

A SURVEY AND TUTORIAL OF DIELECTRIC MATERIALS USED IN THE MANUFACTURE OF PRINTED CIRCUIT BOARDS.

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Introduction

This article was written in response to numerous requests for help selecting the best dielectric for a particular printed circuit board design. The task has always been clouded by a confusing array of materials choices, equally confusing claims by the manufacturers of those materials, confusion about what the actual requirements of an application are and a substantial collection of misinformation circulating in the design and fabrication communities. The goal of material selection should be to choose a material that adequately handles the signaling task and, at the same time, achieves the lowest overall PCB cost.

This task has been further complicated in recent years by the increasing clock frequencies of PCs and by the drive for gigabit and beyond data rates in ethernet related products. Questions arise almost daily about whether FR-4 based materials are capable of serving in these applications. Recent studies that shed some light on this question will be shared in this article.

Two major applications areas, RF/analog and Digital

Electronic packaging can be divided into two major applications areas, each of which has its unique requirements. The requirements are sufficiently different that two classes of materials have been developed to meet their needs. Understanding these areas and their requirements are basic to making the correct material choice.

The two major applications areas are RF/analog and digital. The major differences between these two areas are the ability of the circuitry involved to tolerate signal losses and the complexity of the circuitry.

RF/Analog Circuit Characteristics

RF/analog circuits are usually processing signals that are small or precise. The accuracy with which the circuits perform or the ability of the circuits to process low level signals successfully depends on a package with lowest possible losses. Losses occur as reflections where impedances change and from absorption of some of the signal in the dielectric materials. The latter can be a significant consideration when choosing a dielectric for this type of product.

Losses from reflections are traceable to variations in impedance. These stem from variations in laminate thickness, variations in dielectric constant of the laminate and variations in final etched trace width. The first two of these are traceable to characteristics of the laminate itself. The latter to process uniformity at the fabricator.

The circuit complexity of RF/analog circuits is low enough that PCBs of two or three layers can be used to house most them. As a result, the ability of a material to laminate

in many layers is less important than are losses, dielectric constant and dielectric constant uniformity.

Digital Circuit Characteristics

Digital circuits are designed to tolerate substantial signal loss and still perform their tasks successfully. As a result, material characteristics other than losses tend to be more important. Digital circuits are usually quite complex and require several or many signal and power layers to house them. This puts a priority on processing characteristics such as ease of lamination, ease of drilling and other processing steps. The need for many layers in some designs causes the PCB to be relatively thick. Soldering and reworking these thick PCBs puts significant thermal stress on the vias and other plated through holes on a PCB. In order to insure the PCB will not fail from this, the temperature characteristic, T_g , must be high enough to withstand these processes.

Riding on top of the above needs, digital PCBs tend to be used in products that are subjected to intense price pressures. As a result, costs of the raw laminate and processing costs place an additional demand on the choice of laminate materials used.

Two Major Materials Classes

PCB dielectric materials can be divided into two major classes based on the type of reinforcement used. These are woven glass reinforced and non-woven glass reinforcements. Woven glass reinforced laminates are lower in cost than non-woven laminates and are cheaper to produce and process. Because of the amount of glass in the woven glass cloth, the dielectric constants of laminates based on it are higher than laminates based on other reinforcements. (The glass used in laminates has a relative dielectric constant of 6.0.)

Laminate Properties Important to Use.

A number of laminate properties can be important depending on the application. Most materials have been developed to optimize one or more of these properties. Among these are:

Relative Dielectric Constant, ϵ_r - this property is a measure of the effect an insulating material has on the capacitance of a conductor imbedded in or surrounded by it. It is also a measure of the degree to which an electromagnetic wave is slowed down as it travels through the insulating material. The higher the relative dielectric constant, the slower a signal travels on a wire, the lower the impedance of a given trace geometry and the larger the stray capacitance along a transmission line. Given a choice, lower dielectric constant is nearly always better.

The dielectric constant of nearly all PCB dielectrics changes with frequency and usually goes down as frequency goes up. This manifests itself in two ways in transmission lines. The velocity of signals increases as the frequency goes up, resulting in phase distortion in broadband amplifiers. Broadband RF and microwave amplifiers usually need to be made from laminates with relative dielectric constants as flat with frequency as possible to minimize this problem.

The impedance of a transmission line goes down as frequency goes up resulting in faster edges reflecting more than slower ones. The main effect this has is to cause errors in impedance calculations and measurements. As an example, if the relative dielectric constant measured at 1 MHz is used to calculate impedance and a TDR with a 125 picosecond rise time is used to measure the impedance, there will be disagreement due to the fact that two very different frequencies have been used. **Figure 1** illustrates how relative dielectric constant varies with frequency for some typical PCB laminates.

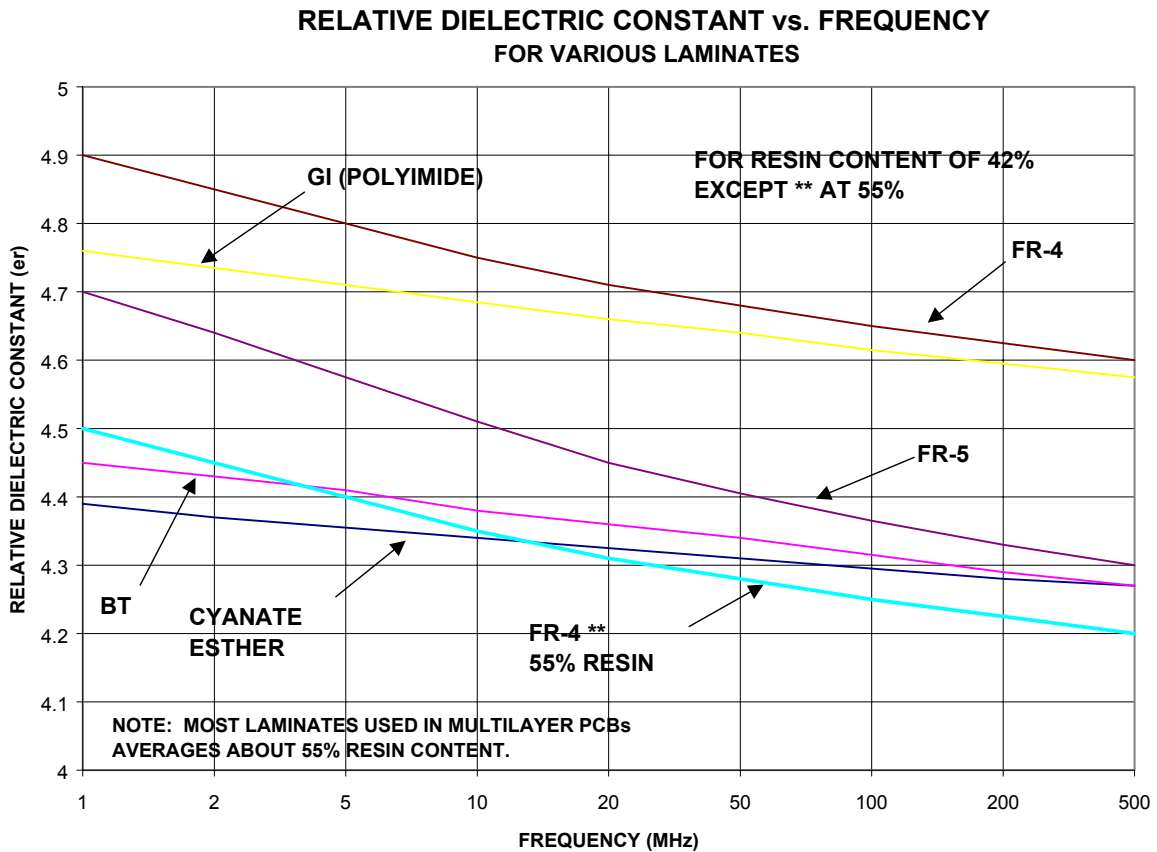


Figure 1, Relative Dielectric Constant vs. Frequency for Several Laminate Types

Another source of relative dielectric constant variation is the ratio of reinforcement or glass to resin used to make a laminate. **Figure 2** shows how the relative dielectric constant of a standard FR-4 laminate changes with the ratio of glass to resin. This chart is based on measuring relative dielectric constant at 1MHz. Many of the disconnects between predicted impedance and measured impedance stem from that fact that the relative dielectric constant for one glass to resin ratio is used to calculate impedance and the actual glass to resin ratio of the material used to fabricate the PCB is different. As an example, the relative dielectric constant 4.7 is for FR-4 with 42% resin measured at 1 MHz. Most multilayer materials contain about 55% resin. Typically, impedance of the finished PCB is measured with a TDR of edge rate about 150 picoseconds which corresponds to about 2 GHz. The relative dielectric constant for this pair of conditions is approximately 4.1. These two sets of conditions, when used on the same PCB, one to calculate the other to measure, can result in an impedance error of as much as 5 ohms in a 50 ohm system.

DIELECTRIC CONSTANT FOR FR-4 TYPE MATERIALS AS A FUNCTION OF GLASS TO RESIN RATIO

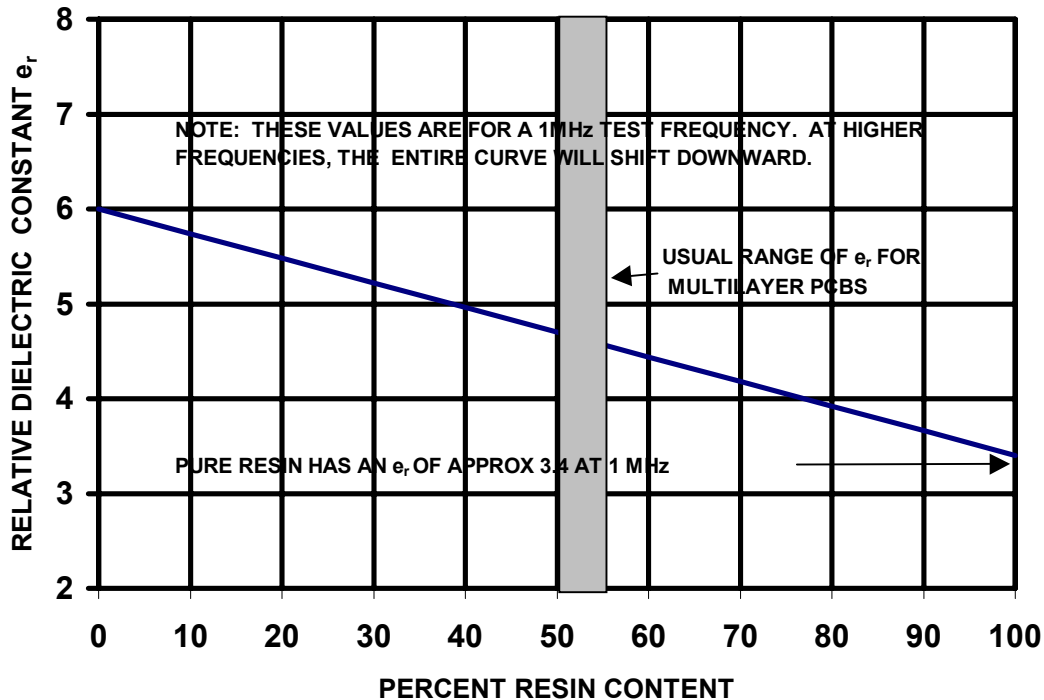


Figure 2, Relative Dielectric Constant vs. Glass to Resin Ratio for FR-4

Glass Transition Temperature, T_g - all common laminate resins exhibit changing temperature coefficients of expansion as temperature increases. **Figure 3** shows this characteristic for a number of common multilayer laminates. Glass transition temperature or T_g is the temperature at which the temperature coefficient of expansion makes a significant change from a low value to a much higher value. This corresponds to a phase change in the resin system.

Notice that the temperature coefficient of expansion at low temperatures is close to that of copper and glass, the two reinforcements in the X and Y directions of a PCB. When the temperature of the composite material system in a PCB exceeds its T_g , the resin part of the package begins to expand at a much more rapid rate than either the copper or the glass. Since the resin cannot expand in either the X or Y directions, virtually all of the volume growth takes place in the Z-axis. The vias and other plated through holes are oriented in the Z-axis and are placed under stress as soldering takes place. The combination of thicker PCBs and multiple soldering operations can produce failed PCBs even before they complete the manufacturing process. Care must be exercised in choosing the proper T_g material for each application.

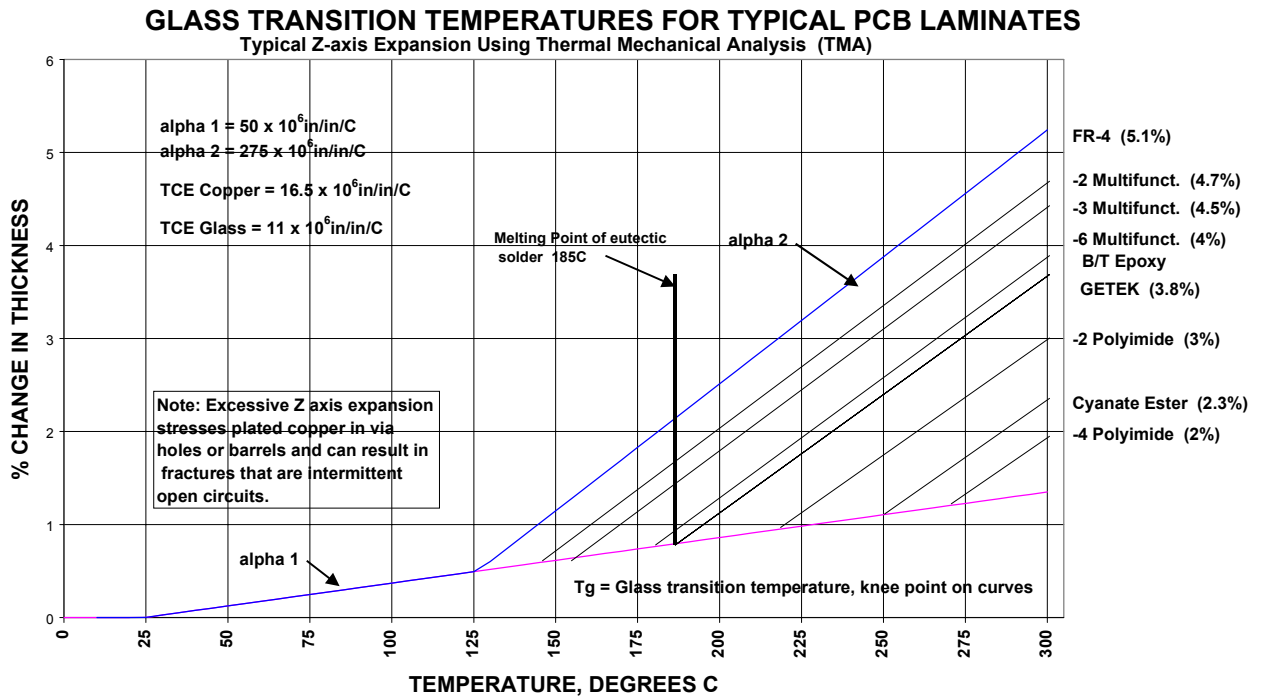
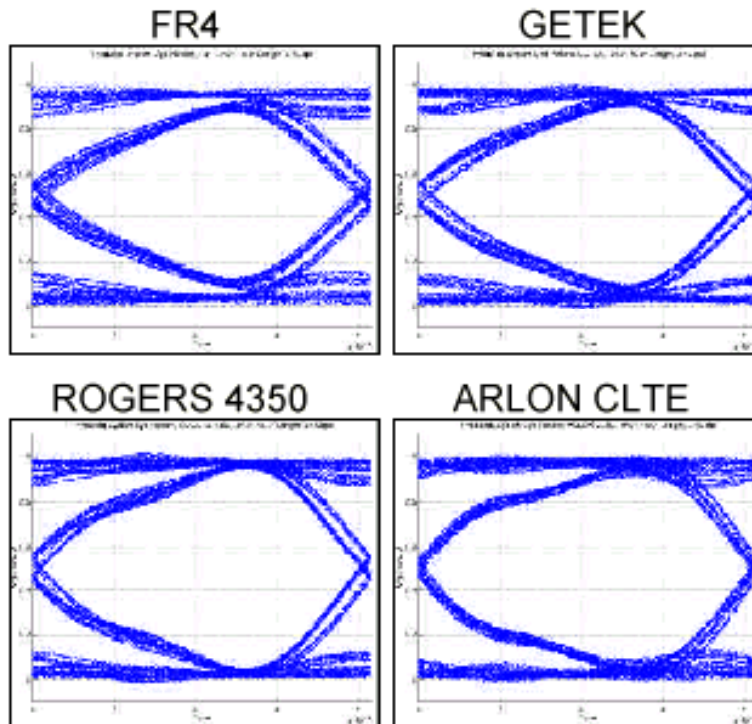


Figure 3, Glass Transition Temperature Curves for Various PCB Laminates

Loss tangent- Loss tangent is a measure of how much of the electromagnetic field travelling through a dielectric is absorbed or lost in the dielectric. This property is one of the least well understood of all those that characterize laminates. As a result, ultra low loss materials are often used in digital applications when they are not needed. This results in increased PCB cost without a corresponding benefit.

Figure 4 shows the classic “eye diagram” used to measure the performance of an Ethernet link. It was created by Amp Packaging Systems as a measure of the performance of four potential laminate materials. The test environment is a 2.4 Gigabit per second back plane with 18” long paths. The materials examined are high temperature FR-4, GETEK from GE, RO 4350 from Rogers and CLTE from Arlon. These materials have loss tangents of .02, .015, .008 and .004 respectively. From this diagram one can gage the improvement in signal size as lower loss materials are used. Even at 2.4 Gigabits per second, the FR-4 material delivers a satisfactory logic signal. This may come as a pleasant surprise to those wishing to use FR-4 based materials for gigabit and higher products and as an unpleasant surprise to those who thought that a lower loss, more expensive material was needed.

SYSTEM EYE PATTERNS (2.4 Gbps)



FR-4:
Jitter = 0.11 UI
Opening = 733 mV

GETEK:
Jitter = 0.09 UI
Opening = 790 mV

ROGERS 4350:
Jitter = 0.07 UI
Opening = 896 mV

ARLON CLTE:
Jitter = 0.05 UI
Opening = 820 mV

The output waveforms shown result from a 1 volt, 32 bit inverting K28.5 input bit pattern (2.4 Gbps, 60 pS edges) that is applied to a system with two through holes, two AMP HS3 connectors, and a 12 mil, 50 ohm stripline trace that is approximately 18" long.

Courtesy AMP Circuits and Design

Figure 4, Ethernet Eye Diagrams Showing Losses in 18" Long 2.4 Gigabit Links Using Four Types of Dielectric Materials. Courtesy of AMP Packaging Systems

Dielectric Breakdown Voltage, DBV- Dielectric breakdown voltage is a measure of an insulator's ability to withstand the stress of high voltages placed across it. From **Table 1**, it can be seen that all of the commonly available laminates have at least 1000 volts per mil of thickness DBV. This means that a 2 mil thick laminate can withstand a voltage stress as high as 2000 volts, more than adequate to meet the Telco specifications applied to many networking products.

Moisture Absorption- All resin systems absorb some moisture or water when exposed to high humidity environments. This absorption affects the PCB in two ways. Water has a relative dielectric constant of approximately 73. If a laminate absorbs a significant amount of water the resulting relative dielectric constant of the combination will be higher than the 4.1 used to calculate impedance and can cause impedance mismatches.

A more important effect of moisture absorption is increased leakage current. Materials with high moisture absorption may exhibit leakages in excess of what the circuits housed on them can withstand. In order to use high absorption materials in such applications, it is often necessary to seal them with a special coating after first baking them dry. This represents an added cost as well as a problem when rework must be done, since the coating must be removed to do the rework and then reapplied. Two materials that have this problem are polyamide and cyanate ester.

The moisture absorption levels of the FR-4 derivatives are satisfactory for all digital applications.

Goal of Each Application Area

As noted earlier the two applications areas, RF/Analog and Digital have somewhat different materials requirements.

RF/Analog applications are characterized by the need for low dielectric losses, low leakage, a need for a low and uniform dielectric constant accompanied by a low layer count. Further, since this type of PCB tends to be small, cost of the dielectric material has less effect on overall product cost than do other cost components. As a result, using more expensive materials to meet performance goals is acceptable. For this class of PCB, choosing a material based on its dielectric constant characteristics and losses usually dominates over other considerations.

Digital applications are characterized by high layer counts and large numbers of drilled and plated holes. The processing costs associated with registering and laminating many layers, coupled with drilling and plating ease usually dominate the choice of materials. Absolute dielectric constant value of the insulating material is important, but less important than processing costs and dimensional stability. As a result, woven glass reinforced materials are nearly always required. The choice of resin system used with the glass reinforcement is made based on keeping Z-axis expansion within acceptable limits. The thicker the PCB, the higher the Tg must be to produce a reliable PCB. Digital applications are nearly always subjected to pricing pressures, so material choices must be made that just achieve performance requirements without adding extra cost.

An exception to the above for digital PCBs occurs when layer counts become extremely high as often occurs with supercomputer products. In order to keep the overall PCB thickness within reasonable limits and still achieve impedances in the 50 ohm range, it is necessary to use laminates without glass. Omitting the glass results in lower dielectric constants and higher impedance with thinner laminates. Dimensional stability is achieved by mating signal layers with power planes on opposite sides of a piece of laminate. The sheet of copper provides the dimensional stability during processing and lamination. Cost of the finished PCB will be higher using this strategy.

One other area that can require the choice of a low dielectric constant material is in ultra-fast switching applications such as gigabit and higher clocked systems. In such products flight time along the wires required to connect components may limit how fast the system can operate. As dielectric constant decreases, the speed of signal travel on a PCB trace increases. A material with a dielectric constant lower than FR-4 or other glass reinforced materials, such as Speedboard may be needed. It should be noted that this increase in speed carries with it a much higher cost PCB. A designer is advised to try all other methods for achieving the desired speed before resorting to this solution.

List of Woven Glass Materials Used in Digital Applications

Table 1 is a list of several commonly available glass reinforced laminates used to fabricate multilayer PCBs. It is arranged in order of increasing Tg or glass transition temperature. Glass reinforced Teflon is listed at the bottom for comparison purposes.

Teflon is rarely used in multilayer applications due to the difficulty of laminating with it. The characteristics listed are for a resin content of 55% and with dielectric constant obtained using a TDR to measure the velocity of travel rather than the parallel plate method at 1 MHz. Notice that the dielectric constant ranges between 3.9 and 4.1 for all of these materials systems.

Material	Tg	ϵ_r^*	Tan (f)	DBV (V/mil)	WA, %
Standard FR-4 Epoxy Glass	125C	4.1	0.02	1100	0.14
Multifunctional FR-4	145C	4.1	0.022	1050	0.13
Tetra Functional FR-4	150C	4.1	0.022	1050	0.13
Nelco N4000-6	170C	4	0.012	1300	0.10
GETEK	180C	3.9	0.008	1100	0.12
BT Epoxy Glass	185C	4.1	0.023	1350	0.20
Cyanate Ester	245C	3.8	0.005	800	0.70
Polyimide Glass	285C	4.1	0.015	1200	0.43
Teflon	N/A	2.2	0.0002	450	0.01
		* Measured with a TDR using velocity method. Resin content 55%			

Tg = glass transition temperature
 ϵ_r = relative dielectric constant
 Tan (f) = loss tangent

DBV = dielectric breakdown voltage
 WA = water absorption

All materials with woven glass reinforcement except teflon.

Table 1. Several Commonly Available Woven Glass Reinforced Laminates

As can be seen from Table 1, the major difference between materials is glass transition temperature, Tg. In fact, all of these materials, except Teflon, were developed in an effort to arrive at a material that is easy to process and low in cost while raising the Tg. The Tg goal is to get as close to the melting point of solder, 185C, as possible. It can be seen that GETEK, BT Epoxy Glass, Cyanate Ester and Polyamide Glass all achieve the desired Tg. Unfortunately, all of these have processing problems that make them more expensive, sometimes much more expensive, to use than the Epoxy based materials.

The original low cost PCB material was FR-4 with a Tg around 125C. This temperature was too low to provide reliable plated vias in PCB thicker than .062" thick. Multifunctional FR-4, Tetrafunctional FR-4 and the "high Tg" FR-4s, such as Nelco N4000-6, have been developed in an effort to preserve the ease of processing that these epoxy resin systems provide while raising the Tg.

The "high Tg" F-4 systems achieve Tg values in the 170-180C range, high enough to build reliable thick PCBs, thick being more than .062" thick. It should be possible to fabricate reliable PCBs as thick as .250" using these materials. The goal of a reliable, thick PCB at the lowest possible cost is the result.

Nonwoven or Very Low Glass Content Materials

Table 2, lists several materials designed to provide good performance in RF and microwave applications. As can be seen the dielectric constants cover a very wide range.

Selecting a material from this list for use in an RF/analog application is far more complex task than choosing a material for a digital application. For example, the Speedboard products are aimed at being included with other multi-layer materials as part of a high performance design where lower ϵ_r is needed. The various Rogers products are aimed at satisfying a broad range of differing RF needs.

In all cases, these materials are more expensive as raw materials and more expensive to process than the epoxy resin based glass reinforced materials. The potential gains, mainly in lower dielectric constant that would result from using these materials in a digital PCB are rarely, if ever, worth the added cost.

Material	Tg	ϵ_r^*	Tan (δ)	DBV (V/mil)	WA, %
Speedboard N	140C	3	0.02	NA	NA
Speedboard C	220C	2.7	0.004	NA	NA
Rogers Ultralam C	280C	2.5	0.0019	NA	NA
Rogers 5000	280C	2.3	0.001	NA	NA
Rogers 6002	350C	3	0.0012	NA	NA
Rogers 6006	325C	6 to 10	0.002	NA	NA
Rogers RO3003	350C	3	0.0013	NA	NA
Rogers RO3006	325C	6 to 10	0.003	NA	NA
Teflon	NA	2.2	0.0002	450	0.01
Information from manufacturer's data sheets.					

Tg = glass transition temperature
 ϵ_r = relative dielectric constant

DBV = dielectric breakdown voltage
 WA = water absorption

Table 2, List of Non-woven or Very Low Glass Content Laminate Materials

Conclusion

A wide variety of materials have been developed for use in the manufacture of PCBs. Each has its target applications. When used in these targeted applications, the resulting PCB will have the lowest cost possible while satisfying the performance and cost goals of application. Due to confusion about the needs of these applications, especially digital applications, higher cost, more difficult to process materials are often selected. The result is a product that costs more than it should without a compensating benefit.

In the digital space, the “high Tg” FR-4 laminates have a Tg sufficiently high that all but the most demanding applications can be handled with them. There is rarely a need to handicap a design with one of the other more exotic materials systems.

For more information on the properties and uses of the non-woven class of materials, see "Materials for High-speed Design, by Rick Hartley of Applied Innovation. This paper was presented at PCB Design Conference west in March of 1999.