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Understanding When To Use FR-4 Or High Frequency Laminates

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Even when electrical performance is not critical for a PCB design, high frequency laminates can offer several benefits. In fact, high frequency laminates are often used for improved impedance control, better thermal management, low moisture absorption and more consistent performance in thermally dynamic environments. Of course the high frequency laminates offer significantly improved electrical performance over FR-4 and often a combination of these materials is used for getting the most "bang for the buck".

Over the years a question that has been asked repeatedly of material suppliers is: "when do I need to use a high frequency laminate over standard FR-4 substrates"? The answer has many aspects to consider. There are circuit fabrication issues, assembly concerns and end-use performance needs. Of course there are material issues as well and how the material interacts with some of the other stated concerns.

To compound this issue there are many different types of high frequency laminates. Some laminates are nearly pure PTFE, filled PTFE and some are thermoset hydrocarbon systems. Of these different high frequency laminates there are also tradeoffs to consider.

We provide some guideline to understanding when to choose FR-4 or high frequency materials. The different areas considered are basic material properties, circuit fabrication, reliability and end-use performance needs. End-use needs will be expanded to include electrical performance issues, in an effort to address the often asked question about when do you actually need the improved electrical performance of the high frequency laminate over an FR-4 substrate. Lastly a topic that is becoming more prevalent will be discussed and that is multilayer hybrid PCBs using a combination of FR-4 and high frequency materials.

Basic material properties to consider

The FR-4 substrate considered in this paper is a high performance FR-4. Specifically it is a FR-4 substrate that is capable of multiple lamination cycles, robust to standard PCB processing, high Tg and capable of lead-free soldering. The high frequency substrates considered are three generic types; nearly pure PTFE, ceramic filled PTFE and thermoset hydrocarbon substrates.

Over the years improvements have been made to FR-4 for PCB fabrication. The typical PCB fabricator can process FR-4 materials and obtain circuits with very high yields and a good cost structure. This may not be the case for some of the high frequency laminates. The nearly pure PTFE laminates offer extremely good electrical performance however they generally require some non-standard PCB processing for most circuit constructions. Material suppliers understood the fabrication issues and responded with the formulation of ceramic filled PTFE substrates that still have very good electrical properties and have less challenges for the PCB fabricator. As the PCB fabrication learning curve matured for high frequency laminate suppliers, they brought to the market thermoset hydrocarbon substrates which had good electrical properties and processed very similar to FR-4 materials. Table 1 shows some general properties or concerns for the different materials.

The typical PCB fabricator may be concerned with some of the comments made in Table 1; however, that will depend on the circuit build that is in question. If the circuit is a simple double-sided thin PCB, which needs the best electrical performance, then the nearly pure PTFE could be used. The high CTE value of this material would normally make PCB fabricators uneasy, although in reality if the PCB is thin, this property is much less of a concern. On the other hand if the PCB to be built is a relatively thick multilayer, then using a nearly pure PTFE would not be advised.

	Tg (C)	CTE	Dimensional Stability	Multilayer Fabrication	Electrical Performance
Hi Pref FR-4	185	50	Very good	Robust	Poor
Nearly pure PTFE	NA	230	Poor	Difficult	Excellent
Filled PTFE	NA	40	Good	Moderate	Very good
Hi Freq Hydrocarbon	280	40	Very good	Robust	Good

Table 1 – Simple comparisons of the different materials as it relates to PCB fabrication concerns

Table 2 – Suggested drilling conditions for the various PCB materials discussed

	Nearly Pure PTFE	Ceramic filled PTFE	Thermoset Hydrocarbon	FR-4
Entry Material	Phenolic	Phenolic	Phenolic	Phenolic
Exit Material	Phenolic	Phenolic	Phenolic	Phenolic
Drill Tool	Carbide	Carbide	Carbide	Carbide
Infeed	1-2 mil / inch	2 - 3 mil / inch	2 - 4 mil / inch	2 - 3.5 mil / inch
SFM	150 - 250	200 - 300	300 - 500	300 - 400
Retract rate	<500 in. / min.	<500 in. / min.	<500 in. / min.	<500 in. / min.
Drill life	~500 - 750 hits	~250 - 500 hits	~75 - 2000 hits	~1000 - 2000 hits

Gasses	NH_3 or (70% H_2 / 30% N_2)
Pressure	100 mTorr Pump-down
Gasses	250 mTorr Operating
Power	4000 Watts
Frequency	40 KHz
Voltage	500 - 600 Volts
Cycle Time	10 - 30 minutes

Table 3 – Recommended plasma cycle for plated through hole (pth) preparation of ceramic filled PTFE substrates

Another consideration is a PCB build that is very dense, with tight tolerance circuit feature registration and the need for very good electrical performance. In this case, dimensional stability should be considered and the better choice would be the high frequency hydrocarbon thermoset laminate.

Circuit fabrication issues

The circuit fabrication issues for the high performance FR-4 are very well defined. The fabrication issues for some high frequency materials can be less defined. The nearly pure PTFE substrates require very special drilling and plated through hole (pth) preparation. The ceramic filled PTFE materials are usually more forgiving in the circuit fabrication process. The thermoset hydrocarbon substrates have processing needs that are more aligned with FR-4 substrates. Some suggested drilling parameters for these materials are shown in Table 2 for reference and comparison.

The plated through hole preparation is critical for multilayer builds. The FR-4 and the hydrocarbon substrates can be typically processed in standard plasma or permanganate processes. The nearly pure PTFE substrate will need very special plated through hole preparation to make the material in the drilled hole wetable. This process is a sodium naphthalene treatment which strips a fluorine molecule, making the PTFE able to accept electroless copper plating. The filled PTFE materials can use the sodium naphthalene treatment or a special plasma cycle. The recommended plasma cycle for the filled PTFE substrate is shown in Table 3 and many fabricators have claimed that a 100% helium cycle works very well.

The drilling and plated through hole preparation are typically the processes of most interest when considering circuit fabrication with high frequency materials. Another process which can be an issue is the multilayer lamination process. Most high frequency materials are compatible with the typical bonding materials and prepregs used in the PCB industry. There has been some false concern that the PTFE materials had to be made wetable prior to the lamination process, however that is incorrect. The main point to consider with the PTFE materials prior to lamination is to have the material clean and ensure that the substrate surface is not mechanically altered after the circuit has been imaged for the inner layers. The surface of the PTFE substrate will have the mirror image of the copper surface that was etched away and that gives more surface area for better bonding. Also the PTFE surface topology is very soft and a mechanical scrub will actually smooth out the surface and essentially polish it. This can cause lamination concerns with some bonding materials as well as distorting the laminate and creating dimensional stability issues.

There are many different bonding materials that can be used to make a multilayer laminate. These are listed in Table 4.

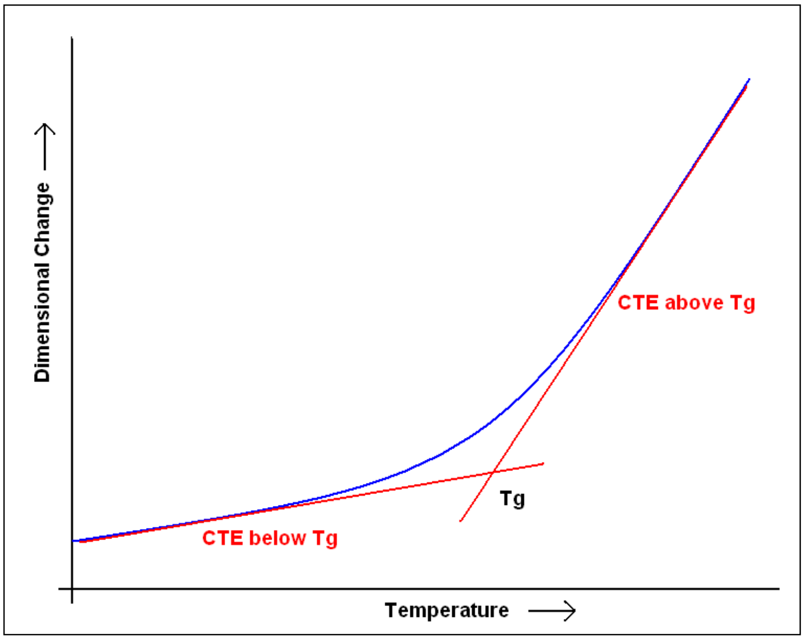
The re-melt temperature of some of the bonding materials can be a concern for some assembly and soldering processes. The FEP bonding material is typically okay with lead-free soldering, although the re-melt temperature is very near the lead-free reflow temperature which can be a concern. Obviously, the 3001 bonding material with a re-melt temperature of 177°C (350°F) should not be considered for PCBs requiring soldering.

The dissipation factor column in Table 4 gives an overview of the potential electrical losses associated with each material. This will be discussed later in the electrical considerations section.

Bonding Material	Dielectric Constant	Dissipation Factor	Lamination Temperature (F)	Preparation for PTH	Re-melt Temperature (F)
FEP	2.10	0.0010	565	Special	520
Ceramic filled PTFE, 3 Dk	3.00	0.0013	700	Special	640
Ceramic filled PTFE, 6 Dk	6.15	0.0020	700	Special	640
LCP	2.90	0.0025	554	Special	520
3001	2.30	0.0030	425	Special	350
Ceramic filled PTFE, 10 Dk	10.80	0.0023	700	Special	640
Thermoset Hydrocarbon	3.90	0.0040	350	Standard	N/A
FR-4	4.50	0.0180	360	Standard	N/A

Table 4 – List of different bonding materials for multilayer PCB builds

Figure 1 – Simple Tg curve showing CTE differences below and above the Tg



	Tg	CTE (alpha 1)	CTE (alpha 2)
High Tg FR-4	185ºC	55 ppm/ºC	265 ppm/ºC
RO4350B™ Laminate	>280ºC	35 ppm/ºC	35 ppm/ºC

Table 5 – Tg and CTE relationships of common PCB laminates

Reliability issues

Generally, the high performance FR-4 has good reliability characteristics. Usually reliability issues for PCBs are related to the pth via thermal cycling reliability. The CTE (coefficient of thermal expansion) of the laminate and the Tg (glass transition temperature) are the most important properties to consider for this topic. Specifically, the CTE of the Z-axis (thickness axis) of the material is of interest. Generally the CTE of high performance FR-4 is around 50 ppm/ºC or less and that is considered acceptable for good pth reliability. The CTE of the nearly pure PTFE can be a concern. However as noted earlier, if it is a thin PCB construction then this concern is much less of an issue.

The CTE of the filled PTFE and the thermoset hydrocarbon laminates are typically within a range that yield good pth reliability. In the case of the thermoset hydrocarbon substrates, some of these are extremely good for pth reliability. The reason is that these materials have an extremely high Tg (>280ºC) so the material will typically not transition beyond the Tg in assembly and soldering processes. With the material staying below the Tg, the CTE remains the same, which in this case is low and considered very good for pth reliability. Most thermoset materials have a CTE that is different above and below the Tg. So even though some laminates have a high Tg, for example 185ºC, the CTE will likely be different below the Tg as compared to above. Typically above the Tg the CTE is much higher and it is at these temperatures that assembly soldering usually takes place. A simple Tg-CTE graphic of this is shown in Figure 1.

Table 5 shows the CTE behavior of two common materials used in the PCB industry.

In this comparison, the alpha 1 test was done in the temperature range of 50ºC to 185ºC and the alpha 2 was 185ºC to 260ºC. The reason why the CTE value didn't change for the hydrocarbon laminate is because the alpha 1 and 2 testing was at a temperature range below the Tg of this material.

General end-use considerations

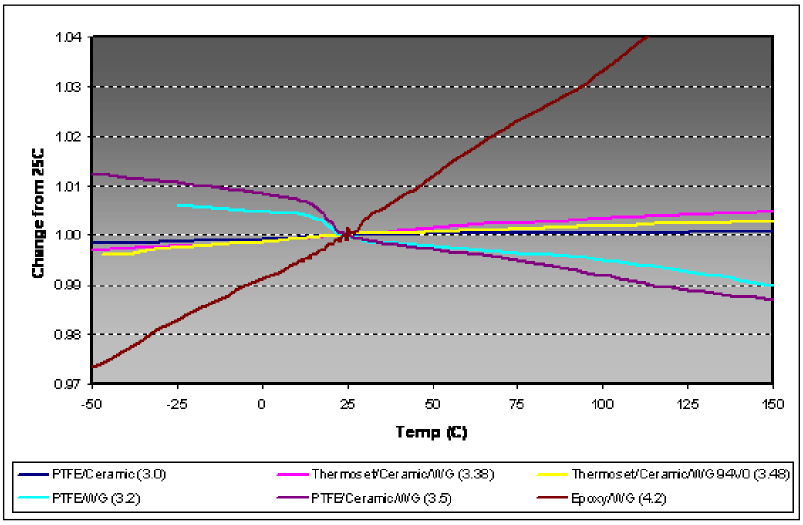
FR-4 materials are being used in numerous PCB applications. They are well proven, relatively low cost and their performance is well understood.

Some PCB applications will have a dynamic thermal environment. The circuit may be exposed to a range of temperatures for differing periods of time. The thermal coefficient of dielectric constant (TcDK) property of a laminate in a dynamic thermal environment is critical. All circuit materials have this property.

Many times the designer will consider high frequency laminates with the thought of electrical loss improvement only. In some cases, the electric losses of the PCB may not be a concern but maintaining the controlled impedance is a critical concern. Most FR-4 materials have a relatively high TcDk and many of the high frequency laminates are formulated to have a low TcDk. Having a low TcDK is desired for consistent electrical performance. The low TcDK means that the laminate has very little change in the Dk (dielectric constant) value with a change in temperature. This translates to very little change in impedance and the designer should consider using the high frequency material for a more stable design in a varying thermal environment. A TcDk curve is shown in Figure 2 for several different types of laminates used in the PCB industry. Epoxy/WG(4.2) is the high performance FR-4 and the Thermoset/Ceramic/WG substrates are the thermoset hydrocarbon high frequency laminates.

When humidity is a concern a high frequency laminate should be used instead of an FR-4 laminate, even though the circuit may not require low electrical loss. Most FR-4 laminates can absorb a moderate amount of moisture due to the humidity in the environment. Some end-use applications are sensitive to humidity and/or the impedance variation due to humidity. In comparison to FR-4 laminate, high frequency laminates are very low in moisture absorption. Table 6 shows typical values of moisture absorption for the different materials considered in this paper.

Figure 2 – TcDk (thermal coefficient of dielectric constant) curve of some common PCB laminate materials



	Moisture Absorption (%)
Hi Pref FR-4	0.50
Nearly pure PTFE	0.02
Filled PTFE	0.10
Hi Freq Hydrocarbon	0.06

Table 6 – Typical moisture absorption values for different PCB substrates

Some PCBs have a need to have better thermal management. Most FR-4 laminates have a thermal conductivity value of about 0.25 W/m/K. Even if the low loss of a high frequency laminate is not required, there may be a significant benefit for using these laminates regarding improved thermal conductivity. The nearly pure PTFE laminates generally do not offer much improvement over the thermal conductivity of the FR-4 substrate. Some of the ceramic filled PTFE laminates have much improved thermal conductivity over FR-4. The thermoset hydrocarbon high frequency laminates can have thermal conductivity that is 2 to 3 times that of FR-4 making this laminate property important to consider in the case of a PCB with thermal management concerns.

Electrical performance considerations

With most RF passive circuits, such as transmission lines, filters and couplers, loss increases as frequency increases. FR-4 has a higher dissipation factor (Df) than most high frequency laminates. Typical Df values for FR-4 laminates are about 0.020 and in comparison many high frequency laminates have a Df value of 0.004 or less. Many of the ceramic filled PTFE laminates have Df values less than 0.002 which is an order of magnitude better than FR-4. Some of the nearly pure PTFE laminates have Df values around 0.001 or less. These values translate to meaningful differences in insertion loss as can be seen in Figure 3.

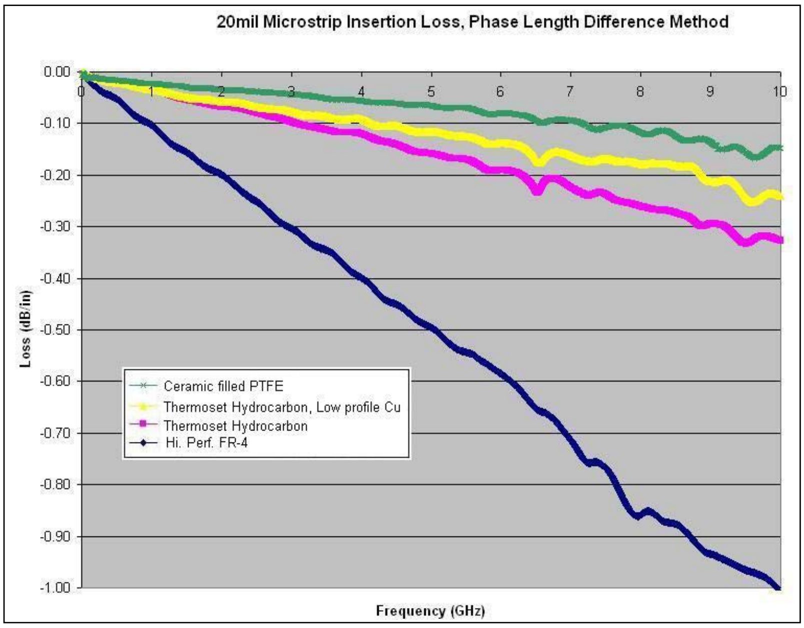
Another issue to consider when choosing between FR-4 and a high frequency laminate is how the losses occur. Most FR-4 laminates typically have a Df which increases steadily with frequency, so as frequency rises, insertion loss increases. High frequency laminates typically exhibit a more stable Df characteristic with frequency, with considerably less loss at high frequencies.

Many new PCB applications are now requiring much tighter impedance control. In the past an impedance target of ±10% was considered challenging and nowadays that is standard. There are many designs requiring an impedance tolerance of ±7%, or ±5% or even lower. There are many variables in the PCB fabrication process that can negatively impact the impedance tolerance, so if there are properties of a laminate that can improve the ability to achieve these tight impedance targets that should be considered. The Dk of most FR-4 laminates can vary ±10% or more. High frequency laminates naturally have stable high frequency properties and good control of Dk is mandatory. Many of these laminates are held to a Dk tolerance of ±2% or better. There are some special high frequency laminates that are held to a Dk tolerance of less than ±1%. Another property of high frequency laminates which can enable improved impedance control, is good thickness control. Most high frequency laminate thickness tolerance is less than ±7%, where as many FR-4 laminates are ±15% or more. This is another case where the low electrical loss of the high frequency laminate is not the reason this material should be chosen and it is other, well controlled properties of high frequency laminates that are needed.

It is well known that FR-4 PCBs are generally lower cost than PCBs using high frequency circuit materials. Nevertheless if the design is a tight impedance controlled design, the use of high frequency circuit materials could make substantial differences in yields of circuits that can be shipped for revenue as opposed to being scrapped due to the impedance being out of specification.

Sometimes the value of the circuit board's Dk can be very important in choosing materials for applications where wavelength-dependent circuit features are involved. Some of these circuits are edge coupled features found in RF and microwave PCBs and the edge coupled element sizes are directly related to the Dk of the PCB. A microwave circuit can be significantly reduced in size if the circuit material used has a higher Dk. Most high frequency laminates are available with many different Dk values specified. There are some filled PTFE substrates which have Dk values as high as 11 and this could significantly reduce the size of a circuit that was designed on a FR-4 with a Dk of about 4.5.

Figure 3 – The RO4350B materials mentioned here are a thermoset hydrocarbon and the RO3035 laminate is a ceramic filled PTFE HF laminate



Hybrid multilayer PCBs

It is becoming more common for multilayer PCBs to use a combination of circuit materials for a variety of different reasons. One important reason is being driven by technology and costs. Another reason for the hybrid is a more reliable PCB.

Many new designs are incorporating more features into the PCB design. It is common to have some layers of the PCB with critical electrical demands, while many other layers of the PCB are not. There have been many new multilayer PCB designs where one high frequency laminate is used with the combination of many layers of FR-4 laminate and prepreg. The critical electrical layers of the circuit may be the top two copper layers as a microstrip, using the high frequency laminate. The other layers of the multilayer use FR-4 materials. In most cases, the circuit fabrication is not much more complicated. However, if a nearly pure PTFE laminate is used in combination with FR-4 then more consideration is necessary. The sequence of how the drilled hole is prepared prior to the pth process is important. The sodium naphthalene treatment should be done after the hole is prepared for the other materials. In the case of a hybrid using FR-4 and nearly pure PTFE, the plasma or permanganate process should be done first for treating the FR-4 material and then followed by the sodium naphthalene treatment.

There is a reliability benefit that can be achieved for some hybrid builds. The nearly pure PTFE substrates offer excellent electrical performance, however due to high CTE values a high layer count multilayer may not be reliable. If the hybrid only has a few layers of critical electrical needs, these can be addressed by the use of the nearly pure PTFE. Then the other layers of the build could use a thermoset hydrocarbon or the FR-4 which are much lower in CTE. So the overall multilayer PCB has a reduced CTE as compared to a circuit entirely made with the nearly pure PTFE.

This article is based on a paper originally presented at the IPC APEX Expo 2011

Compact, Cost-Effective UV Depaneling Laser

LPKF, a leading manufacturer of laser and electronic systems, announces that it has added another laser system to its repertoire. The MicroLine 1000 S presents a compact, cost-effective method for UV laser depaneling of thin-rigid and rigid-flex assembled PCBs. According to the manufacturer, the MicroLine 1000 S combines a low entry-level price with the highest cutting quality and excellent process capabilities. Additionally, it is very flexible and, therefore, suited for high manufacturing mix. With UV laser cutting of assembled and/or unassembled PCBs, those with limited space will benefit. The UV laser beam can cut along delicate components or circuit paths without mechanical or thermal interference. The tool-less method makes any contour possible. Changes to the cutting paths are made by programming the software included with the machine or directly in CAD.

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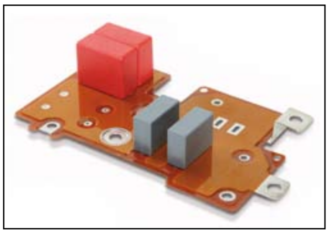
Power Circuit Busbars For Emerging Applications



Rogers's Power Distribution Systems Division has announced a new solution for emerging power electronics applications: RO-Linx PowerCircuit busbars. The PowerCircuit solution was developed to meet the growing power distribution demands in electric vehicle (EV) drives, hybrid electric vehicle (HEV) drives and related charging systems. Other significant applications include solar power inverters, uninterruptable power supplies (UPS) and industrial motor drives. RO-Linx PowerCircuit busbars fill the gap between PCB power distribution solutions and higher power laminated busbar systems, such as Rogers' RO-Linx laminated busbar products.

RO-Linx PowerCircuit busbars combine the performance features of power PCBs and laminated busbars. According to the manufacturer, they are highly engineered solutions for multilayer power distribution delivering optimal thermal management. Unlike two dimensional (2D) power PCBs, PowerCircuit busbars can be made in three dimensions (3D) to reduce weight and footprint and to conform to specific engineering designs to maximize efficiency. In addition, PowerCircuits eliminate assembly steps at the end user reducing complexity and sources of error. RO-Linx PowerCircuit busbars are ideal for applications at current levels from 100 to 500 A, such as industrial variable frequency drives and HEV or EV motor drives. Furthermore they can be combined with industrial mounting of functional components such as capacitors, sensors, and IGBTs.

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