A Heuristic Approach to Assess Anisotropic Properties of Glass-reinforced PCB Substrates

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Abstract

Obtaining dielectric material properties is crucial when modeling PCB transmission lines, vias or rf antennas. One critical property is the relative permittivity (εr) or dielectric constant (Dk). Using incorrect Dk values can lead to impedance miscalculations, potentially affecting the yield of PCB fabrication or the performance margins of the final product. Given that fiberglass reinforced laminates used in PCBs are anisotropic, the effective Dk can vary based on the test method used. This paper introduces a unique heuristic approach to assess anisotropic properties of glass-reinforced PCB substrates, leveraging the Dk/Df construction tables provided by copper-clad laminate suppliers.

Author Biography

Lambert (Bert) Simonovich graduated from Mohawk College of Applied Arts and Technology, Hamilton, Ontario Canada, as an Electronic Engineering Technologist. During his 32-year tenure, at Bell Northern Research | Nortel in Ottawa Canada, he helped pioneer several advanced technology solutions into products. He has held a variety of engineering, research and development positions, eventually specializing in high-speed signal integrity and backplane design. After leaving Nortel in 2009, he founded Lamsim Enterprises Inc., where he continues to provide innovative signal integrity and backplane solutions as a consultant. He has authored several award-winning publications and is holder of two US patents. In addition to being a senior member of IEEE, he currently serves as a member of DesignCon's Technical Program Committee, and Signal Integrity Journal's Editorial Advisory Board. His current research interests include high-speed signal integrity, modeling and characterization of high-speed serial link architectures. His most notable modeling achievement is the invention of the "Cannonball" conductor roughness model, also known as “Cannonball-Huray” roughness model, found in several electronic design automation (EDA) software tools.

Introduction

In the process of designing a printed circuit board (PCB) stackup and computing transmission line characteristic impedance (Z_0), it is crucial to obtain accurate dielectric material properties from reliable sources. A key factor in this regard is relative permittivity or dielectric constant (Dk).

The values of Dk can be different based on the specific test method used. Some methods give results from in-plane measurements, where the electric fields are parallel to the test sample. Conversely, other methods derive Dk from out-of-plane measurements, where the electric fields are perpendicular to the test sample.

Failure to design the stackup properly can be problematic. If the Dk value used in field solver impedance simulation is incorrect, it can lead to time domain reflectometer (TDR) impedance test failures and potentially lower PCB fabrication yield.

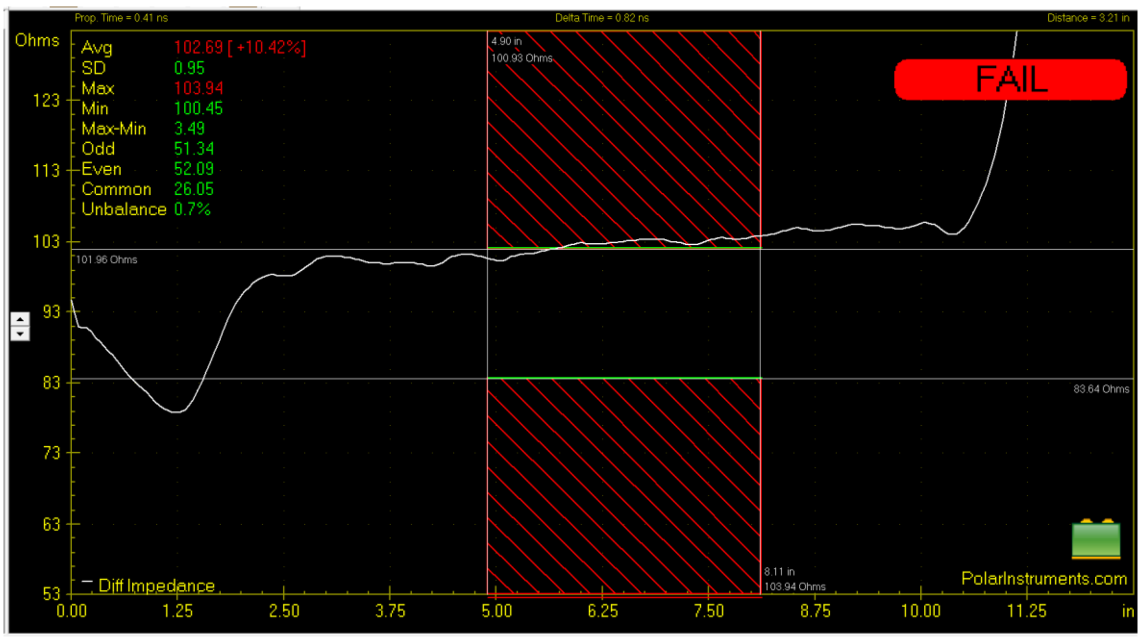


Figure 1 Example of a TDR impedance test failure affecting PCB fabrication yield. Controlled impedance test set (CITS) data courtesy of Ciena Corporation [16].

The propagation of transverse electromagnetic (TEM) waves along transmission lines requires the use of Dk measured by out-of-plane test methods to accurately model and simulate Z_0. If Dk from in-plane test methods are used, the impedance prediction will be lower. This is because Dk measured using in-plane test methods is higher than when measured with out-of-plane test methods. As a result, if in-plane Dk were used instead of out-of-plane Dk to calculate and center Z_0 within a +/- tolerance distribution for test specifications, there would be a net decrease in positive tolerance margin, as shown in Figure 2.

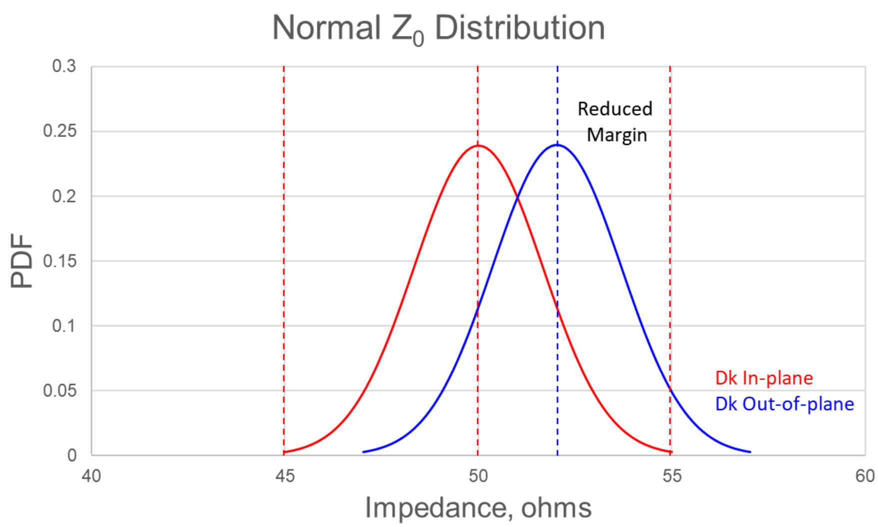


Figure 2 Normal impedance distribution comparison showing reduced margin when incorrect value of Dk is used in the model to define the impedance tolerance. Red curve is impedance distribution using published in-plane Dk values while the blue curve is impedance distribution using the actual Dk values when measured out-of-plane.

Dissipation factor (Df) or loss-tangent (tanδ) is the ratio of the imaginary part (ε”) to the real part (ε’) of the complex permittivity (ε). Real permittivity is also known as Dk and refers to the part that is responsible for the storage of electric energy, while ε” refers to the part that causes the energy to be lost as heat. When designing high-speed PCBs, Df is an essential factor to consider. It assists in choosing the ideal dielectric material to reduce total insertion loss (IL).

Copper clad laminate (CCL) panels used for PCB construction are a mixture of fiberglass and resin, cladded on one or both sides with copper. CCL suppliers use various test methods to determine Dk and Df which are eventually published in their construction tables. PCB fabricators and signal integrity (SI) engineers then rely on these values used to design PCB stackups and perform SI analysis.

There are over a dozen test methods specified in Institute of Printed Circuits (IPC) specifications. These test methods were designed as a means of testing for quality control and do not guarantee the numbers are accurate for design applications. Usually, CCL suppliers include a footnote disclaimer with similar wording to that effect in their construction tables.

All glass weave reinforced laminates are anisotropic, meaning dielectric properties will be different along different axis. Several papers have studied laminate anisotropy.

Dankov et al [1] has shown the effective dielectric properties in the x-y axis can be up to 25% higher than the z axis for some laminate materials tested.

B. Zhao et al [2] studied the impacts of anisotropic permittivity on PCB traces and via modeling. They found that anisotropy had a measurable impact on loss, characteristic impedance, resonance frequency, and resulted in a dramatic increase of far-end crosstalk (FEXT) for a stripline due to anisotropy.

M. Koledintseva et al [3], compared the dielectric properties obtained using the traveling-wave technique based on the S-parameter measurements vs the SPDR technique and explained the discrepancy between the results from the point of view of anisotropy and composite mixing theory.

Unfortunately, the publication of Dk by CCL suppliers does not include anisotropic properties required for precise impedance prediction and signal integrity modeling. H. Zhou et al [4] used Ansys HFSS[9] to model a PCB material sample and extracted out-of-plane Dk from in-plane Dk specs using a cylinder resonator virtual test bench built in HFSS. However, this technique is computationally impractical for many designers due to long modeling time and expensive computing processor and memory overhead.

This paper introduces a new process utilizing heuristics to determine laminate anisotropy based on the Dk/Df construction tables provided by CCL suppliers. Heuristics are mental shortcuts, rules of thumb or problem-solving techniques that help people make decisions and solve problems quickly and efficiently. Heuristics do not guarantee absolute accuracy or completeness. Instead, they are based on past experiences and allows one to use readily obtainable information to come up with solutions when more exact information is not easily available.

PCB Laminate Anisotropy

Figure 3A shows a block of fiberglass reinforced laminate, with the glass weave and copper plates running parallel to the x-y axis. When a DC potential is applied, a uniform electric field is out-of-plane in the z-direction, thereby creating a capacitor. Since the effective Dk is the ratio of actual structure's capacitance, to the capacitance when the structure is replaced by air, we denote this ratio as Dkz.

Figure 3B and C show that when the conducting plates are placed perpendicular to the direction of the glass weave, the E-fields align with the x or y axis and are in-plane. Even though there might be slight variations in the effective Dk in these directions, heuristically we assume they are equal and refer to them as Dkxy.

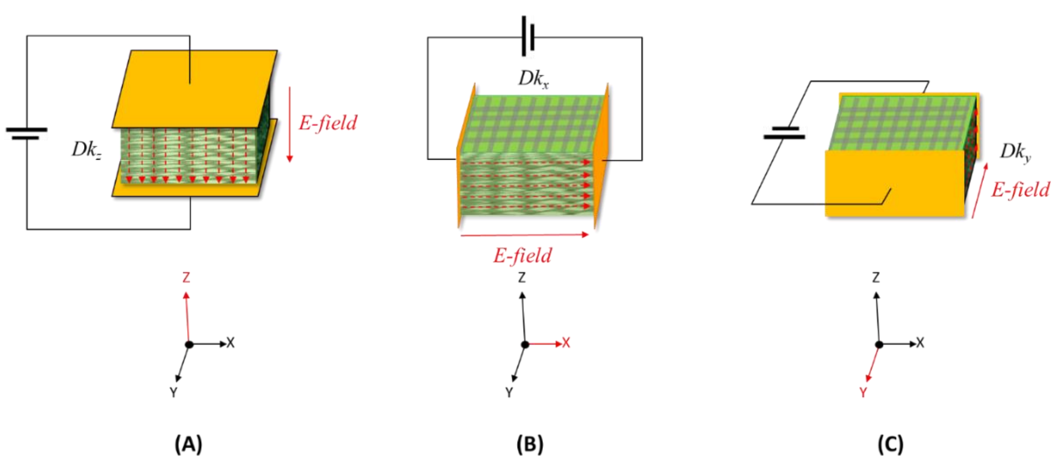


Figure 3 E-field orientation relative to the glass weave reinforcement in PCB laminates when a DC electrical potential is applied. Fig. (A) E-fields are out-of-plane with respect to glass weave, while Fig. (B) & (C) are in-plane with glass weave.

Depending on the test method used, Dk measured may be different due to the test fixture's generated E-field orientation relative to the glass weave. Figure 4 summarizes E-field orientation when compared against popular test methods used by many CCL suppliers. Dk obtained by these test methods are denoted as in-plane (Dkxy) or out-of-plane (Dkz).

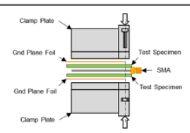
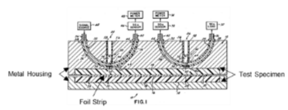
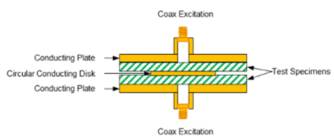
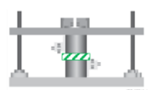
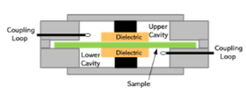
<table>
<tr><th></th><th>Test Method</th><th>E-field
In-plane (Dkxy)</th><th>E-field
Out-of-plane (Dkz)</th></tr>
<tr><td>
</td><td>Clamped Stripline Resonator
Ref: IPC-TM-650 2.5.5.5 RevC</td><td></td><td>✓</td></tr>
<tr><td>
</td><td>Bereskin Stripline Resonator
Ref: Patent US5187,443, Feb. 16, 1993</td><td></td><td>✓</td></tr>
<tr><td>
</td><td>Balanced-type Circular Disk Resonator
Ref: IEC 63185:2020</td><td></td><td>✓</td></tr>
<tr><td></td><td>Split-cylinder Resonator
Ref: IPC-TM-650 2.5.5.13</td><td>✓</td><td></td></tr>
<tr><td>
</td><td>Split-post Dielectric Resonator
(a.k.a. Split-post Cavity)</td><td>✓</td><td></td></tr>
</table>

Figure 4 Comparative table of E-field orientation and resulting Dkxy or Dkz across popular test methods employed by CCL suppliers.

Dkxy is typically higher compared to Dkz, depending on the glass resin mixtures of the sample tested. Refer to Figure 5A. The rules of solid mixtures [5] can be used to estimate anisotropy of the glass and resin mixture. If the E-field is polarized in the z-direction, using a Dk of 6.8 for E-glass (Dkg), a Dk of 2.5 for resin (Dkr), volume fraction of resin (v_{resin} = 0.7), and volume fraction of E-glass (v_{glass} = 0.3), then the effective capacitance of each block is in series and Dkz is determined to be 3.09, using the parallel mixing rule defined by:

Equation 1

$$Dkz = \left[v_{\text{resin}} / Dkr + v_{glass} / Dkg\right]^{-1} = \left[0.7/2.5 + 0.3/6.8\right]^{-1} = 3.09$$

When the conductor plates are moved, as shown in Figure 5B, and the mixture is polarized such that the E-field is parallel to the x-y axis, then the effective capacitance is in parallel and Dkxy is determined to be 3.79, using the series mixing rule defined by:

Equation 2

$$Dkxy = v_{\text{resin}} \cdot Dkr + v_{glass} \cdot Dkg = 0.7 \cdot 2.5 + 0.3 \cdot 6.8 = 3.79$$

Using Equation 3, Anisotropy (**Λ**) of the mixture reveals Dkxy is 23% higher than Dkz.

Equation 3

$$\Lambda = \left(\frac{Dk_{xy}}{Dk_z} - 1 \right) 100 = \left(\frac{3.79}{3.09} - 1 \right) 100 = 23\%$$

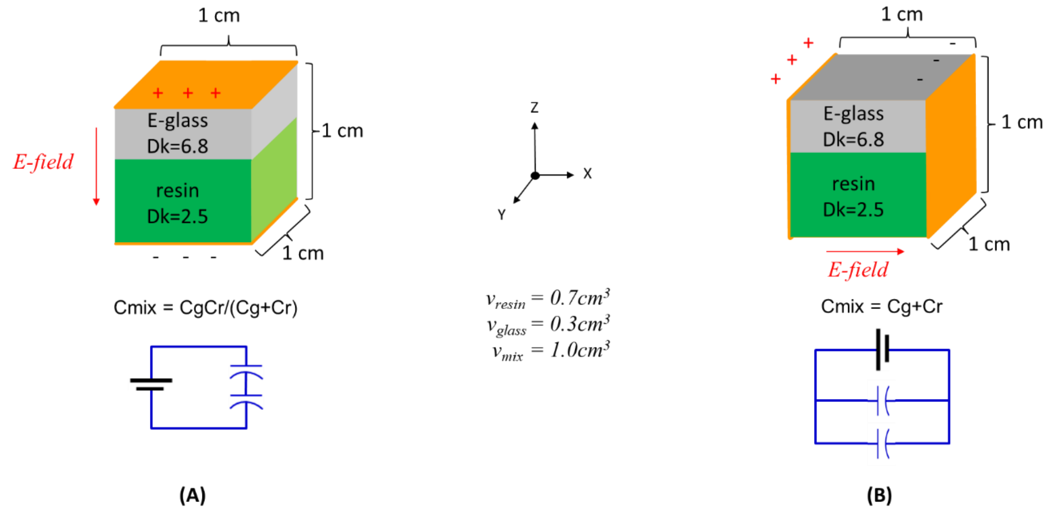


Figure 5 Rule of solid mixtures. Fig. (A) Parallel mixing rule is used when E-fields polarized in Z-direction. Fig. (B) Series mixing rule is used when E-fields are polarized in X-Y direction.

When applying both series and parallel mixing rules. the relationship of Dk vs resin content is shown in Figure 6. In Figure 6 (A), a Dkg of 6.8 for E-glass and Dkr of 2.5 for resin has a maximum anisotropy of 27% at 50% resin content by volume. Conversely, when substituting L-glass with a Dkg of 4.8 and the same Dkr of 2.5, Figure 6 (B) reveals anisotropy decreases to 11% at the 50% resin mark. Essentially, this implies that the closer Dkg aligns with Dkr, material anisotropy is reduced.

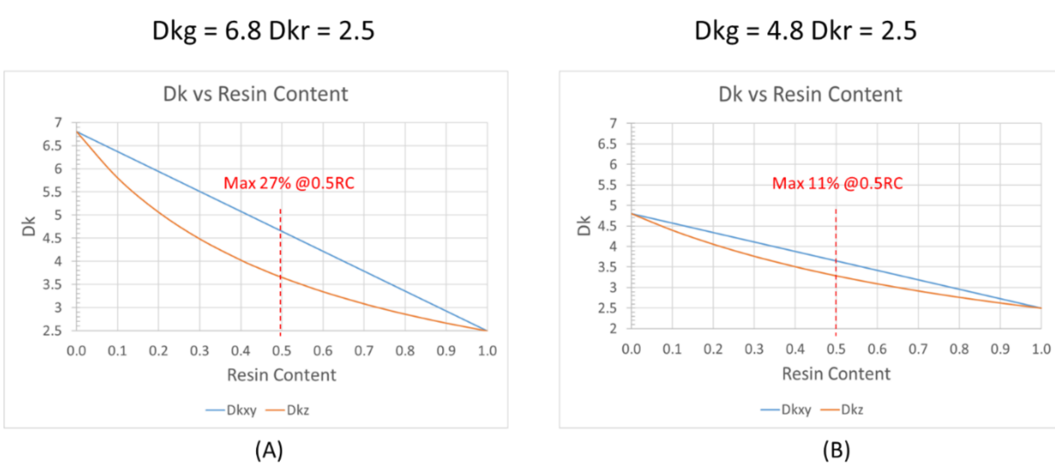


Figure 6 Dk vs resin content using series and parallel mixing rules showing the closer Dkg aligns with Dkr, material anisotropy is reduced.

Determining Df anisotropy for a mixture of two different dielectrics using the rule of mixtures is not as straightforward. This is because the rule of mixtures primarily applies to ideal mixtures and may not directly translate to the calculation of Df for a mixture of two different dielectrics.

In practice, determining the anisotropy of Df for a mixture requires experimental measurements, or complex modeling that takes into account the specific properties and interactions of the two dielectrics.

Anisotropy Implications for Transmission Line Impedance Modeling and Validation

PCB transmission lines run parallel to the glass weave. For single-ended transmission lines, E-fields are mainly out-of-plane and thus Dkz is needed for accurate modeling of impedance. Using Dkxy instead, means the impedance predicted from the field solver will be lower than what would actually be measured if the board was made exactly as specified in the stackup.

The case for differential pairs and grounded coplanar waveguide geometries, a portion of E-fields are both in-plane and out-of-plane. For striplines on the same layer, the space between differential pair or grounded coplanar waveguide geometries is mostly filled with resin in the x-y direction. The resin is assumed to be isotropic and its Dk value is used in the model. The value of Dkz is then used in the field solver for dielectric above and below the signal layer.

In microstrip, the x-y space between a differential pair or coplanar waveguide geometry is filled with soldermask or air. An effective Dk is calculated using the Dk of air above the trace, the Dk of the fill between copper traces (air or soldermask), and the Dkz of the substrate. Thus it is important that the field solver has the capability to model these different Dk x-y-z regions of the geometry.

The implication of using Dkxy instead of Dkz is that the true nominal impedance is not centered within the +/- tolerance window. Instead, it will be skewed in the positive direction which effectively reduces the + tolerance and risks scrapping the board due to manufacturing process variation. This is explained further with reference to Figure **7**.

Polar SI9000 2D field solver [18] is used for comparison in this example to calculate characteristic impedance. Using Dkxy, the lossless characteristic impedance calculated is 95 ohms. Modeling an 8-inch (20.32 cm) long lossy transmission line in Polar Si9000, then simulating with Keysight Pathwave ADS [17], the differential TDR plot in green shows the impedance starts at ~95 ohms and has a slow monotonic rise over the length of the trace. The steepness of the slope is mainly due to DC resistive loss of the trace.

But what is the characteristic impedance of the measurement?

IPC-TM-650 2.5.5.7 test method manual, dated 03/2004 [19], specifies the measurement zone between 30-70% of the TDR measurement. Most PCB fabricators will measure a min/max impedance over this range. Any excursion into the +/- tolerance mask would be flagged as a failure, and the board may be scrapped. But this is a lossy measurement and not the lossless characteristic impedance modeled with a 2D field solver, which would be near the beginning of the TDR plot.

When the last issue of the IPC-650 spec was revised, back in 2004, the slope tended to be flatter because thicker copper and wider traces of the day, resulted in less resistive loss. Also a higher dielectric loss material used, compensated for the resistive loss somewhat and flattened the slope, so measurements between 30-70% was approximately the same as characteristic impedance. However, with today's low loss dielectrics and thinner, narrower line widths, we see a steeper slope.

Referring back to Figure **7**, if the nominal impedance spec of 95 ohms +/-10 % tolerance were based on Dkxy, then there is already a positive reduction in tolerance in the impedance mask, depending on the steepness of the slope. Factoring anisotropy and using proper Dkz, the characteristic impedance increased to 97.5 ohms and positive margin is eroded even further. In this case the impedance test would fail, based on IPC-TM650 spec, as shown by the red TDR plot.

In order to correct this, A wider line-width and/or spacing adjustment is needed to recenter the impedance back to 95 ohms based on Dkz.

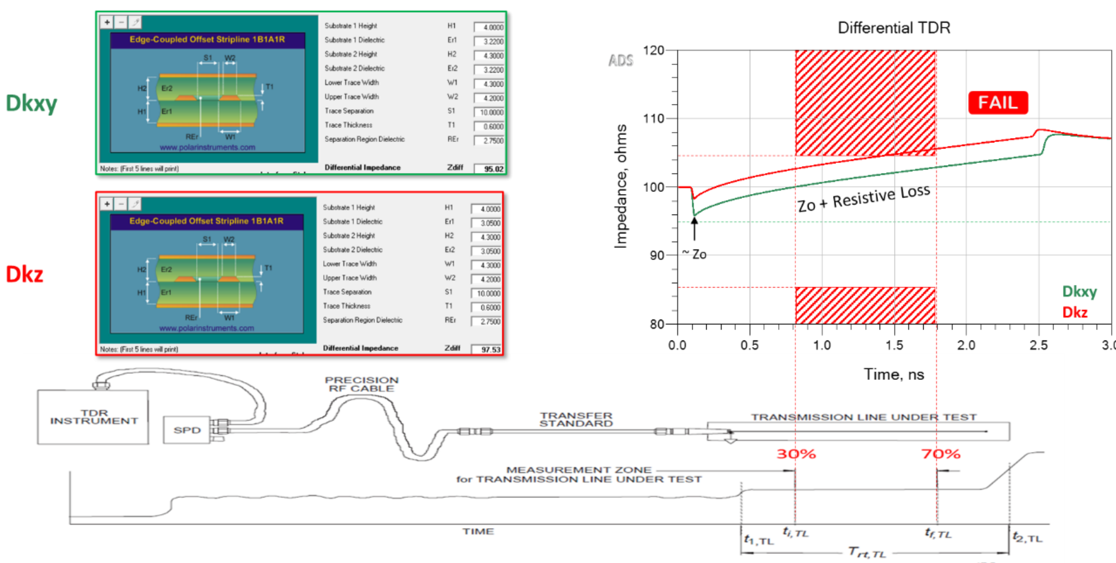


Figure 7 **Implications on characteristic impedance modeling when wrong Dk value is used. The green simulated differential TDR plot is a lossy 8 inch (20.32 cm) transmission line using Dkxy. The failed red differential TDR plot is the same length geometry, but simulated with Dkz. Modeled with Polar SI9000 [18] and simulated with Keysight Pathwave ADS [17].**

Anisotropy Implications for Antenna Modeling

Just as with transmission line modeling, the accuracy of planar antennas on PCBs depends on the correct use of out-of-plane Dkz values. Using the wrong value will result in an inaccurate antenna resonant frequency.

Figure 8A presents an example of a microstrip quarter wave transformer-fed rectangular patch antenna, designed with Sonnet-Lite software [25]. The physical dimensions of the patch antenna were determined using a Matlab [26] script found in [24].

For Case 1, an in-plane Dkxy value of 3.79 was intentionally used to design for a frequency of 2.4 GHz. However, as indicated by the red S11 plot in Figure 8B, the simulated resonance was observed to be 2.35 GHz. It's important to note that the antenna was not precisely optimized for a 2.4 GHz frequency for the purpose of Dk comparison in the model.

In Case 2, while keeping all other antenna dimensions constant, the Dkxy value was substituted with a Dkz value of 3.09. This modification resulted in an increase in the resonant frequency to 2.6 GHz, as illustrated by the blue plot in Figure 8B.

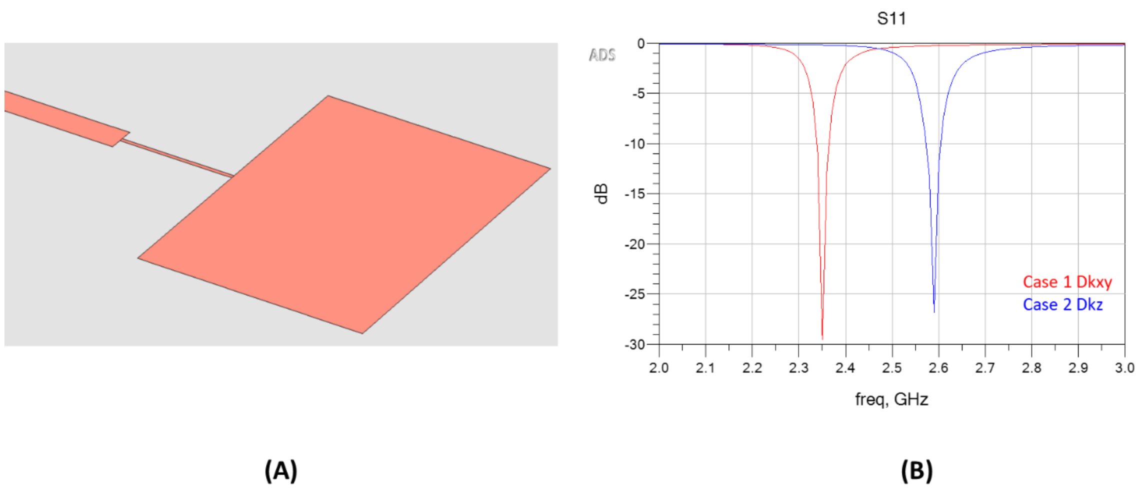


Figure 8 Microstrip quarter-wave transformer-fed rectangular patch antenna simulation. Fig. (A) Sonnet-Lite [25] physical model illustration. Fig. (B) Simulated results of the antenna design when using a Dkxy value of 3.79 (red) versus a Dkz value of 3.09 (blue).

This comparative case study of antenna design highlights the significant impact of using an in-plane Dkxy value over an out-of-plane Dkz for a material with considerable anisotropy.

Anisotropy Implications for Via Modeling

In the case of modeling vias, it gets more complicated. In Figure 9, given a cross-section view of a typical via and stub, we observe the E-fields as the signal propagates, from left to right, along the microstrip transmission line on the top layer, through the via to an inner stripline layer 3 and continuing through the stub.

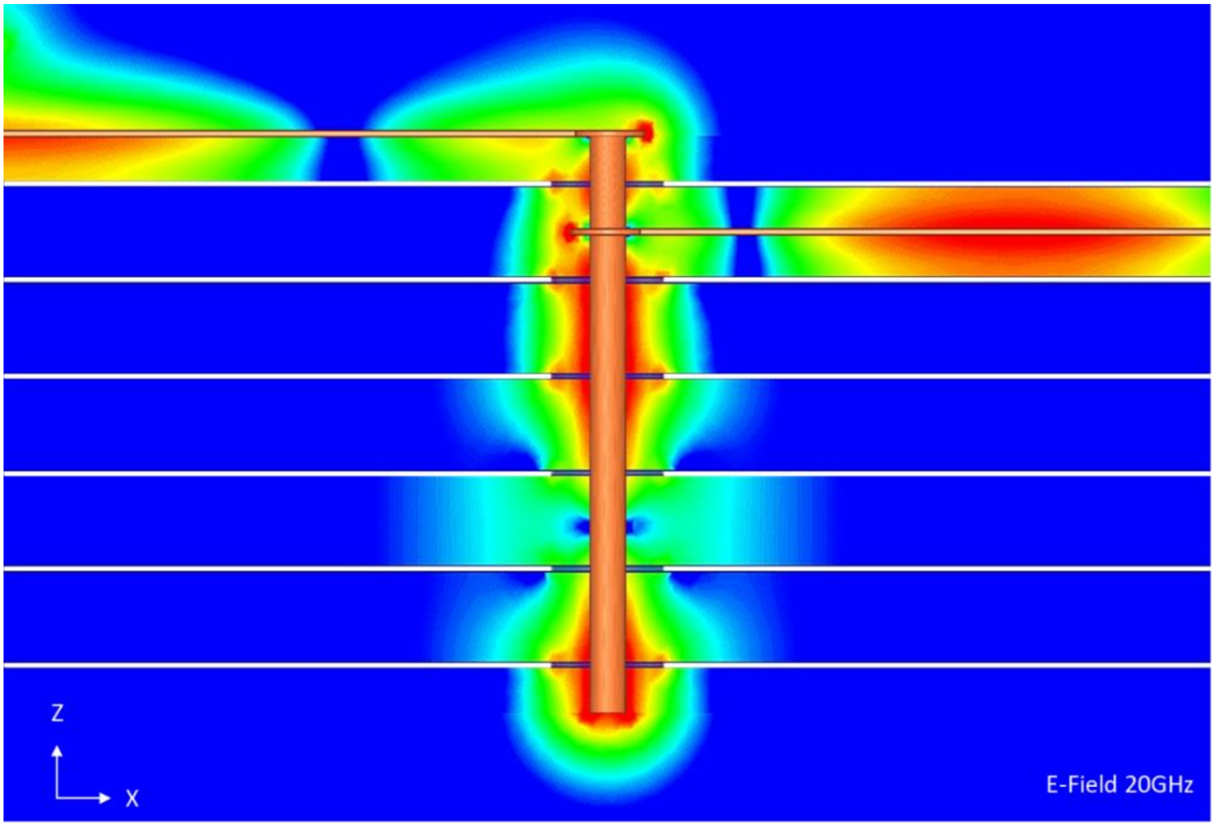


Figure 9 Cross-section view of E-fields as a 20GHz signal propagates from microstrip top layer through a via with stub to a stripline layer 3. HFSS simulation courtesy of Juliano Mologni, Ansys [9].

Using the same value for Dk when modeling transmission lines and vias leads to inaccurate results for one or the other. If the CCL supplier's published numbers are out-of-plane, Dkz, then the impedance for transmission lines will be correct, while the via impedance will end up being lower than modeled. On the other hand, if the published numbers are in-plane, Dkxy, then the via impedance will be correct and the transmission line impedance will end up being higher.

Furthermore, using the wrong Dk for modeling via stubs will result in poor simulation correlation to measurements [6] and potentially loss of channel margin due to maximum stub length guidelines based on simulation analysis [7]. This can be problematic for 112/224 GB/s interconnect by reducing already tight margins.

Figure 10 shows an example of this. A 26mil (0.66 mm) pitch differential via with 10 mil (0.254 mm) stub model was created in Keysight Pathwave ADS [17] via designer (Figure 10A). A Dkz of 3.09 and Dkxy of 3.79 from Equation 1 and Equation 2 were used in the model for comparisons. After finite element method (FEM) simulation, S-parameters were saved in touchstone format and simulated in the circuit schematic shown in Figure 10B.

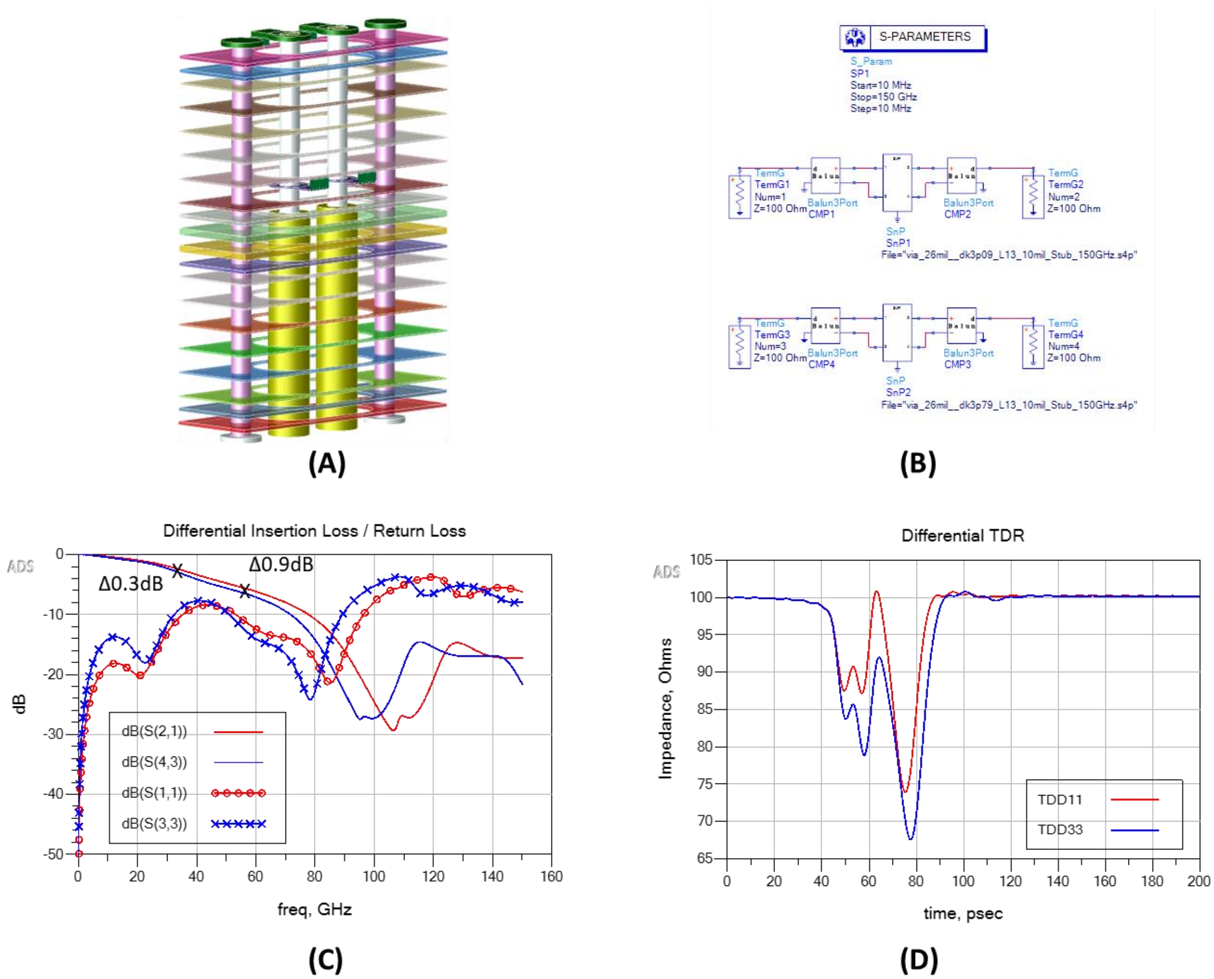


Figure 10 Differential via model and simulation results. Fig. (C) Differential IL/RL with 10 mil (0.254 mm) stub using Dkz of 3.09 (red plots) and Dkxy of 3.79 (blue plots) for laminate. Fig. (D) Differential TDR impedance. Modeled and simulated with Keysight Pathwave ADS [17] via designer

Figure 10C compares differential insertion loss (IL) and return loss (RL) and Figure 10D compares differential time TDR impedance. The red plots are using out-of-plane Dkz and the blue plots are using in-plane Dkxy. As can be seen, when out-of-plane Dkz value is used in the model it under estimates IL and impedance by approximately 8 ohms. For 112Gb/s the difference in loss at 28GHz Nyquist frequency is ~ 0.3 dB. At 56GHz Nyquist for 224Gb/s, the delta is ~ 0.9 dB caused by the difference in stub resonant nulls at 106 GHz and 95GHz.

But this doesn’t tell the whole story. While it is widely known that short, highly reflective channels can negatively impact channel performance, the issue has been exacerbated by the introduction of 4-level pulse amplitude modulated (PAM4) signaling, which reduces the signal-noise ratio by 9.5dB. As bit rates continue to increase exponentially, traditional IL/RL masks and eye diagrams are no longer sufficient for assessing channel quality.

Channel operating margin (COM) [20] is a system-level metric approach adopted by the IEEE 802.3ck standard to validate the performance of a serial link. It makes use of an open source, statistical simulation using agreed upon transmitter and receiver minimum capability. As part of COM, there is an effective return loss (ERL) figure of merit that compares the amount of signal to the amount of noise caused by reflections when referenced to a set symbol error rate (SER) also known as detector error ratio (DER).

Thus, COM can be used to see how Dk anisotropy affects key metrics. A short chip to chip (C2C) channel topology, was simulated using Keysight Pathwave ADS[17]. This was done by linking two 4-port S-parameter via models, from Figure 10 with a 4-port S-parameter file that represents a 2-inch (5.08 cm), 100 ohm differential transmission line, as shown in Figure 11. The differential transmission line was modeled and simulated with Polar SI9000[18] using Dkz value of 3.09.

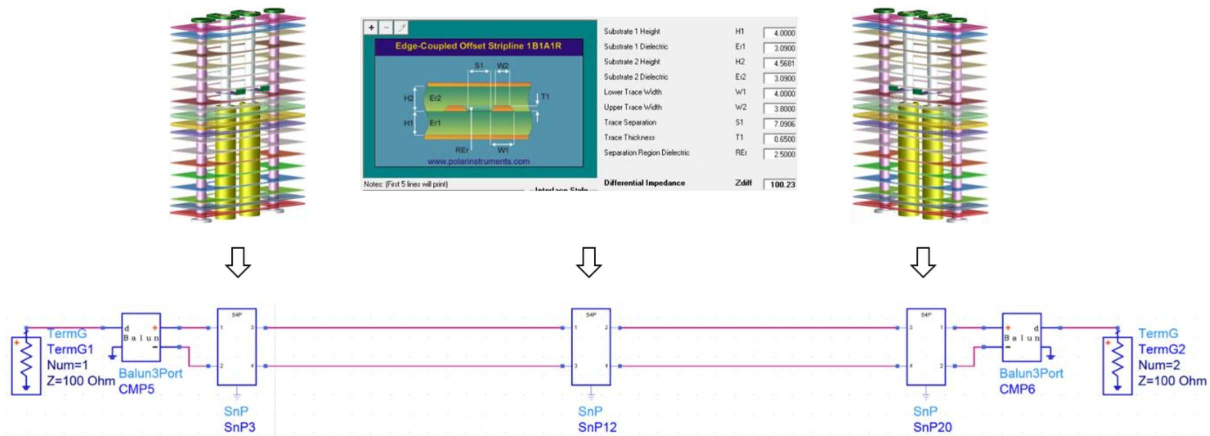


Figure 11 A 2-inch C2C topology channel used for TDR and COM analysis. The differential vias were modeled and simulated separately using Keysight Pathwave ADS via designer, with a Dkz of 3.09 and Dkxy of 3.79. Additionally, a 2-inch edge-coupled transmission line was designed for 100 ohms using Polar Si9000, also with a Dkz of 3.09.

Two simulations were performed. The first simulation used the S-parameters of the differential vias and transmission line, which were modeled using a Dkz of 3.09. The second simulation used the S-parameters of the vias, modeled with a Dkxy of 3.79 and transmission line modeled with Dkz of 3.09. The differential TDR plots resulting from these simulations are displayed in Figure 12A and Figure 12B, respectively.

Following this, COM was executed in Keysight Pathwave ADS on both scenarios using a short package model specified in the configuration file. As depicted in Figure 12C, all COM metrics passed when Dkz was applied to both the vias and transmission line models. However, when the via models used Dkxy instead, COM passed with reduced margin, but ERL failed, as shown in Figure 12D.

This example illustrates the importance of using the correct Dk value for via modeling and being aware of the test method used by CCL suppliers when they publish their values in data sheets and construction tables.

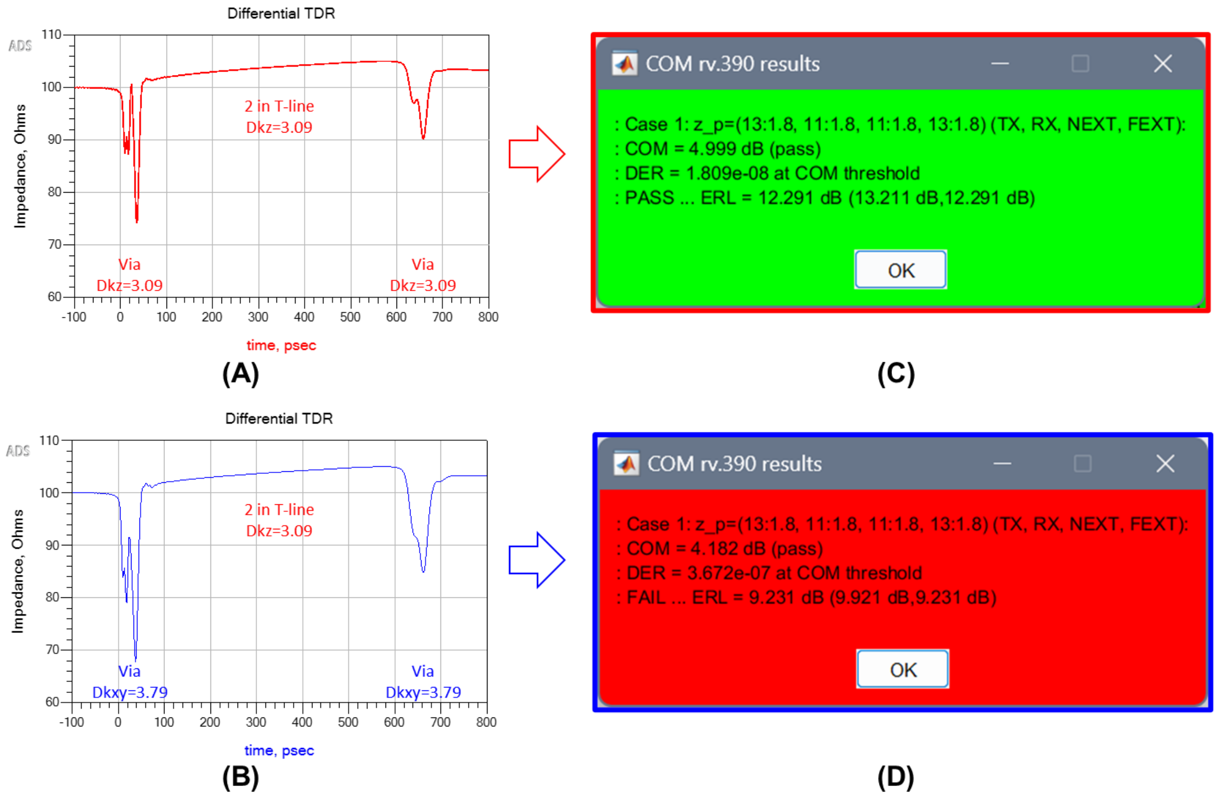


Figure 12 Simulated differential TDR and COM results. Fig. (A) & (C) Dkz was used for vias and transmission lines. Fig. (B) & (D) Dkxy used for via models and Dkz used for transmission lines. When Dkz was used for all models COM & ERL passed with DER of 9.112E-07 threshold, but when Dkxy was used for the via models, COM & ERL failed with DER of 1.11E-6 threshold.

Of course this was an extreme example with high Dk anisotropy. Choosing a dielectric with low Dk glass and higher resin content would improve the results, but if you have a tight loss and impedance budget, using the wrong numbers could still push you over the edge in compliance tests.

Thus, it is important to determine material anisotropy for more accurate high-speed channel modeling to minimize reflective loss, and to ensure electronic design automation (EDA) software includes anisotropic compensation algorithms.

CCL Dk/Df Construction Tables

Fortunately, heuristics can be used to determine laminate anisotropy from CCL suppliers' Dk/Df construction tables. Figure 13 shows an example of Tachyon 100G construction table from Isola Group [8]. The left-most column lists the glass styles for respective resin content (RC) and prepreg thickness. Glass styles have a unique number (e.g., 1035) which describes the fabric count of warp and fill threads per inch of the final woven glass cloth.

Glass Style	Resin Content %	Offering	Thickness (inch)	Thickness (mm)	Dielectric Constant (Dkz)						Dissipation Factor (Dfz)					
					1 GHz	2 Ghz	5 Ghz	10 GHz	15 Ghz	20 Ghz	1 GHz	2 Ghz	5 Ghz	10 GHz	15 Ghz	20 Ghz
1035	69.00%	Standard	0.002	0.051	3.06	3.06	3.06	3.06	3.06	3.06	0.0017	0.0017	0.0017	0.0017	0.0017	0.0017
1035	75.00%	Standard	0.0026	0.066	2.97	2.97	2.97	2.97	2.97	2.97	0.0014	0.0014	0.0014	0.0014	0.0014	0.0014
1078	65.00%	Standard	0.0029	0.074	3.14	3.14	3.14	3.14	3.14	3.14	0.0019	0.0019	0.0019	0.0019	0.0019	0.0019
1078	67.50%	Standard	0.0031	0.079	3.09	3.09	3.09	3.09	3.09	3.09	0.0018	0.0018	0.0018	0.0018	0.0018	0.0018
1078	70.50%	Standard	0.0035	0.089	3.04	3.04	3.04	3.04	3.04	3.04	0.0016	0.0016	0.0016	0.0016	0.0016	0.0016
1078	72.00%	Standard	0.0037	0.094	3.02	3.02	3.02	3.02	3.02	3.01	0.0015	0.0016	0.0016	0.0016	0.0016	0.0016
1078	75.00%	Standard	0.0042	0.107	2.97	2.97	2.97	2.97	2.97	2.97	0.0014	0.0014	0.0014	0.0014	0.0014	0.0014
1078	78.00%	Alternate	0.0046	0.117	2.92	2.92	2.92	2.92	2.92	2.92	0.0013	0.0013	0.0014	0.0014	0.0014	0.0014
2116	62.00%	Standard	0.0058	0.147	3.19	3.19	3.19	3.19	3.19	3.19	0.0021	0.0021	0.0021	0.0021	0.0021	0.0021
2116	65.00%	Alternate	0.0064	0.163	3.14	3.14	3.14	3.14	3.14	3.14	0.0019	0.0019	0.0019	0.0019	0.0019	0.0019
1067	70.00%	Standard	0.0022	0.056	3.05	3.05	3.05	3.05	3.05	3.05	0.0017	0.0017	0.0017	0.0017	0.0017	0.0017
1067	71.50%	Standard	0.0024	0.061	3.02	3.02	3.02	3.02	3.02	3.02	0.0016	0.0016	0.0016	0.0016	0.0016	0.0016
1067	74.00%	Standard	0.0026	0.066	2.98	2.98	2.98	2.98	2.98	2.98	0.0014	0.0014	0.0015	0.0015	0.0015	0.0015
1067	76.50%	Standard	0.0029	0.074	2.94	2.94	2.94	2.94	2.94	2.94	0.0013	0.0013	0.0013	0.0013	0.0013	0.0013
106	76.00%	Standard	0.0023	0.058	2.95	2.95	2.95	2.95	2.95	2.95	0.0013	0.0013	0.0014	0.0014	0.0014	0.0014
1080	72.00%	Standard	0.0038	0.097	3.02	3.02	3.02	3.02	3.02	3.01	0.0015	0.0016	0.0016	0.0016	0.0016	0.0016
1080	75.00%	Standard	0.0043	0.109	2.97	2.97	2.97	2.97	2.97	2.97	0.0014	0.0014	0.0014	0.0014	0.0014	0.0014
1080	78.00%	Alternate	0.0046	0.117	2.92	2.92	2.92	2.92	2.92	2.92	0.0013	0.0013	0.0014	0.0014	0.0014	0.0014
3313	63.50%	Standard	0.0046	0.117	3.16	3.16	3.16	3.16	3.16	3.16	0.002	0.002	0.002	0.002	0.002	0.002
3313	66.50%	Standard	0.0051	0.129	3.11	3.11	3.11	3.11	3.11	3.11	0.0018	0.0018	0.0018	0.0018	0.0018	0.0018

Figure 13 An example of a CCL supplier's prepreg construction table sorted by glass style. Values measured by TM-650-2.5.5.5C. Source: Tachyon 100G Isola Group [8].

RC is the per-cent resin content by weight. When combined with glass cloth style, the combination determines the final thickness of prepreg sheet. For example, 1035 glass with RC of 69% has a total thickness of 2 mils (0.051 mm), while 1035 with RC 75% has a total thickness of 2.6 mils (0.066 mm).

Dk/Df values measured from 1-20 GHz were from IPC-TM-650-2.5.5.5C clamped stripline resonator test method. They are out-of-plane measurements.

Since the RC published in construction tables are based on weight, a variation of Equation 1 or Equation 2 cannot be used to determine anisotropic properties without first converting the RC from weight to volume. To do that the density (D) and other properties of the glass or resin is needed.

Unfortunately, the properties of resin are a closely guarded secret by CCL suppliers and are difficult to obtain. But the properties of glass are more publicly available, enough to heuristically estimate the resin's Dk and volume from CCL suppliers' construction tables.

Glass Properties

Popular glass fiber types used for PCB laminate construction are E-glass and L-glass. Table 1 from AGY [10] compares the properties of both types. The E in E-glass represents its early use for electrical applications. It was the first glass composition developed for continuous filament creation, making it the most popular glass used within the PCB industry. As shown in Table 1, E-glass has a density of 2.54 g/ cm^3 and a Dk of 6.8 at 10GHz.

Low Dk glass fiber, specifically NE-glass or L-Glass, is increasingly used in high-performance, low-loss laminates. NE-Glass is proprietary to Nittobo Group [11], whereas L-glass is a more generic name for low Dk glass with similar properties

Table 1 Properties of L-glass and E-Glass. Source: AGY [10]

Glass Fiber Properties	Units	L-Glass	E-Glass
Dielectric Constant (Dk)	@1 GHz	4.8	7.0
	@10 GHz	4.8	6.8
Dissipation Factor (Df)	@1 GHz	< 0.001	0.005
	@10 GHz	0.003	0.006
Density	g/cm3	2.3	2.54
Softening Point	°C	850	846
Coefficient of Thermal Expansion	ppm/°C	3.9	5.4
Tensile Load to Failure (D450 fiber)	N	8.5	8.9
Tensile Modulus	Gpa	62	75

Table 1 shows AGY L-Glass fiber has a Dk of 4.8 at 10GHz and a density of 2.30 g/cm^3. Glass with a lower Dk provides a closer match with resin, resulting in an overall lower Dk of the glass/resin mixture. For identical impedance specifications, a lower overall Dk allows for the use of thinner dielectric spacing in the PCB stackup. Additionally, minimizing the difference in Dk between glass and resin can help mitigate intra-pair skew caused by fiber-weave effect (FWE).

Determining Laminate Dk Anisotropy

The first step to determine dielectric anisotropy is to obtain the CCL supplier's Dk/Df construction tables and validate the test method used to arrive at the published values. This step is vital to establish whether the values are in-plane or out-of-plane measurements.

Once that is established, we need to validate from the CCL supplier the type of glass. It is probably safe to assume that Dk < 3.5 and Df numbers < 0.005 use L-glass but it is best to confirm with laminate supplier.

For the rest of the discussion, we will use Tachyon 100G as an example.

The trickiest part is establishing the correct glass/resin mixture by volume of each constituent. Since Dk/Df construction tables only specify RC by weight, there is no easy way to convert percent weight to percent volume. But there is a way to establish the volume mixtures from glass properties and total thickness of respective prepreg sheets.

IPC-4412B standard [12] provides detailed descriptions of glass style properties used for laminate construction tables. Table 2 includes a subset of those styles used in Tachyon 100G. Included in the table is the warp and fill yarns per unit length, the thickness of each glass cloth style and the weight per unit area.

However, the properties listed only apply to E-glass, while Tachyon 100G utilizes L-glass which differs slightly in weight. As shown in Table 1, L-glass density is approximately 90% of E-glass density, so heuristically we assume the weight of L-glass styles listed in Table 2 is 90% of E-glass.

Table 2 Subset of finished fabric E-glass styles in SI Units. Source: IPC-4412A -Amendment 1 Feb-2008 [12]

IPC-4412A - Amendment 1 Feb-2008 Table II-1 Finished Fabric Glass Styles in SI Units									
Style	Warp per cm		Fill per cm	Yarn (SI)	Thickness mm	Nominal weight g/m²	Min weight g/m²	Max weight g/m²
1035	26	x	26.8	5 5.5 1x0 5 5.5 1x0	0.028	30	27.2	32.6
106	22	x	22	5 5.5 1x0 5 5.5 1x0	0.033	24.4	23.4	25.4
1067	27.6	x	27.6	5 5.5 1x0 5 5.5 1x0	0.035	30.7	29.5	31.9
1078	21.3	x	21.3	5 11 1x0 5 11 1x0	0.043	47.8	46.8	49.2
1080	23.6	x	18.5	5 11 1x0 5 11 1x0	0.053	46.8	45.1	48.5
3313	23.6	x	24.4	6 16.5 1x0 6 16.5 1x0	0.084	81.4	79	83.7
2116	23.6	x	22.8	7 22 1x0 7 22 1x0	0.094	103.8	100.7	106.8

The thickness and weight of woven glass style fabric is unique due to its weave pattern. However, the fabric's thickness cannot be directly used to determine the glass volume within a particular thickness of a prepreg sheet, because the weave is a combination of glass fiber and air, as illustrated in Figure 14A. When the woven cloth is impregnated with resin, the air volume is replaced, consequently increasing the resin volume in proportion.

To apply the rule of solid mixtures properly, we first need to determine the volume of the solid glass fibers alone. This can be done by imagining the glass weave melted into a solid sheet with a reduced thickness proportional to its unit area, as illustrated in Figure 14B.

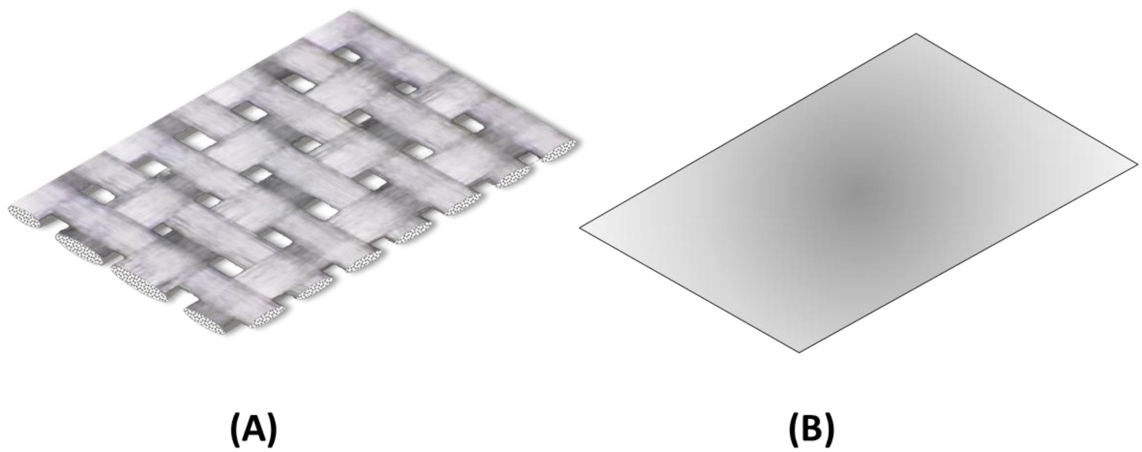


Figure 14 Volume of glass weave (A) vs equivalent volume of solid glass per unit area (B) if all the glass were melted into a solid sheet with a reduced thickness proportional to its unit area.

Thus, given the glass style and prepreg thickness (t) from construction tables, along with the density of glass (D) per unit volume and the weight of glass cloth (Wg) per unit area (A), we can determine the ratio of glass content by volume (GCv) to the total volume of the prepreg sheet (V_{total}) as:

Equation 4

$$GCv = \frac{Wg \times A}{(D \times V_{total})} = \frac{Wg \times A}{(D \times A \times t)} = \frac{Wg}{(D \times t)}$$

From IPC-4412A, we can get Wg and from construction tables we can get prepreg thickness (t) to determine GCv.

Convert Dkz to Dkxy:

If Dkz is measured out-of-plane, we can then estimate dielectric constant of resin (Dkr) by rearranging the parallel mixing rule as:

Equation 5

$$Dkr = \frac{Dkz(1-GC_v)}{\left(1-\left(\frac{DkzGC_v}{Dkg}\right)\right)}$$

Then we simply use series mixing rule equation in terms of GCv to determine Dkxy:

Equation 6

$$Dkxy = (1-GC_v)Dkr + (GC_v)Dkg$$

Convert Dkxy to Dkz:

Using the same heuristic, if Dkxy values are measured in-plane, then we rearrange the series mixing rule to estimate dielectric constant of resin (Dkr) as:

Equation 7

$$Dkr = \frac{Dkxy - GC_v(Dkg)}{(1-GC_v)}$$

And then use parallel mixing rule in terms of GCv to determine Dkz as:

Equation 8

$$Dkz = \left[\frac{(1-GC_v)}{Dkr} + \frac{GC_v}{Dkg}\right]^{-1}$$

Dk anisotropy can be estimated as:

Equation 9

$$\Lambda_{20GHz} = \left(\frac{Dkxy}{Dkz} - 1\right)100$$

It should be noted that once we determine Dk of glass and resin, heuristically we assume they are isotropic and the same respective values, once calculated, are used to determine the in-plane or out-of-plane anisotropy of the mixtures.

Practical Example:

For this example, we'll use Tachyon 100G construction table shown in Figure 13. It is based on IPC-650-2.5.5.5C test method, which measures Dkz out-of-plane. We will use 1035 glass style; 69% RC and total prepreg thickness of 51 µm (2mil). The Dkz value for 1035/69% prepreg, at 10GHz is 3.06.

Given:

A = 1 m^2

t = 51 um

D = Density of NE-glass (L-glass) = 2.3E6 g/m^3

W_g = Weight of 1035 L-Glass = 0.9(Weight of 1035 E-glass from Table 2) = 0.9(30 g/m^2) = 27 g/m^2

Step 1:

Determine the volume fraction of glass content (GCv):

Equation 10

$$GCv = \frac{Wg \times A}{(D \times A \times t)} = \frac{27g/m^2 \times 1m^2}{(2.30E6g/m^3 \times 1m^2 \times 5.10E-5m)} = \frac{27}{(2.30E6 \times 5.10E-5)} = 0.23$$

Step 2:

Using a GCv of 0.23 and a Dkg of 4.8 for L-glass at 10GHz and rearranging the parallel mixing rule equation, estimate Dkr value:

Equation 11

$$Dkr_{10GHz} = \frac{Dkz_{10GHz}(1-GC_v)}{\left(1-\left(\frac{Dkz_{10GHz}GC_v}{Dkg_{10GHz}}\right)\right)} = \frac{3.06(1-0.23)}{\left(1-\left(\frac{3.06 \times 0.23}{4.8}\right)\right)} = 2.76$$

Step 3:

Using series mixing rule equation, determine Dkxy:

Equation 12

$$Dkxy = (1-GC_v)Dkr + (GC_v)Dkg = (1-0.23)2.76 + (0.23)4.8 = 3.23$$

Step 4:

Finally 1035/69% RC, 2 mil prepreg @10GHz has a Dk anisotropy of:

Equation 13

$$\Lambda_{20GHz} = \left(\frac{Dkxy}{Dkz} - 1\right)100 = \left(\frac{3.23}{3.06} - 1\right)100 = 5.56\%$$

Applying Equation 11 to Equation 13 for each prepreg glass style from Figure 13, Tachyon 100G Dkxy and anisotropy is summarized in Figure 15. As can be seen Dk anisotropy varies from a low of 4.4%, to a high of 5.9%.

Glass Style	Resin Content %	Offering	Thickness (inch)	Thickness (mm)	Dielectric Constant (Dkz)						Dkxy						Anisotropy
					1 GHz	2 Ghz	5 Ghz	10 GHz	15 Ghz	20 Ghz	1 GHz	2 Ghz	5 Ghz	10 GHz	15 Ghz	20 Ghz	xy:z
1035	69.00%	Standard	0.002	0.051	3.06	3.06	3.06	3.06	3.06	3.06	3.23	3.23	3.23	3.23	3.23	3.23	5.6%
1035	75.00%	Standard	0.0026	0.066	2.97	2.97	2.97	2.97	2.97	2.97	3.11	3.11	3.11	3.11	3.11	3.11	4.7%
1078	65.00%	Standard	0.0029	0.074	3.14	3.14	3.14	3.14	3.14	3.14	3.31	3.31	3.31	3.31	3.31	3.31	5.5%
1078	67.50%	Standard	0.0031	0.079	3.09	3.09	3.09	3.09	3.09	3.09	3.26	3.26	3.26	3.26	3.26	3.26	5.5%
1078	70.50%	Standard	0.0035	0.089	3.04	3.04	3.04	3.04	3.04	3.04	3.20	3.20	3.20	3.20	3.20	3.20	5.1%
1078	72.00%	Standard	0.0037	0.094	3.02	3.02	3.02	3.02	3.02	3.01	3.17	3.17	3.17	3.17	3.17	3.16	5.0%
1078	75.00%	Standard	0.0042	0.107	2.97	2.97	2.97	2.97	2.97	2.97	3.11	3.11	3.11	3.11	3.11	3.11	4.6%
1078	78.00%	Alternate	0.0046	0.117	2.92	2.92	2.92	2.92	2.92	2.92	3.05	3.05	3.05	3.05	3.05	3.05	4.5%
2116	62.00%	Standard	0.0058	0.147	3.19	3.19	3.19	3.19	3.19	3.19	3.37	3.37	3.37	3.37	3.37	3.37	5.7%
2116	65.00%	Alternate	0.0064	0.163	3.14	3.14	3.14	3.14	3.14	3.14	3.31	3.31	3.31	3.31	3.31	3.31	5.4%
1067	70.00%	Standard	0.0022	0.056	3.05	3.05	3.05	3.05	3.05	3.05	3.21	3.21	3.21	3.21	3.21	3.21	5.2%
1067	71.50%	Standard	0.0024	0.061	3.02	3.02	3.02	3.02	3.02	3.02	3.17	3.17	3.17	3.17	3.17	3.17	4.9%
1067	74.00%	Standard	0.0026	0.066	2.98	2.98	2.98	2.98	2.98	2.98	3.12	3.12	3.12	3.12	3.12	3.12	4.8%
1067	76.50%	Standard	0.0029	0.074	2.94	2.94	2.94	2.94	2.94	2.94	3.07	3.07	3.07	3.07	3.07	3.07	4.4%
106	76.00%	Standard	0.0023	0.058	2.95	2.95	2.95	2.95	2.95	2.95	3.08	3.08	3.08	3.08	3.08	3.08	4.4%
1080	72.00%	Standard	0.0038	0.097	3.02	3.02	3.02	3.02	3.02	3.01	3.16	3.16	3.16	3.16	3.16	3.15	4.7%
1080	75.00%	Standard	0.0043	0.109	2.97	2.97	2.97	2.97	2.97	2.97	3.10	3.10	3.10	3.10	3.10	3.10	4.4%
1080	78.00%	Alternate	0.0046	0.117	2.92	2.92	2.92	2.92	2.92	2.92	3.05	3.05	3.05	3.05	3.05	3.05	4.4%
3313	63.50%	Standard	0.0046	0.117	3.16	3.16	3.16	3.16	3.16	3.16	3.35	3.35	3.35	3.35	3.35	3.35	5.9%
3313	66.50%	Standard	0.0051	0.129	3.11	3.11	3.11	3.11	3.11	3.11	3.28	3.28	3.28	3.28	3.28	3.28	5.6%

Figure 15 Tachyon 100G Dk anisotropy.

Anisotropic Model Validation

A high performance, low-loss dielectric material, from TUC[21], commonly used for high-speed digital applications, was chosen for material characterization and validation. A PCB test coupon, with suitable 2x-thru test structures, was designed with stripline geometry. After fabrication, the appropriate test traces were measured and respective touchstone files were later de-embedded for analysis and comparison.

The PCB test coupon was later cross-sectioned and examined under a microscope to determine the precise geometries of the stripline and copper roughness as fabricated. The differential pair conductor thickness, line widths, and space parameters were then modified in the simulation model to match these measurements. The thicknesses of the core and prepreg were also adjusted in the model accordingly. The Huray-Bracken roughness parameters, used in the Simbeor software [22], were derived using the Simonovich Cannonball roughness model [23].

The Dk values in TUC's construction tables were derived using IPC-TM-650 2.5.5.13 test method and thus were in-plane. Using respective glass and resin Dk values and appropriate series mixing rule equations, the 1035/65% RC cores and prepregs used in the stackup had a Dk anisotropy of 5.4%. The Df values from TUC construction table was used in the simulation.

The measured results, courtesy of Ciena Corporation [16], are presented in Figure 16. The measurements are shown in red and compared to simulated results, shown in blue and green on all four graphs. The green results were simulated using Dkxy and adjusted for roughness [15]. Initially, there was a poor correlation to measurements on all four graphs. However, after converting to Dkz, by adjusting for anisotropy, and similarly correcting for conductor roughness, the plots with blue circles showed a strong correlation to measurements on all four graphs.

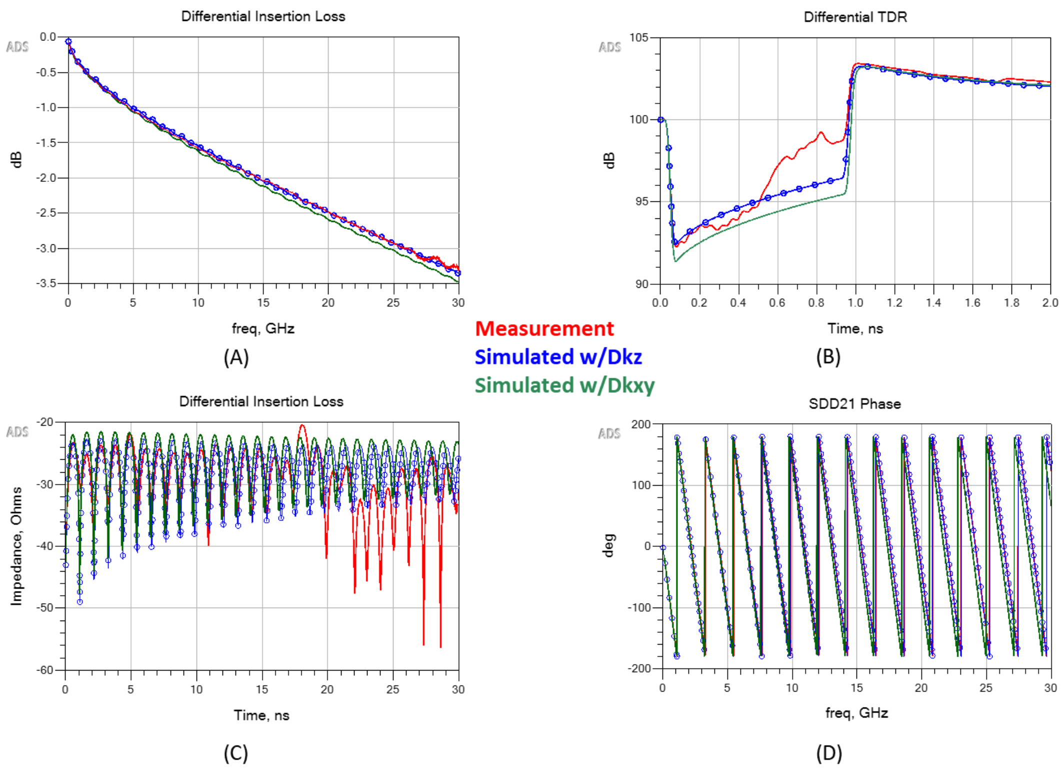


Figure 16 Simulation correlation to measurement results (red) using Dkxy (green) vs Dkz (blue circles). When Dkxy was corrected for anisotropy and Dkz used, there was excellent correlation in all four graphs. Modeled with Simbeor [22] and simulated with Keysight Pathwave ADS [17]. Measured data courtesy of Ciena Corporation [16]

Summary and Conclusions

Obtaining accurate Dk/Df material properties is crucial when designing a PCB stackup for characteristic impedance and predicting transmission line losses. Heuristic methods presented in this paper can provide more accurate Dk values and prevent impedance and transmission loss miscalculations, ultimately ensuring a successful PCB fabrication yield.

Using out-of-plane Dkz values instead of in-plane Dkxy values for via modeling can lead to misleading simulation results which may result in reduced margins and potential compliance test failures when the design is built and tested. It is recommended that CCL suppliers provide anisotropic properties in their Dk/Df construction tables.

Given that woven glass reinforced PCB substrates are anisotropic, EDA design and modeling software should have provisions to model anisotropic material especially for via transitions.

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