

Making Sense of Laminate Dielectric Properties

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Abstract

System operating speeds continue to increase as a function of the consumer demand for such technologies as faster internet connectivity, video on demand, and mobile communications technology. As a result, new high performance PCB substrates have emerged to address signal integrity issues at higher operating frequencies. These are commonly called low D_k and/or low loss (D_f) materials. The published “typical” values found on a product data sheet provide limited information, usually a single construction and resin content, and are derived from a wide range of test methods and test sample configurations. A printed circuit board designer or front end application engineer must be aware that making a design decision based on the limited information found on a product data sheet can lead to errors which can delay a product launch or increase the assembled PCB cost. The purpose of this paper is to highlight critical selection factors that go beyond a typical product data sheet and explain how these factors must be considered when selecting materials for high speed applications.

Introduction

Whether making a decision to buy electronic equipment, a mobile phone, or substrate material, the first place a person will look is a technical data sheet. The data sheet provides a ‘snap shot’ of the product attributes which can be used to compare similar products. A laminate material data sheet should be used by the user as a guideline and comparison tool and should not be used as a design tool; however it is often used for that purpose.

The terms permittivity (D_k) and loss tangent (D_f) are used on the data sheet to describe laminate electrical performance properties. Both of these properties vary with changes of resin content, temperature, and the moisture content of the substrate material^{1,2}. In addition to these factors, the test methods that are used to evaluate the laminate properties can produce values that vary significantly. A typical high T_g laminate data sheet states the “typical” electrical

properties (D_k and D_f), at 1 MHz – 1 GHz for one resin content. For high speed digital substrates, a data sheet will provide “typical” (not exact frequencies) data points for 2, 5 and 10 GHz for one resin content. In some cases, the data sheet will specify the test method that was used to test the material. A PCB designer will need more information about the test methods used to prepare the laminate electrical data in order to make informed decisions about which laminate is the right choice for the application.

Making an informed decision means the designer should consider the variations in the material properties as well as the test methods used to develop the material data. The typical data sheet does not provide this type of detailed information. As design requirements for high speed digital applications continue to push the envelope of performance, it becomes critical to consider these influences.

I. Basis for Comparison

In order to better understand the influence of material and test variations on electrical performance, one can use the following equations to approximate the dielectric and conductor losses and thus will be used in this paper as the foundation for comparisons. It is important to include the conductor losses as part of the comparison, because that portion of the loss can account for a substantial portion of the overall loss. The calculation for conductor loss does not include the effects of surface roughness of the conductor and should not be ignored. However, it is not discussed in the scope of this paper.

The following first order approximations can be used to show the difference in attenuation⁸.

$$\alpha_{\text{material}} = \alpha_{\text{dielectric}} + \alpha_{\text{conductor}}$$

$$\alpha_{\text{dielectric}} = 2.3 \cdot f \cdot D_f \cdot \sqrt{D_k} \text{ (dB/in) Eq. \#1}$$

where,

$\alpha_{\text{dielectric}}$ is the dielectric loss

f is the frequency (GHz)

D_f is the material loss tangent

D_k is the material relative permittivity

and,

$$\alpha_{\text{conductor}} = 36 \cdot \sqrt{f} / Z_o \cdot w \text{ (dB/in) Eq. \#2}$$

where,

$\alpha_{\text{conductor}}$ is the conductor loss

f is the frequency (GHz)

Z_o is the impedance (Ω)

w is the trace width (mil)

These approximations have been demonstrated to be accurate enough to make informed decisions regarding material performance. These two equations will be used below to help

demonstrate the influence of the variables mentioned previously.

II. Effects of Resin Content

Differences in resin content percent have a significant effect on the D_k and D_f values. The resin content percent varies based on the glass style, on target thickness for a given glass style, and manufacturing tolerances. The following chart (Figure 1) demonstrates these differences between resins contents of 40% to 75% at three nominal frequencies at room temperature.

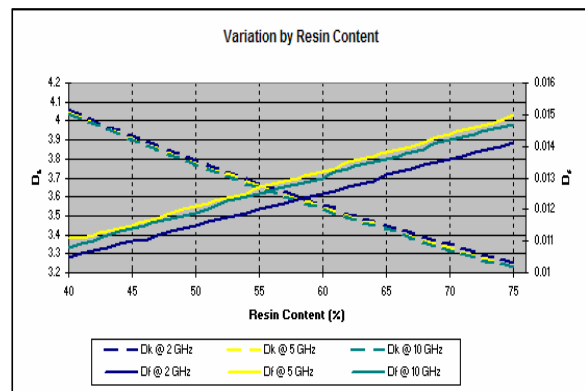


Figure 1. Resin Content percent impact on D_k and D_f

Typical resin content percent ranges for laminate and prepreg product lines range from approximately 40-50% on thick cores with heavy glass cloth like 2116, 1652 and 7628 and 65-75% for 106 and 1080 which are typically used to bond inner layer cores together. Typical thin core constructions in the 0.003 to 0.005" thickness range are around 50 % for single ply glass cores and the 60 % resin content range for 2 ply glass cloth cores.

Different laminate thicknesses require different glass styles and subsequently different resin contents to achieve the desired thickness. Using a Mid D_k material operating at 2GHz, from the example above, one can determine the values for the electrical properties for a single ply of 1080, 2116, and 7628 laminate and 106 and 1080 prepreg. The following example (Table 1)

reveals how these values change with resin content.

Mid D_k Resin System

Thick-ness (mils)	Constr-uction	Resin Content %	D_k	D_f
2.5	1x1080	57	3.63	0.0122
4.5	1x2116	49	3.82	0.0114
7.0	1x7628	40	4.06	0.0115
106 PP	-	75	3.25	0.0141
1080 PP	-	65	3.45	0.0131

Table 1. D_k and D_f changes due to Resin Content percent

III. Effects of Temperature

The reported values on the laminate data sheet are typically derived from testing at room temperature; however the electrical performance of the substrate will also vary with the operating temperature of the PCB. Most high end designs typically incorporate components that develop a significant amount of localized heat during operation. The designer should be aware of the influence of increased temperatures of the material due to localized heat generated by the components mounted on the board. Selection of a material with a minimal response to increased temperatures should be considered when operating temperatures are elevated.

The following charts (Figures 2 and 3) demonstrate that using lower D_k and lower D_f product provides a more stable performance over a wider range of temperatures. As an example, the difference in Permittivity, D_k , and loss tangent, D_f , for a 'Mid D_k ' resin system between 23°C to 50°C is about 0.5% and 10% respectively. The change in permittivity is small while the difference in loss tangent is significant. The approximate increase in attenuation using equation #1 is ~10% or -0.266 dB/in versus -0.295 dB/in.

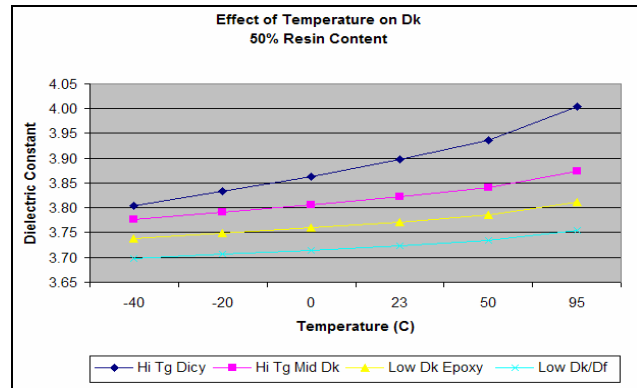


Figure 2. Effect of Temperature on D_k

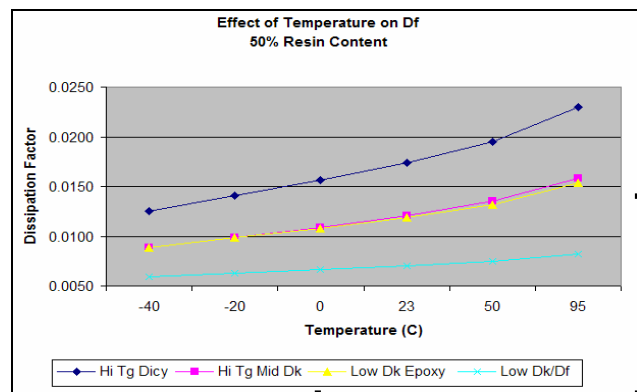


Figure 3. Effect of Temperature on D_f

IV. Effects of Moisture

As designers continue to push the design envelop and operating frequencies continue to increase, humidity dependant loss should be considered². The rate of diffusivity and thus the equilibrium moisture content can be calculated using Ficks' Law of Diffusion for a given laminate using a specific resin system and thickness. Laminate data can be used for comparison between material choices and to make predictions about the potential influence during system operation. Moisture dependant electrical performance data is very difficult to define on a data sheet, but it should be considered.

Chart #3

The rate of moisture uptake of the material is dependent on several factors which include: ambient environmental and process temperatures, time of material exposure during fabrication, influence of wet PCB manufacturing processes, prepreg, etched laminate, and PCB storage conditions, inner layer and PCB thickness, PCB packaging, resin type and resin content, PCB design and construction, all of which allow, introduce, or trap the moisture in the PCB. These factors influence the amount of moisture that might be in a PCB and the definition of each point of ingress can not be modeled simply and thus is not easily predicted.

V. Effects of Differences in Construction

Laminate properties are dependent on construction because each construction is made using different glass styles and resin contents. The designer should be aware of the differences in D_k and D_f values between single ply and two ply laminate constructions for the *same thickness*. A typical data sheet lists only one construction and one resin content and does not show the range of construction options. The following (Table 2 and Table 3) is an example comparing single ply construction to a two ply construction showing the electrical properties are significantly different within a given thickness. These differences do become critical when bandwidth is at a premium.

Construction	Resin	D_k		
	%	2 GHz	5 GHz	10 GHz
Mid Dk, Df 0.004" 1 X 2116	45	3.920	3.910	3.900
Mid Dk, Df 0.004" 1 X 3070	49	3.820	3.800	3.800
Mid Dk, Df 0.004" 1 X 3313	54	3.700	3.680	3.670
Mid Dk, Df 0.0043" 106/1080	61	3.540	3.520	3.510

Table 2. D_k Differences Based on Construction

Construction	Resin	D_f		
	%	2 GHz	5 GHz	10 GHz
Mid Dk, Df 0.004" 1 X 2116	45	0.0110	0.0115	0.0114
Mid Dk, Df 0.004" 1 X 3070	49	0.0114	0.0120	0.0118
Mid Dk, Df 0.004" 1 X 3313	54	0.0119	0.0125	0.0124
Mid Dk, Df 0.0043" 106/1080	61	0.0126	0.0133	0.0132

Table 3. D_f Differences Based on Construction

On an existing design, substituting a single ply core for a two ply core construction to save cost will result in differences in the laminate electrical properties. One common mistake that is made is a substitution of a single ply laminate or prepreg for a two ply dielectric openings to save money and offer a reduced cost PCB without consideration of the changes in electrical performance. The result may be a non-functional or poorly functioning system.

Compare the properties of laminate used in a design built using a 2x106 3.5 mil core and one substituting a single ply 1x2113 3.5 mil core. The following (Table 4 and Table 5) compares the data sheet and the construction options for Mid D_k material. Given this information, one should note that the 1x2113 3.5 mil core electrical properties are a relatively close match the material data sheet while the 106 & 2113 prepreg and 2x106 3.5 mil core are significantly different. This is a critical difference that must be considered when bandwidth budgets are tight.

Construction Freq (GHz)	D_k		
	2	5	10
Material Data Sheet	3.77	3.75	3.75
Mid D_k 1x2113 3.5 mil Core	3.77	3.75	3.75
Mid D_k 2113 prepreg	3.63	3.62	3.60
Mid D_k 2x106 3.5 mil Core	3.41	3.39	3.38
Mid D_k 106 Prepreg	3.25	3.23	3.23

Table 4. D_k Differences (Data Sheet Comparison)

Construction	D_f		
	2	5	10
Material Data Sheet	0.0116	0.0122	0.0120
Mid D_k 1x2113 3.5 mil Core	0.0116	0.0122	0.0120
Mid D_k 2113 prepreg	0.0122	0.0129	0.0127
Mid D_k 2x106 3.5 mil Core	0.0133	0.0140	0.0138
Mid D_k 106 Prepreg	0.0141	0.0150	0.0147

Table 5. D_f Differences (Data Sheet Comparison)

As an example and referring to Tables 4 and 5, consider a PCB which has a 10 inch long, controlled impedance transmission line operating at 2 GHz that has been designed, tested, and prototyped using the 2x106 construction and *correct dielectric properties*.

In an effort to reduce cost, the PCB shop might decide to convert the design to single ply stack up and substitute a 2113 construction for the 2x106 dielectric openings. The problem arises when the line widths must be reduced to match the desired impedance due to the higher D_k values of the 1x2113 core and 2113 prepreg (which in this case matches the data sheet). In order to match impedance, the PCB engineer would typically calculate the line width based on a 50 Ω impedance target and would arrive at ~3.6 mils on half ounce copper. However, for the 2x106 construction, the line width would be ~4.4 mils on half ounce copper.

By reducing the line width, the conductor losses increase and this is where the substitution becomes a problem. The resulting attenuation due to conductor losses alone, as determined by equation #2, would be approximately -0.280 and -0.233 (dB/in) respectively. Combining these with the dielectric losses, the 2x106 construction would result in an attenuation of approximately -3.44 dB and the 1x2113 construction would result in an attenuation of approximately -3.83 dB. This is a 10% increase from the original construction and may result in system performance issues.

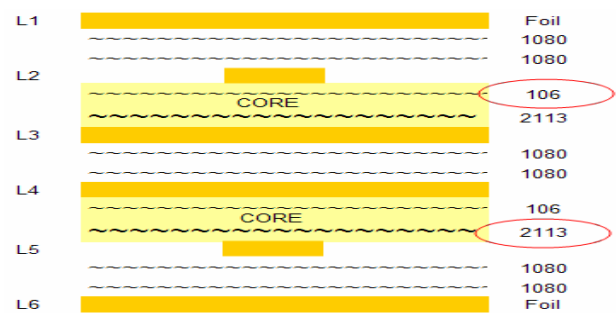


Figure 4. Unbalanced Laminate Construction

In another example (Figure 4), an unbalanced laminate construction also poses a potential risk. The local ϵ_r (D_k) on one side of the laminate in a 106/2113 5.3 mil core construction will be different from side to side⁶. Orientation of the panel during design and fabrication becomes critical and care must be taken to ensure the panel is printed on the correct side. The difference in the D_k and D_f values from the 2113 to the 106 side approximately 12% and 19% respectively.

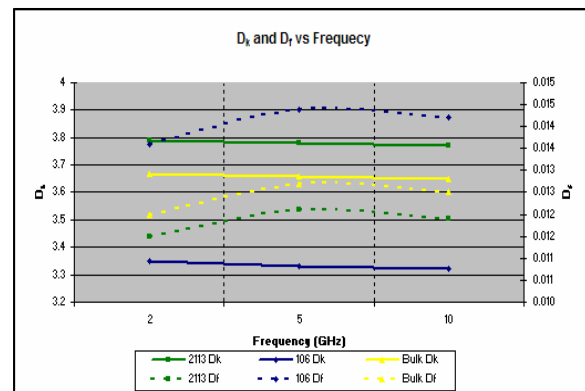


Figure 5. Difference in Attenuation Between Bulk Properties and Local Properties

The resulting difference in attenuation between the bulk properties and the local properties of a strip line configuration placed on the 106 side of the laminate using the construction above at 5 GHz, as determined by equation #1, would be -0.36 dB/in which would have a significant impact on the band width budget.

Figure 5 demonstrates the variation in the local dielectric properties as compared to the bulk dielectric properties. Note that the laminate test methods used to determine the bulk dielectric properties of materials can not be used to take in to account the localized effects of construction.

VI. Differences in Resin Systems

PCB designers and engineers must be careful to note that each resin system will have different D_k and D_f values depending on resin content. A common mistake is making a substitution from one resin system to another with out fully understanding the differences in material performance. This often results in boards that do not function at all. One example of this error is the substitution of a High T_g lead free *Phenolic* cured resin system versus a High T_g non-lead free *Dicy* cured resin system. This error can occur when the electrical properties are not fully investigated and the performance of the Phenolic cured system falls short. The following charts demonstrate the differences between four different resin systems.

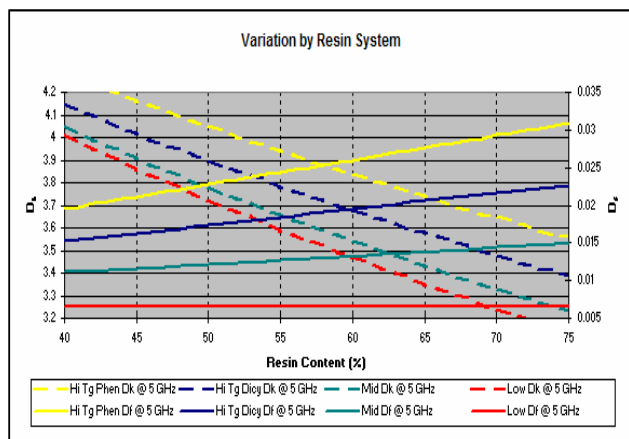


Figure 6. Variation in Dielectric Properties by Resin Systems

The following tables (Tables 6-8) compares the four materials at 50% resin content. Note the significant difference in material performance between resin systems.

Resin System	@ 2 GHz		
	Dk	Df	Loss dB/in
Hi Tg Phen	4.16	0.0196	0.460
Hi Tg Dicy	3.92	0.0169	0.385
Mid Dk/Df	3.79	0.0115	0.103
Low Dk/Df	3.76	0.0061	0.054

Table 6. Dielectric Properties (2 GHz) between Resin Systems

Resin System	@ 5 GHz		
	Dk	Df	Loss dB/in
Hi Tg Phen	4.05	0.0228	0.528
Hi Tg Dicy	3.90	0.0174	0.395
Mid Dk/Df	3.78	0.0121	0.271
Low Dk/Df	3.72	0.0066	0.146

Table 7. Dielectric Properties (5 GHz) between Resin Systems

Resin System	@ 10 GHz		
	Dk	Df	Loss dB/in
Hi Tg Phen	4.05	0.0229	0.530
Hi Tg Dicy	3.90	0.0174	0.790
Mid Dk/Df	3.77	0.0119	0.531
Low Dk/Df	3.72	0.0070	0.311

Table 8. Dielectric Properties (10 GHz) between Resin Systems

By using equation #1, one can evaluate the difference and benefit of using lower D_k/D_f laminate material. A simple estimated bandwidth analysis at 5 GHz gives the following results: -0.527, -0.395, -0.271, -0.146 dB/in respectively. In theory, the line length for a low loss material could be 3.6 times longer.

VII. Differences in Test Methods

The methods (Table 9) commonly used for testing laminate are Parallel Plate, Two Fluid Cell, Split Post Cavity Resonator, IPC X-Band Stripline, Bereskin Stripline, and Full Sheet Resonance methods. All of these methods have limitations that are dependant on the sample thickness, frequency used for the test, accuracy of the test method, and repeatability of the measurements^{3,4,5}. Because of the number of different test methods and resin contents used by laminate suppliers, it is extremely difficult to make an accurate comparison between one laminate and another using the data sheet.

The results of testing with these test methods vary and sometimes vary dramatically from method to method⁴. The applicable test frequency range, sample requirements, and accuracy of the results vary depending on the method used. The test fixture also plays a role since air gaps between the samples and fixture can skew the results. And indeed, the differences in fixtures for the same method produce significant differences in test values due to air gaps.

Methods	IPC Spec	Sample		Frequency Range
		Thick-ness	Size	
Two Fluid Cell	IPC 2.5.5.3	5 - 250 mils	3.2" x 3.2"	1 MHz
Parallel Plate	IPC 2.5.5.9	15 - 120 mils	2" x 2"	1 MHz - 1.5 GHz
IPC Stripline	IPC 2.5.5.5	58 - 62 mils	2" x 2.75"	10 GHz
Bereskin Stripline	-	20 - 62 mils	4" x 1.75"	2 - 15 GHz
Post Cavity	IPC 2.5.5.13	30 mils*	2" x 2.75"	1 GHz - 35 GHz

All samples for electrical test methods above are tested without copper

*Split Post Cavity Sample thickness is dependent on the frequency you are testing at.

Table 9. Dielectric Properties Test Methods

Therefore, for the purpose of D_k testing, the two methods are very comparable and yield similar results. The following (Table 10) compares the resulting test values of these two methods. However, when testing identical samples using these two methods, the differences become apparent when comparing the D_f values. The values for the Split Post Cavity Method are 20-30% lower for each material than for those derived using the Bereskin Stripline Method. *When comparing laminate data sheets, the designer should be aware that the product tested using certain methods may appear to have better loss properties than a product tested using the another method.*

Test Method	Frequency (GHz)	PPO Epoxy	Low D_k Epoxy	Mid D_k Epoxy	Low D_k/D_f
Split Post Cavity	2 GHz	0.0099	0.0084	0.0095	0.0044
	5 GHz	0.0102	0.0089	0.0096	0.0050
Dissipation Factor (D_f)	10 GHz	0.0110	0.0089	0.0096	0.0053
Bereskin Stripline	2 GHz	0.0140	0.0120	0.0129	0.0060
	5 GHz	0.0141	0.0127	0.0131	0.0066
Dissipation Factor (D_f)	10 GHz	0.0141	0.0125	0.0131	0.0071

Table 10. Dielectric Properties based on Resins Systems versus Test Methods

VIII. A Problem with Substitution

A major problem can arise when material substitutions are made when using laminate data sheets as a guide, *especially when the data is derived from different laminate test methods*. While initial impedance calculations look acceptable because the D_k values are similar, the actual board performance may be significantly different and may result in poorly functioning or non-functioning boards. Matching the D_k is important, but matching the D_f is critical.

The example in Figure 7 is for a 16" long strip line using a Mid D_k epoxy resin system. Using

equation #1 with no conductor losses included, it can be determined that the difference between data derived from the Split Post Cavity Method and that derived by the Bereskin Stripline Method is as large as -2.54 dB at 10 GHz which is over 80% of the typical -3 dB budget for a typical transmission line.

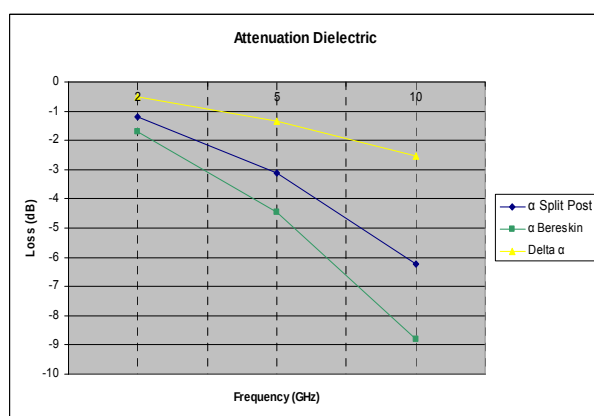


Figure 7. Variation in Dielectric Properties by Test Method

Making a material substitution is a serious endeavor. A lack of understanding of the actual material properties can result in a costly and embarrassing mistake.

Summary

Data sheets do not provide adequate information for design purposes. The laminate supplier should provide detailed information about the laminate performance over a range of resin contents, glass fabric constructions and frequencies. They should demonstrate expertise and complete understanding of the test method(s) used to acquire the data and how it relates to other methodologies which should include PWB and system test methods. Better, more complete information can assist in reducing the design cycle and prototyping steps and aid the designer in making stack up selections that reduce cost and/or provide a cost to performance advantage. Furthermore, characterization of the material in a standardized test vehicle should be performed to fully understand the performance of high speed

digital materials. The tooth height of the copper used and roughness of the oxide on the inner-layers will have an effect on the impedance as well. These should be included in the characterization of materials used for High Speed Digital Designs.

Data sheets can be a useful tool during an initial material electrical properties comparison if the test methods used to derive the data are identical. Care should be taken to fully understand any differences between the test methods used to derive the properties as they may produce significantly different results. Differences in the test method can make a one to one comparison misleading and can result in major performance issues when a laminate substitution is made and may potentially result in a nonfunctioning system. One of the most common mistakes that is made is making a material substitution with out considering the actual electrical performance properties of the laminate material.

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