed Dielectrics

The following formulas can be used to predict the Dk and Df of a mixed dielectric package.

Where ε_r = Dielectric constant

$$\varepsilon' \equiv \frac{\varepsilon_r^1 \varepsilon_r^2}{\varepsilon_r^1 V2 + \varepsilon_r^2 V1}$$

$$\tan\delta \equiv \frac{\tan\delta^1 + \dfrac{\varepsilon_r^1 V2}{\varepsilon_r^2 V1}\tan\delta^2}{1 + \dfrac{\varepsilon_r^1 V2}{\varepsilon_r^2 V1}}$$

tanδ = Dissipation factor
V = volume fraction

Using the above relationships of mixed dielectrics, TPA #3 laminates were tested with several different prepreg materials. Figure 7 shows the predicted values and the measured values of the different combinations.

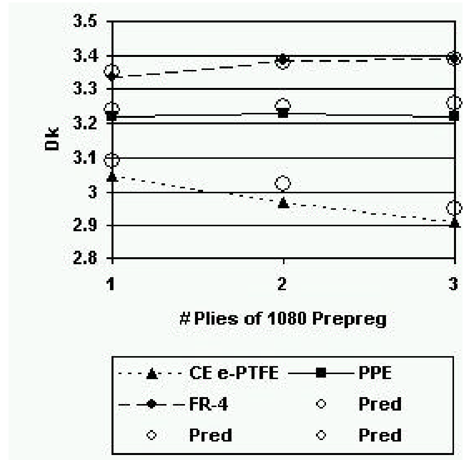

Figure 7 - Modeling of Mixed Dielectics

TPA #3 Processing and Reliability

This material is unique in that it is the first low loss, high performance material that is reinforced, thin and can be processed in roll-to-roll or panel processes. Lines and spaces to 75 micron have been produced with 25-micron lines currently being validated. Laser vias, punched vias and drilled vias all produce acceptable hole quality. Currently a rigorous program of microvia thermal cycling, JEDEC testing, including 168 hours of unbiased PCT (pressure cooker test), and biased HAST are being performed. Quality Assurance Validation has been performed by a number of fabricators through standard FR-4 and flexible circuit (Polyimide) processes. Target market fabrication requirements for thin core multi-layer, chip packaging and flexible circuit applications have been proven through alpha site testing.

The unique roll-to-roll capability of the TPA #3 product allows the additional benefits of roll-to-roll fabrication and assembly. The importance of this is in thin core application where material handling is reduced. Reducing material handling enhances yield and reduces labor. Material utilization is enhanced by varying progressions and creating panel sizes that reduce waste. Advantages over film circuitry include the improved dimensional stability and elimination of pre-bakes due to moisture absorption. Combining the cost advantages of utilizing roll to roll material availability and a fabricator’s roll to roll process create relative cost comparisons that show the potential of using high performance laminates in applications without significantly increasing cost.

Conclusion

The TPA laminates are cost effective products that can be utilized in microwave, RF and high-speed digital applications. Born from high volume, consumer grade products, high volume, cost effective manufacturing techniques and materials are utilized to meet market requirements typically satisfied by products that are much more costly. The TPA materials and the continuous lamination process create unique products that provide for microwave solutions with electrical, mechanical, thermal and processing characteristics that surpass competitive products.