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Laminate Materials with Low Dielectric Properties

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Abstract
Wireless Communications and Broadband technologies are driving the need for advanced laminate materials with improved dielectric properties. This paper focuses on new laminate materials with potential uses in multilayer printed circuit boards (PCBs) for high-speed digital/RF/microwave applications.

The objective of this paper is to discuss the resin structure to property relationship of these new materials. The primary focus will be on the interaction of various factors, such as, glass, chemical composition and laminate construction on the dielectric constant and the dielectric loss properties of laminate composites at frequencies in the 2-10 GHz range. This work is focused on epoxy based and non-epoxy based thermoset polymeric resins.

Introduction

The market for low dielectric materials has continued to grow as wireless communications and broadband applications have reached further into mainstream business and consumer use. The need for materials with improved dielectric properties materials has historically been needed only for RF and wireless transmission circuits. However, as the need for higher bandwidth has grown to support high volumes of data transmission for applications, such as streaming video and B2B commerce, the need for these materials has grown into many high volume digital applications. The electrical properties of the materials are the main differentiation from standard printed circuit board laminates. These are typically reported as dielectric constant (D_k) or ε', and the loss factor (D_f) or ε''. The loss tangent is given by: $\tan \delta (D_f) = \varepsilon''/\varepsilon'$. The values of D_k and D_f are important, but the flatness of response across the frequency range is critical in emerging, digital and high frequency applications. The dielectric constant determines two very important areas concerning the circuit, the size of the board and speed of the signal. Dissipation factor of the material controls dielectric losses and hence the integrity of the signal across distance. The losses in the circuit are caused by resistance in the conductors and attenuation of the electromagnetic wave fields in the substrate.

The dielectric properties of the materials that are used in the fabrication of high speed digital printed circuit boards directly affects the signal transmission characteristics of the interconnect medium. Some of the transmission characteristics of a PCB, that are a function of D_k, include signal propagation speed, characteristic impedance and cross talk. Both D_k and D_f influence the extent to which energy is absorbed from a propagating pulse by the surrounding dielectric material. Unfortunately, the value of D_k and D_f ,or a given material, is not a constant but varies as a function of frequency, temperature, moisture uptake and as a function of the relative proportions of its components. An understanding and knowledge of material dielectric properties over a range of these variables is therefore essential if the transmission characteristics of high speed digital PCBs are to be predictable for realistic operating conditions.

The dielectric losses within a material result in power loss in the signal due to energy absorption by the material in the form of heat as the electromagnetic wave passes through the material. A low loss material will absorb less energy from the propagating signal. The lower energy absorption can have benefits in different aspects of the electronic design. In a transmitting station less power will be required to propagate energy, which can mean longer battery life in a portable device. In a receiving station a low loss material can increase the antenna sensitivity providing clearer signals and reduce the cost of receiver detection electronics.

In high speed digital applications the properties of dielectric materials are better displayed in terms of Eye Pattern parameters. These Eye Pattern parameters are difficult to measure due to the inherent characteristics of the measurement set-up (SMA connectors, impedance imbalance, skin effect losses, etc.) affect the measurement. Eye Patterns provide the following quick answers to designers:

- What is the maximum allowed line length and data rate for the proposed system?
- How much transition jitter will it exhibit?

Effect of Resin Structure on Electrical Properties of Laminate

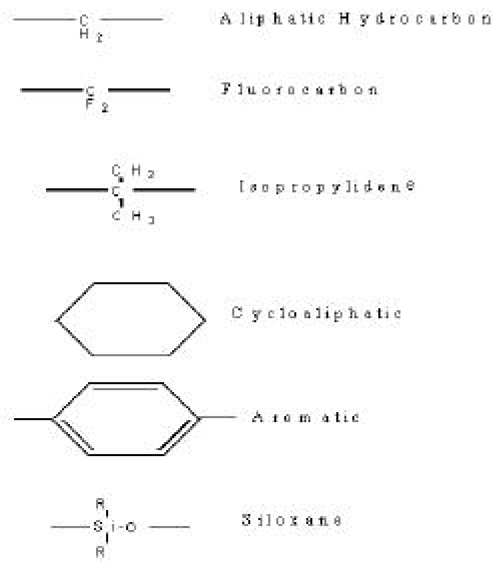
In designing a resin system for low dielectric properties three factors must be taken into consideration, impurities, moisture absorption characteristics and the structure of the polymer. In terms of the first criterion, ionic contamination, such as, trace amounts of catalyst, can increase the conductivity of the resin, and subsequently change the D_k and D_f. Trace levels of ionic contaminants can also exacerbate any humidity resistance problem a given polymeric system may have.

In addition to the negative affects from interactions with ionic impurities, moisture absorption can also affect the dielectric properties of the material by increasing the polarity of the composite matrix of a PCB. The moisture absorption in a composite is a function of inherent polarity of the polymer, cross-link density (which can be controlled in the cure cycle selection and optimization), and fiber-resin adhesion. As the glass fibers are a significant portion of typical PCBs, the extent of moisture migration into the laminate by diffusion and absorption of moisture at fiber surface are matters of concern.

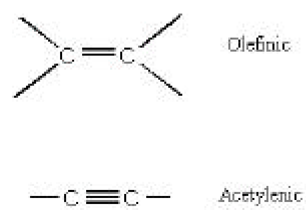
Ideally, for a material to have a low relative D_k and a D_f, the material should be highly symmetric, contain a low number of polar groups, contain chemical bonds with low polarizability, and maximize the intermolecular volume in the polymer matrix. Most thermoset resins tend to exhibit higher D_k and D_f properties due to their polar functionality. In terms of dielectric loss, the D_f of non-polar materials is less than those that are polar with permanent dipoles. Tan δ loss maxima occur at frequencies, or temperatures, corresponding to changes in molecular or dipole motion of the polymer.

By taking advantage of the structural dependence of these dielectric properties, polymers can be tailored by controlling the reactive end groups, polar structural moieties, and of the curing mechanism. However, these three factors must be balanced with the processability, thermal stability, mechanical properties, and adhesion to the PCB substrate that the resulting polymeric material would exhibit.

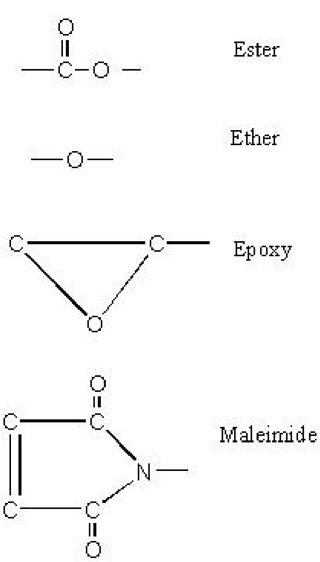
1. Desirable groups for polymer backbone structures



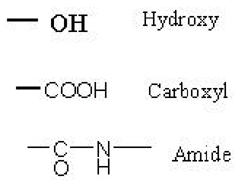
2. Reactive groups for coupling and cross-linking that lead to low dielectric reaction products



3. Groups useful in building polymer segment and cross-linking, but detract from low dielectric and should be kept at minimum



4. Groups to avoid due to their strong effect on increasing dielectric values



The distinguishing feature of most polymeric materials is that they are polarizable. That is, an inherent charge in the chemical structure that can move in response to an external electric field. Ideal dielectrics consist of no polarizable bonds and no delocalized electrons. In addtion, they have mobilities of zero for any free charge applied to their surface and thus are insulators.

In dielectric materials there are many sources for the polarization vactor field. One is electronic polarization, P_e, which concerns the displacement of the electrons in relation to their associated nuclei. The displacement of nuclei relative to other nuclei in a molecule results in atomic polarization, P_α. These two types of polarization are similar in that they are nearly independent of material temperature and frequency of the field – they are both instantaneous responses, and are always in phase with the external field. These two types of polarization combine to generate induced polarization, P_α:

$$P_\alpha = P_e + P_\alpha$$

Induced polarization occurs in molecules which do not have a permanent electric moment.

Polar molecules, with a permanent electric moment, will rotate under the influence of an electric field so that their dipole moments tend to align with the field. They thus create an orientation polarization, P_u, which is both temperature and frequency dependent. The temperature and frequency dependence arises primarily from agitation of molecules and exchange of energy between dipoles. Therefore, the total polarization is the vector sum of contributions:

$$P = P_\alpha + P_u$$

The dielectric constant of a polar solid typically increases with increasing temperature. The permanent dipole become able to align more easily with the applied electric field as molecular mobility increases.

Most polar polymers containing hydrogen-bonding moieties, are susceptible to moisture. Water molecules can become incorporated into them upon exposure to humidity. In addition, D_k is often sensitive to the presence of even small quantities of many common plasticizers, stabilizers and other additives.

It is known that fluorination normally reduces D_k, however, asymmetric fluorination can sometimes create very large dipole moment vectors, and result in polymers, which have high D_k values, and sometimes also have other unusual effects on electrical properties, which cannot be predicted by existing structure-property relationships.

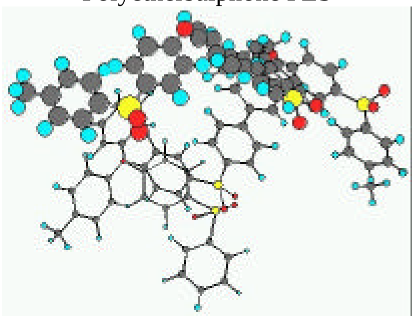
Typically, structural and/or compositional modifications change the dielectric constant and the dissipation factor of a polymer in the same direction. For example, moisture and polar plasticizers increase both D_k and D_f, although the magnitude of the change is often much larger for D_f than for D_k.

PTFE and PES Structure, Electrical Properties and Test Method

Prior to the evaluation of different formulation strategies to develop a new low loss material, the first step involves a thorough evaluation and understanding of the loss measurement test method used to down select materials, and to further understand and quantitatively differentiate the contributions of the laminate system components. The method should have the minimum characteristic of being **accurate**, (capable of resolving true quantifiable material differences) and **precise** (repeatable with minimal variation from the test itself). Any special causes from factors related to the test method should be identified and corrected using control charts for the test method to have any value in resolving true material differences. In this case the Bereskin test method was selected.

The Bereskin test method was selected for its ability to measure D_k and D_f of materials in the frequency range of interest 2, 5 and 10 GHz (up to 20 GHz with some equipment upgrades). In keeping with the following screening plan: (a) resin (b) laminate (c) printed circuit board (d) OEM application process, the Bereskin test method offers the advantage of measuring unclad neat resin properties for down selection and further characterization in the first stage of the screening development process. Two well known polymer materials with D_f properties in the range of interest (0.002 - 0.004 and 0.006 - 0.008) were selected to evaluate the test method for its ability to resolve material differences in the previously mentioned frequency range of interest. These were pure polytetrafluoroethylene (PTFE ~ 0.002 D_f) and polyethersulphone (PES ~ 0.007 D_f) Backbone structures are listed in Figure 1. The other test factors selected to evaluate D_f variation included specimen plaque thickness (0.060” +/-0.002” vs. 0.080” +/- 0.002”); foil strip length 3.5” vs. 3,” foil placement, (end vs. center); test side; strip; and 2 different strips of the same type. The design for this experiment is listed in Table 1.

Polyethersulphone PES



Polytetrafluoroethylene PTFE

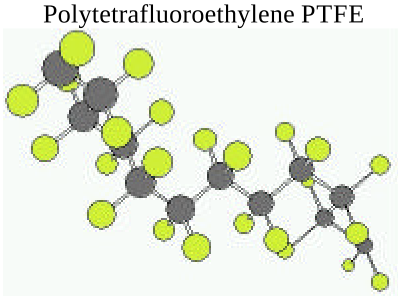


Figure 1 – Idealized PES and PTFE

Table 1 - Experimental Design 2^{5-1} Fractional Factorial

-	0.06	PTFE	-40	3	2
+	0.08	PS	-50	3.5	10
Sample	Casting Thickness	Resin Type	Coupling Gap	Foil Length	Test Frequency
1	-	-	-	-	+
2	+	-	-	-	-
3	-	+	-	-	-
4	+	+	-	-	+
5	-	-	+	-	-
6	+	-	+	-	+
7	-	+	+	-	+
8	+	+	+	-	-
9	-	-	-	+	-
10	+	-	-	+	+
11	-	+	-	+	+
12	+	+	-	+	-
13	-	-	+	+	+
14	+	-	+	+	-
15	-	+	+	+	-
16	+	+	+	+	+

The sample dimensions were 3-1/8" x 1-3/16" x (0.02" x 0.060") samples were tested in randomized order to detect any background special causes from testing bias and to increase the degree of belief in any factor effects of the rationalized data. From the results shown in Figures 2 and 3, the material type (polymer backbone) can clearly be seen as the the main factor observed to affect the D_k and D_f at 2-10 GHz in the rationalized XBAR & R charts in Figure 3 and Figure 4 respectively. The other factors of specimen thickness for 0.020" – 0.060", copper length, placement or specimen test side did not affect the variation significantly. In this case both materials responded similarly at both ends of the frequency range, although the higher PES material exibited slightly increased variation than PTFE. Sample thickness (between 20 – 80 mil) was not observed to be a significant factor in neat resin castings.

Subsequent laminate specimen measurement studies have shown the loss factor response to vary depending on weave style, reinforcement composition, resin content, specimen taper and thickness. Polymer density and adsorbed moisture may also significantly impact both neat resin and reinforced composite specimens. In this study, moisture adsorbption effects were minimized through an IPC 24 hr. 50% relative humidity conditioning step for all specimens immediately prior to testing. Post-curing may be required to normalize the castings to achieve full cross-link density in the case of thermosets.

From the resin formulator and laminator points of view, the measurable loss characteristic of neat resins in the context of the Bereskin test method provide a unique window to observe the quantifiable loss characteristics of various formulated polymer systems unfettered by the downstream confounding factors of reinforcement substrate in laminates and printed circuit board design factors. Indeed this provides for a clearer understanding of the quantifiable contribution and interaction of laminate components in a systematic, constructive approach towards the prediction of material substrate performance in increasingly complex laminate and printed circuit board system evaluations. See Figure 1 and Table 1.

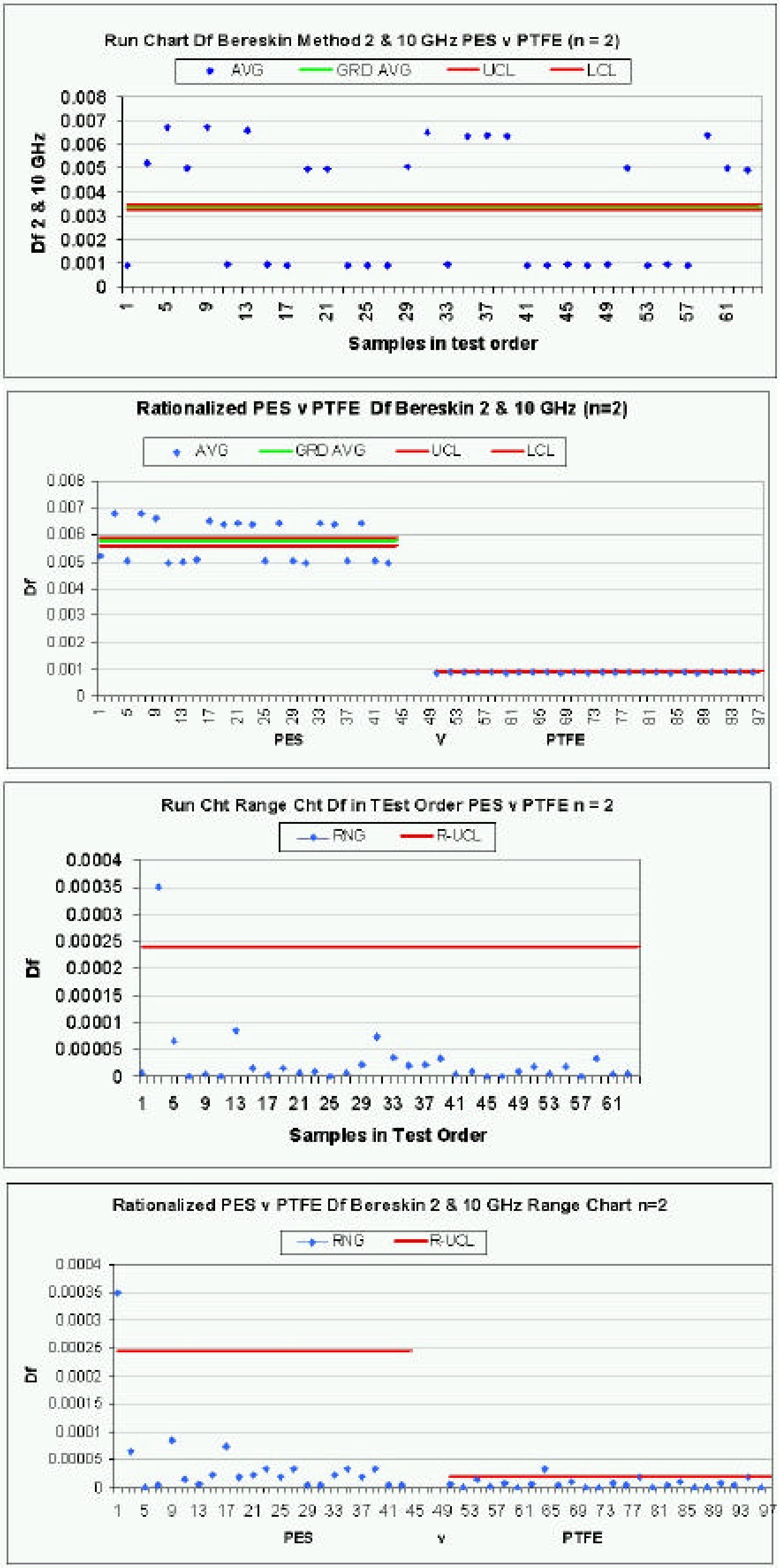


Figure 2 – Bereskin D_f Results

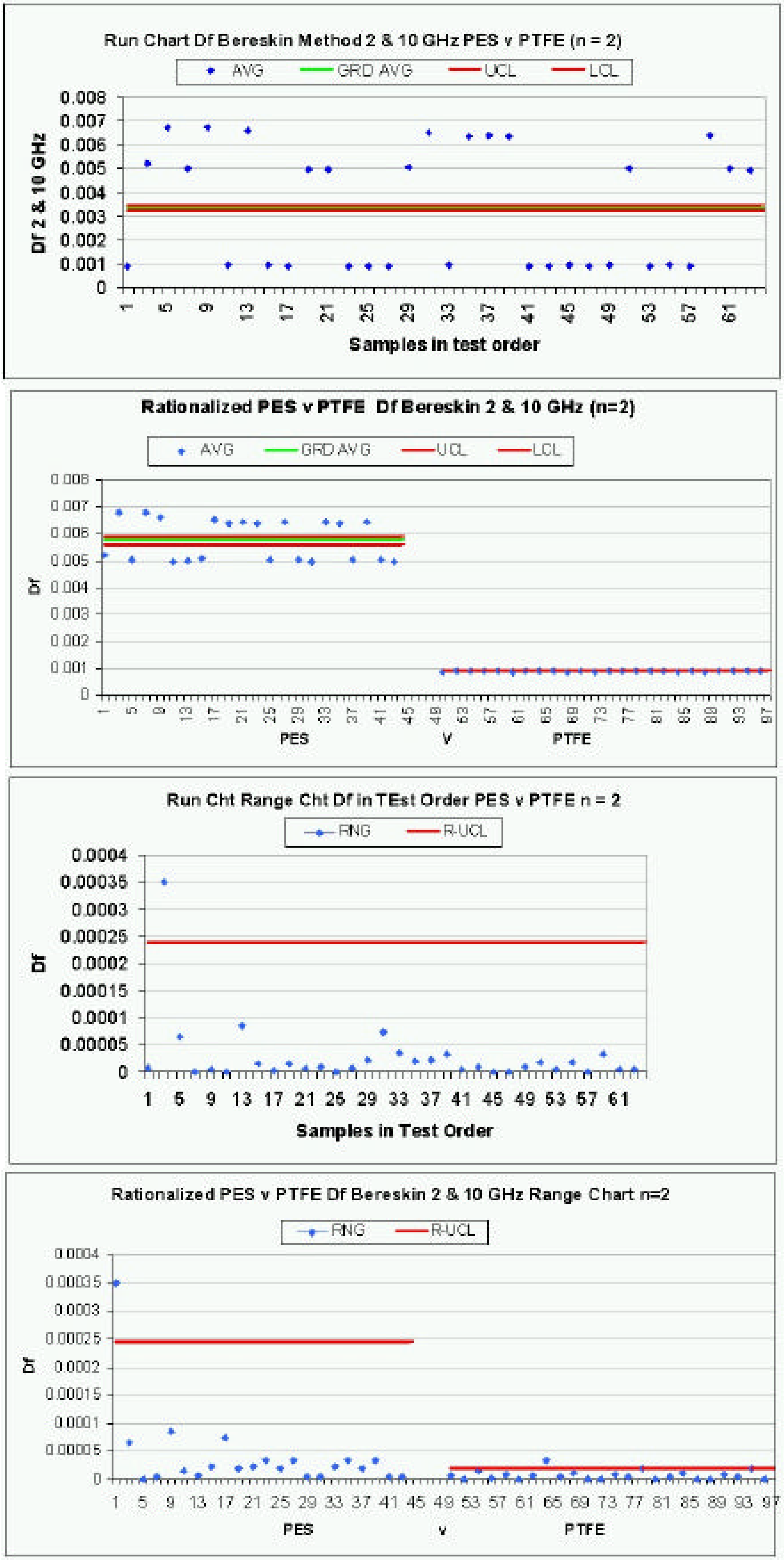


Figure 3 – Bereskin D_k Results

Relationship between Laminate Dielectric Properties and Glass-to-Resin Ratio

Laminates used in the manufacture of PCBs are composite materials comprised of a resin matrix, a reinforcement and copper foil. It is well known that dielectric constant of a laminate ε'_{lam} may be calculated, and there are several theoretical models that have been developed to predict the dielectric properties of a given laminate composite. The key factor in these models requires an understanding of the dielectric properties of the resin and the reinforcement. Typically, the main factor influencing the dielectric properties of the laminate consistency is the variation of the glass-to-resin ratio. If one varies the thickness of the laminate by adding or removing resin, or the frequency at which the measurement is performed, the measured D_k and D_f of the composite will change.

Variation in thicknesses are generally due to the differences in the weight of resin per unit area of laminate and the dielectric thickness of glass fabric style. Dielectric properties of resin play an important role in determining the overall dielectric properties of laminate.

Laminates produced from resin systems of lower D_f values than glass generally exhibit lower D_f values with thinner glass whereas resin systems with higher D_f than glass gives higher D_f with thinner glass and lower D_f with thicker glass. See Tables 2 and 3.

Table 2 - Resin System with a Lower D_f than E-Glass

Material	Dk (10GHz)	Df (10GHz)	% Resin
Laminate – 2116 Glass (E-Glass)	3.05	0.0033	52
Laminate – 7628 Glass (E-Glass)	3.3	0.0046	45
Neat Resin – A	2.4	0.0026	100

Table 3 - Resin System B with a Higher D_f than E-Glass

Material	D_k (8.5GHz)	D_f Df (8.5GHz)	% Resin
Laminate – 1080 Glass (E-Glass)	3.51	0.0122	55
Laminate – 7628 Glass (E-Glass)	3.85	0.0117	40
Neat Resin – B	2.58	0.013	100

D_k - E glass – 6.3 @ 1 MHz
D_f – E-glass – 0.0037 @ 1 MHz

D_k/D_f of E-glass fabric is not available at high frequency. It is assumed that D_k of glass is higher than most of epoxy and non-epoxy based resin systems. See Table 3.

Example of High Frequency Laminate Material

An intermediate dielectric properties (IDP) laminate, based upon the structure / property relationship principles and theory just discussed and on an epoxy chemistry, was developed.. Electrical properties are extremely flat over the frequency range of 1 – 5 GHz. Laminates were prepared on E-Glass. The D_k / D_f data is summarized in Figure 4.

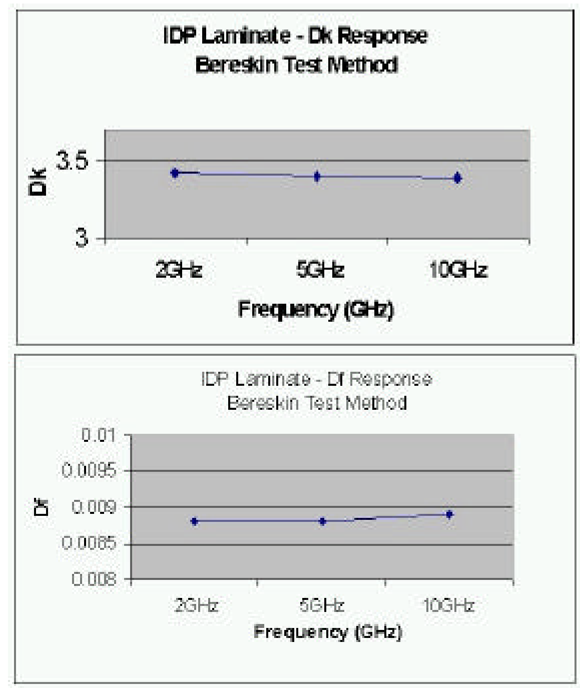


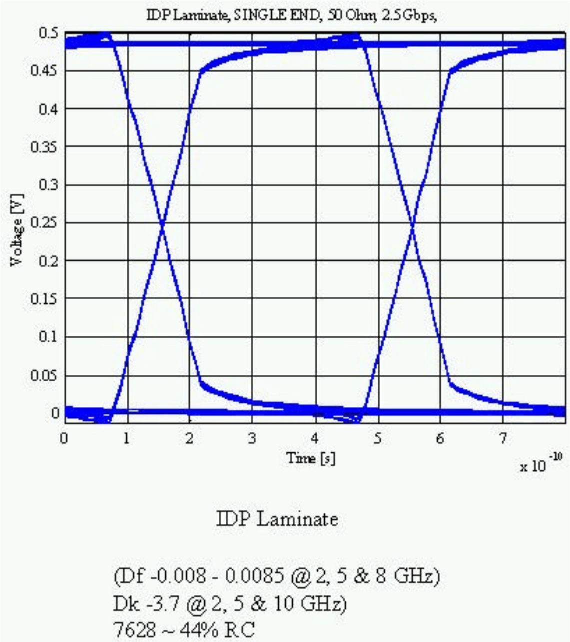
Figure 4 – IDP Laminate Dk and Df

Eye Patterns for the IDP laminate were generated to demonstrate how the dielectric properties of these materials will behave in high-speed digital applications. The Eye Patterns shown in Figure 5 were developed by computer simulation.

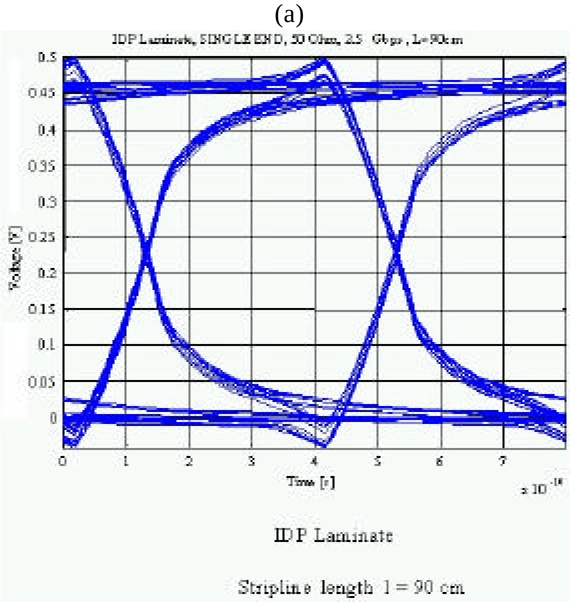
The IDP laminate shows a larger Eye Pattern opening and also for long traces (70-90 cm) and a small jitter.

Low Dielectric Properties of the Next Generation Laminate Material

The next generation of laminate material is designed to obtain D_f in the range of 0.003 – 0.004 @ 10 GHz to support RF/microwave market place. Laminates were prepared on E-Glass. D_k/D_f data is shown in Figure 6.



(a)



(b)

Figure 5 - IDP Laminate Eye

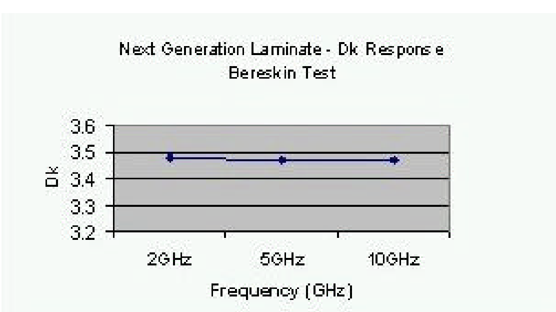


Figure 6 – Next Generation D_k and D_f

Conclusion

In this paper we have demonstrated that understanding the structure/property relationship of a laminate composite can help the scientist to develop and select the proper components to build a system that can balance the critical factors that affect D_k/D_f of a laminate composite. We have also shown that test methods that can differentiate various material attributes are essential to successfully achieving the desired electrical properties. With these capabilities established, we have shown how these bas ic tools can be used to develop laminate composites with unique electrical performance in key attributes and have provided one example of these capabilities.

References

1. Stephen J. Mumby, " An Overview of Laminate Materials with Enhanced Dielectric Properties." J. Electron. Mateer., Vol. 18 (2), P. 241-250 (1989).
2. T.D. Newton, " Predicting Dielectric Properties." Proceedings of the IPC Meeting. Boston, Spring 1986.
3. Fundamental and Industrial Applications of MW & RF Fields by G. Roussy and J.A. Pearce.
4. A.B. Bereskin, "Microwave Dielectric Property Measurement." Microwave Journal, vol 35, no.7, pp.98-112.