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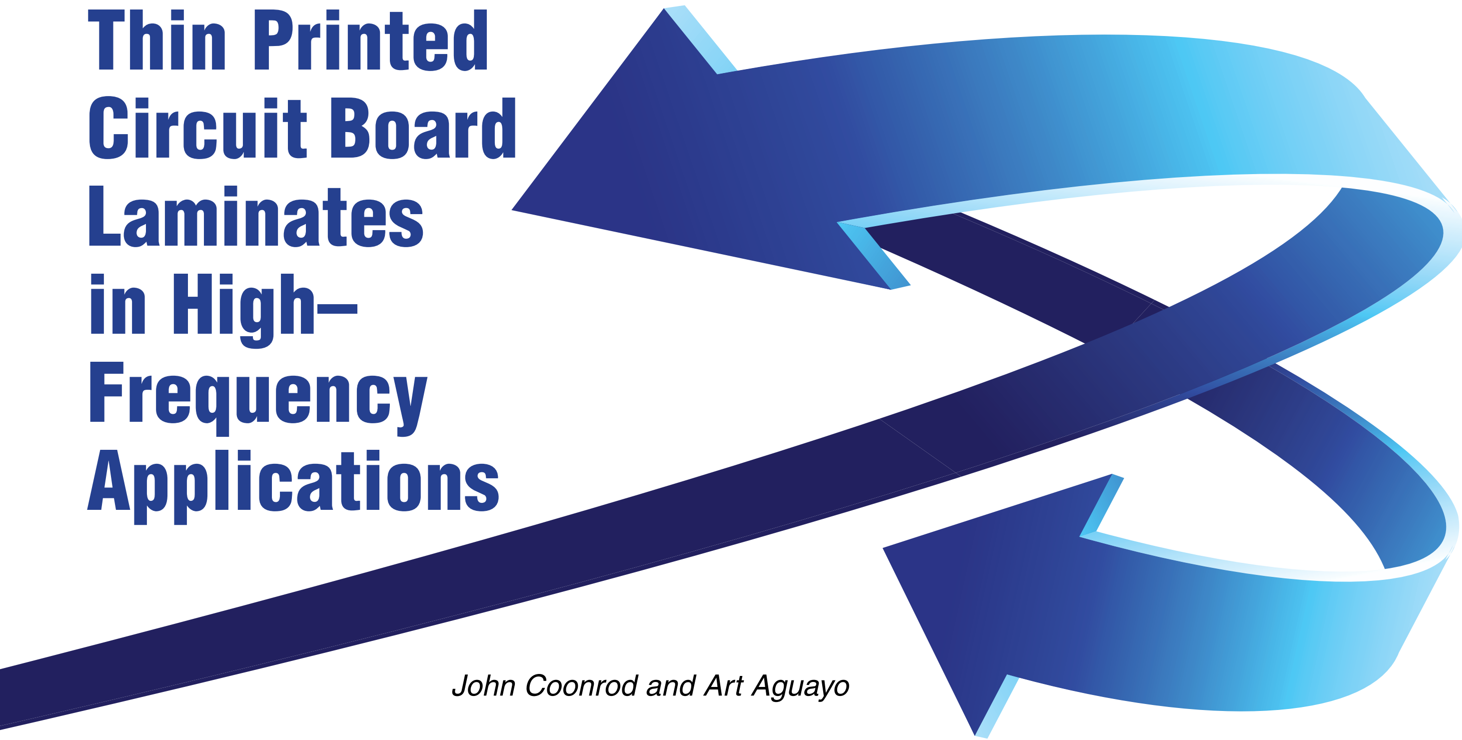
Thin Printed Circuit Board Laminates in High–Frequency Applications



John Coonrod and Art Aguayo

High-frequency applications use a number of different printed circuit board materials for many different reasons. In some microwave or millimeter wave applications, use of thinner substrates often becomes necessary. This article will discuss some reasons for using thinner materials for higher frequencies, types of thin laminates used, and several material properties that are important.

Why thin dielectrics?

In general, for higher frequencies (30GHz and higher), a thinner laminate is desired. This is done to avoid unwanted disruptive modes of wave propagations. In addition, low dielectric constant (Dk) are preferred for both electrical and PCB manufacturing reasons. High Dk materials will cause the wavelength to be shorter, which means a high frequency circuit would be reduced in size (shorter conductor lengths) and conductor widths become narrower for a given impedance. The downside to the higher Dk is that when a laminate is used at higher frequencies, the combination of high Dk, thin dielectric and narrow conductor generate higher losses. For this reason high Dk materials are not usually used at high frequencies. However, there have been cases where thick high Dk materials have been used – e.g., in some antenna applications. A high Dk, thin material with a controlled impedance line at 50 ohms can have a conductor width that is extremely narrow and almost impossible to fabricate with high yields, as can be seen in Figure 1 for a Dk 10, 3 mil. material.

Thin material choices

There are several different types of high frequency laminates to consider. Many consist of a resin and a filler used for mechanical integrity while some new material options are made up of unfilled resin only. PTFE is a common resin in high frequency laminates, low filled random glass PTFE (polytetrafluoroethylene), woven glass PTFE, ceramic filled PTFE, woven glass/ceramic filled PTFE, ceramic filled hydrocarbon resin systems, and LCP (liquid crystalline polymer). Each of these laminate types has different advantages and disadvantages in the areas of electrical performance or circuit fabrication.

Laminate Thickness (mils)	Material dk	Conductor Width (mils)
2	4.5	3.3
2	2.2	5.6
3	10	2.5
3	4.5	5.1
3	2.2	8.6
4	4.5	7
4	2.2	11.7
5	4.5	8.9
5	2.2	14.8

Fig 1 Example of Dk vs. Conductor Width for a 50 ohm Controlled Impedance Line

A benefit of a thin PTFE laminate is that these materials typically have the lowest Dk and loss tangent (dissipation factor or Df) values. When the laminate is thin and there is a requirement to maintain a 50 ohm controlled impedance line, then a wider conductor can be used if the material has a lower Dk value. A wider conductor generally translates to better fabrication yields and lower losses. A few examples are shown in Figure 1. These examples assume a microstrip structure, 0.5 oz. copper, and a 50 ohm impedance target. Moisture absorption is extremely low, which can be very important for good and consistent electrical operation of the PCB. In addition, the Dk and Df values are stable over a wide frequency range and can play an important role in very wide bandwidth systems.

Should the design call for higher impedance, then the conductor widths will need to be reduced. When it is necessary to have narrow conductor widths, the peel strength of the substrate can be important. Another advantage of this type of material is that it tends to have high copper peel strength.

The low filled random glass PTFE laminates require more attention during circuit fabrication compared to woven glass PTFE choices. High values for Z-axis CTE (coefficient of thermal expansion) can make PTH reliability a concern. However, when working with thin layers overall expansion is minimized and PTH concerns are reduced. If the design calls for a multilayer, then testing needs to be performed to ensure the PTH's can survive throughout the life of the application. MLB designs exist today that use these materials in the high reliability defense market.

Other areas that will require close attention when processing low filled random glass PTFE are drilling and handling. All PTFE-based materials require special hole-wall preparation prior to plating while the lack of rigidity makes this material more prone to handling damage unless proper systems are in place to deal with the softness.

Low filled woven glass PTFE laminates offer much of the same electrical benefits as the low filled random glass PTFE materials, with a few exceptions. Due to the woven glass filler, Dk anisotropy (change in Dk X vs. Y) can be greater and Z-axis CTE will increase due to the constraint in the X and Y that the woven glass creates. Dimensional stability will be better than random glass PTFE due to the weave and the material will show a greater level of rigidity. The other concerns mentioned about processing the nearly pure PTFE apply.

A concern some designers have about woven glass at high frequencies is its possible effect on electrical signals due to the "weave effect." Weave effect references the relationship that the periodic nature of the weave has with respect to the signal quarter wavelength (more of an issue at +60 GHz). Basically, in a layer of glass fabric, there are knuckles where the glass layers overlap and there are open areas where there is no glass weave (filled with pure resin). These micro-variations in dielectric constant can have an effect on electrical properties, depending on the application. Circuit features may fall on resin rich areas, and thus experience different performance. As higher frequencies and thinner laminates are used, the effect then becomes a greater concern and needs to be evaluated by the designer.

The ceramic filled PTFE substrates offer some advantages to the circuit fabricator and the end user. However, their electrical properties are not as good as the low filled random glass PTFE laminates. These properties are still considered very good and the benefit of eased fabrication needs will give better yields for the fabricator. Also, the addition of the ceramic filler works to lower the CTE in a range that is considered good. These kinds of materials are often the best in class for PTH reliability. The filler particle size can constrain how thin the laminate can be made. Many ceramic filled laminates cannot be made thinner than 5mil.s.

When a design is using a thin laminate at high frequencies, then the pitch between ground vias is also much closer. As the frequency goes up, the pitch will get smaller. Some ceramic filled laminates can have a limit to how close the holes can be drilled due to the particle size. The low filled random glass PTFE laminates can have the web between the drilled holes very small and in some cases around 10 mil. The ceramic filled PTFE will typically need more room, but is dependant on the filler particle size that is used.

There are woven glass and non-woven glass ceramic filled PTFE laminates. Typically, the woven glass will improve dimensional stability during circuit fabrication and increase rigidity. Electrically, however, it will increase the Df values due to the addition of the woven glass. Some low Dk ceramic filled and ceramic filled woven glass PTFE materials can have extremely low thermal coefficient of dielectric constant, making these materials ideal for temperature varying applications.

The hydrocarbon resin systems are much better for circuit fabrication, but have higher losses compared to the PTFE/glass and ceramic filled PTFE substrates. Many ceramic filled hydrocarbon resin systems are a good intermediary between good electrical performance and good circuit fabrication properties. Most, if not all, of this type of laminate are woven glass reinforced. Since these are ceramic filled laminate systems, it is possible to get laminates with some limited range of Dk values. The greatest advantage of these products, if they meet the electrical specifications of the application, is that they are usually the lowest overall cost option, due to their processing similarity to FR4.

Like PTFE, LCP (liquid crystalline polymer) is a resin that can be used at high frequencies, however, most LCP materials available today are homogeneous (unfilled), which offer several electrical and fabrication advantages. They are typically thin laminates only and are usually available in the range of 4 mil. or thinner. They offer many distinct advantages for the end-user, although they have several special requirements for circuit fabrication.

LCP has excellent, very high frequency capabilities. A paper was written regarding the use of thin LCP laminates in which an LCP circuit was tested over a very wide range of frequencies up to 110 GHz. The test vehicle was a conductor backed coplanar waveguide (CBCPW) and a simple drawing of that transmission line is shown in Figure 3.

The electrical performance in this study[1] was outstanding and can be seen in Figure 4.

The circuit fabrication issues associated with LCP depend heavily upon the circuit construction. The circuit mentioned in the high frequency study was a relatively simple double-sided, plated-through-hole (PTH) circuit. This construction is fairly easy for fabrication with a caution of having very good drilling parameters and a plasma cycle prior to PTH (similar to PTFE), which is non-stan-

Fig 2 Example of Glass Weave on Microvariation of Dielectric Constant

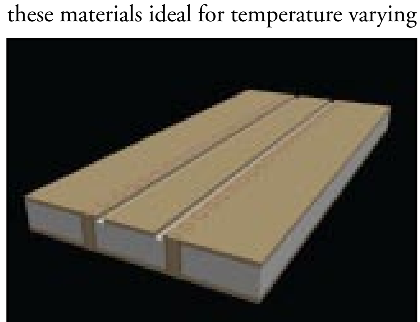


Fig 3 Conductor Backed Coplanar Waveguide (CBCPW)

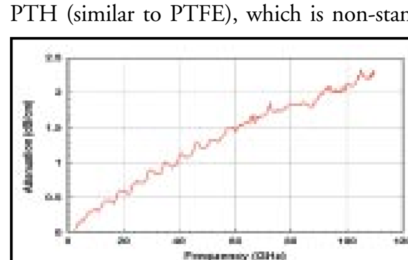


Fig 4 Attenuation Curve of CBCPW Using 2-mil. Thick LCP

dard. Simple multilayer (3 to 4 layers) can be achieved while more complex constructions requiring sequential lamination are not recommended due to the thermoplastic nature of both the core and bond layer.

The roughness of the conductor and the interface between the conductor and the dielectric has a big impact on the overall loss of the circuit.

Lack of fillers in LCP materials translates to being able to have PTH vias drilled very close together, which is often needed at higher frequencies in order to obtain proper grounding and unwanted mode suppression.

Thin dielectric material properties

In microwave circuits, there are three main types of losses associated with PCB technology. The losses are dielectric losses, conductor losses, and radiation losses. Radiation losses are more design dependent and outside of the scope of this article, while dielectric losses are mainly related to the Df of the material and are usually well understood by the designer. On the other hand, conductor losses are not always properly accounted for in many designs and can be the source of discrepancies between modeled and measured values. We will discuss the effects of both conductor roughness and metal finish (surface plating).

The roughness of the conductor and the interface between the conductor and the dielectric has a big impact on the overall loss of the circuit. A rougher copper surface will translate to more surface area and a longer path for the wave to propagate. This effect becomes more dominant as both frequencies increase or dielectric thickness decreases (in the case of millimeter wave applications, both are true). Use of low profile coppers (or reverse treat) is recommended for high frequency applications and an example of the reduced insertion loss due to a smoother copper/dielectric interface is given in Figure 5.

The use of a low profile copper on the ceramic filled hydrocarbon material improves the insertion loss by about 40 percent, allowing the designer to use these materials at frequencies where once losses were prohibiting its usage. This improved performance on a ceramic hydrocarbon laminate narrows the gap in loss between this type of substrate and the lower Df PTFE substrates, enabling the designer to extend the frequency use of these more cost effective materials.

Plating finishes can impact the overall loss of the circuit due to lower conductivity metallizations that cover the edges of the trace and the currents that run at these locations. Silver plating may be the only exception to this increased loss effect due to its similar conductivity to copper. This finish, however, is not as preferred as other finishes like electroless nickel/immersion gold (ENIG) or immersion tin.

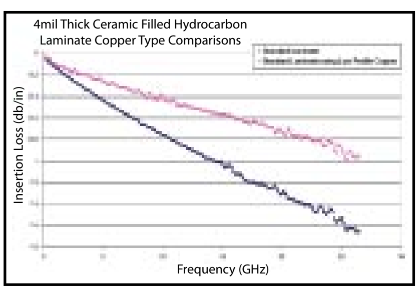


Fig 5 A Ceramic Filled Hydrocarbon Laminate Compared to the Same Laminate Using a Low Profile Copper and Showing Insertion Loss Over Frequency[2]

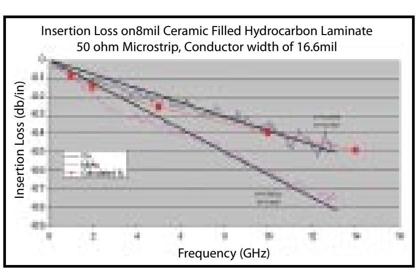


Fig 6 Data Showing Insertion Loss vs. Frequency of Copper Only as Compared to Copper Plated With ENIG (electroless nickel/immersion gold)

ENIG is a finish that has been widely used throughout the PCB industry over the past years. This finish is very good for maintaining a good clean surface and remains easy for soldering over a long period of time. Unfortunately, the nickel is not a good conductor and is much lower in conductivity than the copper. Also, nickel has a ferromagnetic property, which can adversely affect the magnetic fields. Most of the plating chemistry suppliers in the PCB industry have addressed the ferromagnetic properties with a certain alloy of nickel that is used in this process. However, the lower conductivity remains an issue. An internal study[3] was performed regarding the effect of ENIG plated finish and conductor loss. A chart summarizing some of the information in that study is shown in Figure 6.

The selection of low-profile copper and low-loss plating are just as critical as the selection of proper material when designing high frequency circuits. Material choices are quite diverse and use of fillers or homogeneous resins are important considerations for both electrical performance and ease of manufacturing. A balance between performance, reliability, and cost must be achieved in order to increase the chances of commercial success for the design.

There are many complexities to how a circuit material may perform in a circuit fabrication environment as well as the end-use performance and there may be some possible interactions. Therefore, the user will need to determine the fitness for use of the selected materials by conducting appropriate short-term and long-term reliability testing as dictated by the needs of the application. □

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