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Apples-to-Apples Laminate Characterization

Enhanced Signal Integrity using Reliable Dk and Df Verification throughout PCB Design and Fabrication

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Abstract

Employing accurate material parameters in PCB design is critical to electrical performance, ensuring both signal and power integrity. PCB laminate manufacturers publish construction tables with resin-content and permittivity (Dk, Df) specifications. Do we trust them?

How does an engineer ensure that they have an “apples-to-apples” comparison across multiple laminate systems, constructions, and data sources?

In this paper we demonstrate a quick and direct method of acquiring actual dielectric constant (Dk) and loss tangent (Df) values from the same materials that will be used by your fabricator. This replaces guesswork and trust with actual values acquired from your own bench.

Authors’ Biographies

Bill Hargin is the director of everything at Z-zero (www.z-zero.com), providing stackup design and PCB material selection software to OEMs, ODMs and PCB fabricators worldwide. Bill is an author of multiple articles on signal integrity, a regular columnist for Printed Circuit Design and Fabrication, and More than 10,000 engineers and PCB designers worldwide have taken Hargin’s workshop on high-speed PCB design. With more than 20 years of experience dealing with PCB signal integrity, Mr. Hargin served as product manager for Mentor Graphics’ HyperLynx SI software and as the Director of North American Marketing for Nan Ya Plastic’s PCB laminate division in Taiwan.

Dr. Don DeGroot is the president of CCN (www.ccnlabs.com), a test equipment and service business he co-founded in 2005 to support high-speed electronic design. Don has over 30 years of experience in high-frequency electrical measurements and design, including a PhD degree from Northwestern University and 12 years of research at NIST. From 2006-2015, Don held a faculty position at Andrews University where he innovated project- based learning in electronic communications. He currently serves as Chair of the IPC D24 subcommittee on high-speed and high-frequency test methods. Don has published and presented over 100 technical papers on measurement science and electronic design research. He currently focuses on PCB interconnection and material characterization.

Overview

Engineers often rely on copper clad laminate (CCL) specification sheets to obtain dielectric constant (Dk) and loss tangent (Df) parameters for design. When the engineer does not consider complicating factors, relying on spec sheets alone may cause their circuit board design to miss critical impedance and signal loss goals—particularly at high speeds.

Many OEM designers and researchers advocate the construction and testing of transmission line test vehicles to capture the true performance of dielectric and copper foil materials as pressed and etched by their preferred fabricators [refs]. Prior to volume production, this is the most direct method of extracting copper- and dielectric-influenced design parameters, such as propagation constant or effective permittivity. These parameters can be used with confidence for transmission line designs and constructions similar or identical to those incorporated in the test vehicles.

When starting a design project, engineers may not have the luxury of fabricating and testing a wide range of test vehicles for each of their potential materials, particularly while evaluating laminates. Instead, initial analysis is typically based on the available laminate data from copper-clad laminate or PCB manufacturers. This readily-available data is often used to narrow the list of potential materials that could be specified in the design. This is to say that for critical path, high-speed signals, the engineer cannot just tell an ODM or contract manufacturer that they want a 100 ohm differential line with 4 GHz loss of 0.42 db/inch; it's advisable for OEM engineers to *own* the process of optimizing electrical performance—working directly with their design and supply partners to dial in line widths, spacing, and/or laminate choices to meet electrical requirements without compromizing mechanical and thermal demands.

As material costs and loss are optimized, it's important to measure and analyze the variance in material parameters prior to production, including tracking of geographic sourcing, and potential variation in volume production.

Nominal Dk and Df values included in the laminate manufacturers' construction tables do not typically capture the parameter variance in manufacturing, meaning the spec sheet values are unlikely to be worst-case values for the application. Compared to nominal values of Dk and Df, the actual laminate parameters may put the design over the loss margins or create inter-plane impedance that is too large.

Additionally, the manufacturers' Dk and Df data may be acquired with any variety of test methods. Each permittivity test method has known quirks and biases that are large enough to raise concern when choosing materials or designing circuit boards.

Lastly, the test frequency used in the CCL specification sheet and particularly the values used by PCB fabricators may not cover the application frequency. Due to all these factors, comparing different materials or laminate constructions will lead to sub-optimal laminate choices and signal quality.

How does a board designer ensure that they have an "apples-to-apples" comparison of Dk and Df across multiple laminate systems and constructions? And how does an engineer know that they used the best values and variance for their selected laminate in their design simulations?

This paper sheds light on the relevant Dk and Df concerns and proposes a straightforward methodology for ensuring that board designs employ dielectric characteristics that reflect what's actually included in volume production. This same methodology is useful in optimizing material selection, cleanly separating dielectric losses from total losses, and ensuring acceptable Dk and Df variation in production.

Terminology

This paper will employ the following terms interchangeably:

- CCL, copper-clad laminate, laminate
- Loss tangent, tan δ, Dissipation Factor, Df
- Real part of relative permittivity, ε_r, Dielectric Constant, Dk

Designing for Impedance and Insertion Loss

Lossy transmission-line effects become significant signal integrity concerns at clock frequencies above roughly 1 GHz and/or for interconnect lengths that exceed 12 inches. When selecting laminates, hardware designers often want to make tradeoffs between different resin systems, glass constructions and resin content (%), and material costs when planning stackups for target impedances and loss. Often, the task is delegated to the PCB fabricator, and assumptions are made for frequency—where 1 GHz is commonly assumed—as well as retained copper (%) assumptions on signal layers. Including frequency and resin content, there are seven variables at work here—along with trace width, copper weight, dielectric height, Dk, and Df, retained copper (%), which impacts prepreg thickness, and copper roughness. Most of these factors have an impact on impedance and each of these parameters has an impact on insertion loss and cost. In this study, our focus is on more-accurately representing dielectric constant (Dk) and dissipation factor (Df).

For the purpose of stackup design, many engineers rely on PCB fabricators to perform stackup design. Fabricators will typically use Dk values at 1 GHz along with assumed retained copper (%) values, calculating trace widths to achieve target impedances. This may work fine at 1 GHz, in fact, but at higher speeds hardware engineers should be concerned about improving the accuracy of each of these parameters for pre-prototype signal-integrity simulations. Characterizing Dk and Df more accurately—for use in signal-integrity simulation software—is one purpose of the proposed methodology.

Key Loss Components

There are two components of propagation loss: dielectric loss and conductor loss. In transmission line analysis, loss is the real part of the propagation constant and describes how much signal is "lost" per unit length of signal propagation. The loss factor is most often reported in decibels per unit length (for example, dB/inch). It represents the signal power lost after the signal propagates down that length of uniform transmission line.

Dielectric Loss: Dielectric loss increases nearly linearly with frequency, and varies with a material's "dissipation factor" or Df—a function of the material's resin type, molecular structure, and fillers. Depending on resin content and the resin system, circuit-board laminate materials have Df values ranging from:

- ≤ 0.005 – Ultra-Low Loss
- 0.005-0.010 – Low Loss
- 0.010-0.015 – Mid Loss
- 0.015-0.020 – Standard Loss

Lower Df values equate to more of the output signal getting to its destination, as well as higher material costs, as compared to standard-loss materials.

Conductor Loss: From DC through frequencies up to a few MHz, the current in a trace moves through the entire cross-sectional area of the trace. At higher frequencies, however, current flows along the surfaces of the conductors rather than uniformly across the entire cross section. As a result, the series resistance of the signal and return path of smooth conductors increases with the square root of frequency as the effective cross section of the interconnect path is reduced. This type of loss is often referred to as "skin effect" and is of concern at 1 GHz and above, depending on the geometry of the transmission line. Additionally, copper foils are treated to increase adhesion between layers in the stackup. As explored in numerous studies[7], the roughness of the copper increases conductor loss above that of ideally smooth copper and in a manner that is not easily separable from the ideal-copper response or from the dielectric-loss response.

Why Accurate Dielectric Characterization is Important

The first purpose of this research was to see whether laminate-vendors' dielectric-only measurements agree with the Dk and Df values obtained with a calibrated stripline resonator system that had been verified using reference materials and values from national metrology institutions. One of the concerns with regard to as-fabricated measurement methodologies is that the results apply only to specific copper weights, trace widths, and copper profiles.[7] While this may be helpful for extracting design parameters for a specific trace geometry on a specific board from a specific fabricator, it does not lend itself to identify the dielectric loss component by itself. A more general and simpler solution is one where dielectric characterization is performed separate from, though possibly in addition to, the as-fabricated transmission line characterizations. A dielectric-only test removes as much uncertainty as possible from the dielectric-selection and design process, allowing efficient material choice.

Fortunately, all mainstream signal integrity simulators and stackup design tools have the ability to model copper effects, including copper roughness—as part of the loss-budgeting process. When calculating or simulating total loss, engineers are faced with *adding* copper loss to dielectric loss or *subtracting* copper loss from total loss in order to understand the contribution of the dielectric.

Background of Dk and Df Measurement Methods

Unfortunately, there's no NIST-traceable "gold standard" for Dk and Df values outside of a small number of standard reference materials that can be used to check results against rigorous standards. As a result, there's no way to know whether a vendor-provided Dk/Df measurement is an accurate representation of what's going to end up in a circuit board. Some laminate-savvy engineers note that laminate vendors tend to gravitate toward the measurement methodology that makes their laminates look the best. It's impossible to generalize from this, but it's a question that we sought to understand further in our research.

It's well understood that most methods used by CCL manufacturers come from industry or standard associations like the IPC and ASTM. Such methods have been shown to be gauge capable, ensuring reproducibility, but the accuracy is not traceable to a global or national metrology institution like NIST. Such methods are great for tracking differences in materials relative to the same test, but results from such methods are reported with unknown measurement certainty.

And, to compound the confusion, there's no industry consensus on which test method to use. IPC's own test method manual, the TM-650, includes a total of 12 different methods for everyone to pick and choose from, as shown in Figure 1 below. As a result, datasheet Dk/Df values don't correlate "apples-to-apples" across laminate manufacturers.

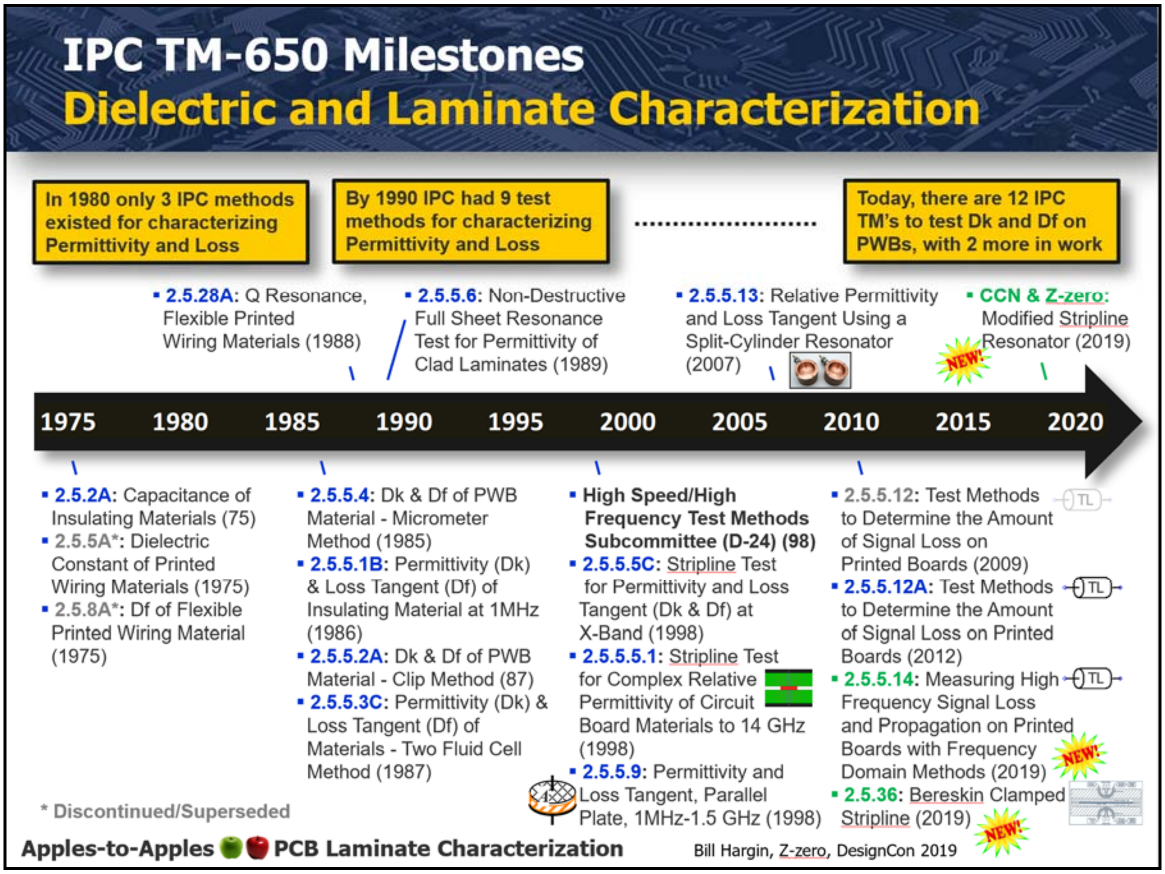

Figure 1: The 45-year history of IPC dielectric and laminate characterization methods included 3 techniques in 1975, and will include a dozen methodologies in 2019.

It should be noted that the IPC and ASTM methods are gauge capable, linear, repeatable and reproducible, so there is a high degree of correlation between measurements made across the different dielectric test systems.[1] This allows for benchmarking, but not direct access to the Dk and Df values a high-speed signal actually "sees" as it propagates down the transmission line.

Another distinction between dielectric and laminate characterization methods ties to how and whether copper is incorporated into the test samples. At a high level, we can characterize two different groups of measurement approaches for obtaining dielectric properties, including: a) dielectric (only) testing; and b) transmission-line based measurements on actual copper-clad test vehicles. As Figure 2 indicates, below, these approaches are not mutually exclusive and both can be successfully employed for different purposes in a successful design flow. The authors recommend dielectric test methodologies for apples-to-apples material comparisons and initial design efforts prior to prototyping—followed by transmission-line based approaches using as-built constructions later in the design process, leading up to formal part-number qualification. Once production is underway, both approaches can be employed: dielectric testing, for supply chain monitoring, with as-designed impedance coupons as part of each panel layup for ongoing impedance monitoring.

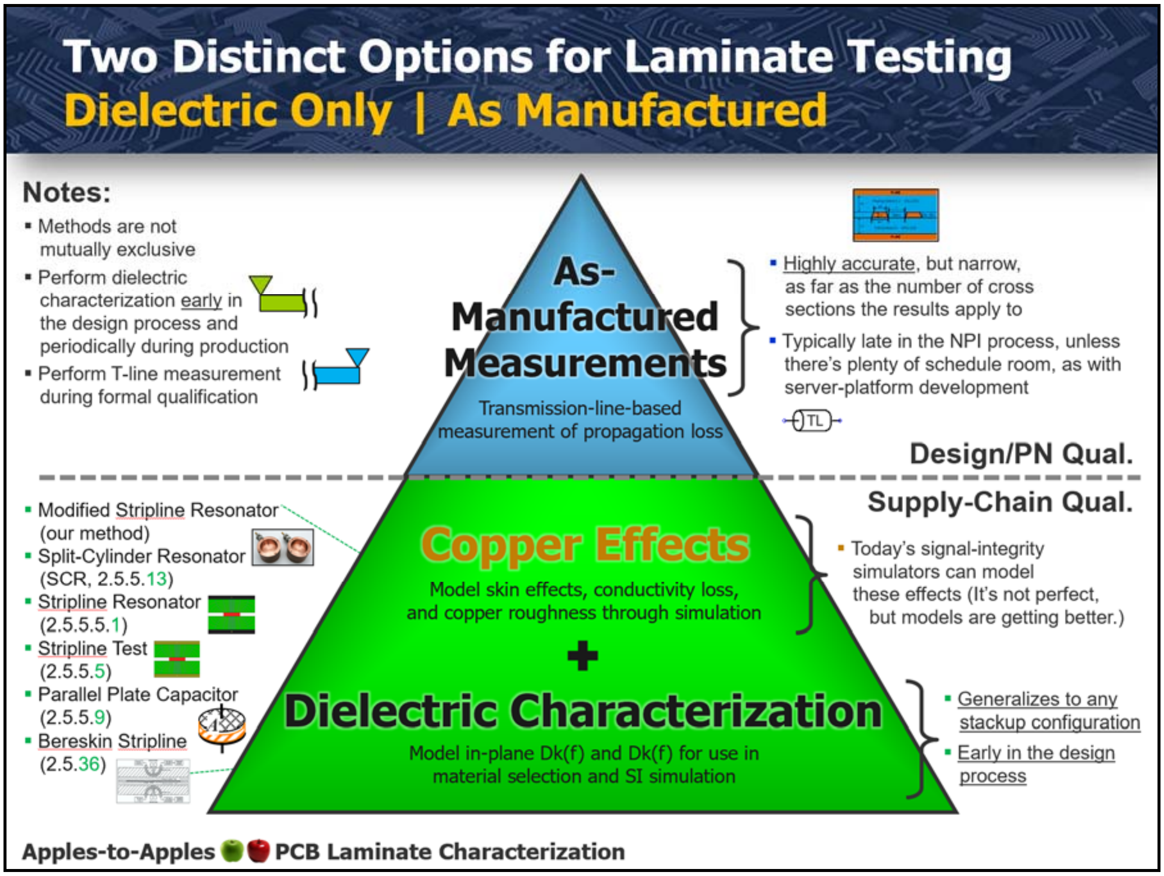

Figure 2: Two high-level categories for dielectric testing.

Anisotropy and E-Field Orientation

Electric fields on a PCB are oriented normal to signal-transmission lines, as shown by the blue field lines in the stripline cross section in Figure 3 below. Note that the heaviest concentration of E-field lines are in the z-direction, or "out of plane." Because of this, the authors believe that dielectric measurements should be performed out of plane, in line with the "apples to apples" theme of this paper.

As the figure shows in the microsection on the right, PCB laminates are a sequentially-layered mixture of glass and resin. From a high-speed signal's point of view, the resin and glass layers look like a series combination of the capacitances of each, resulting in Dk(z), as shown in the figure.

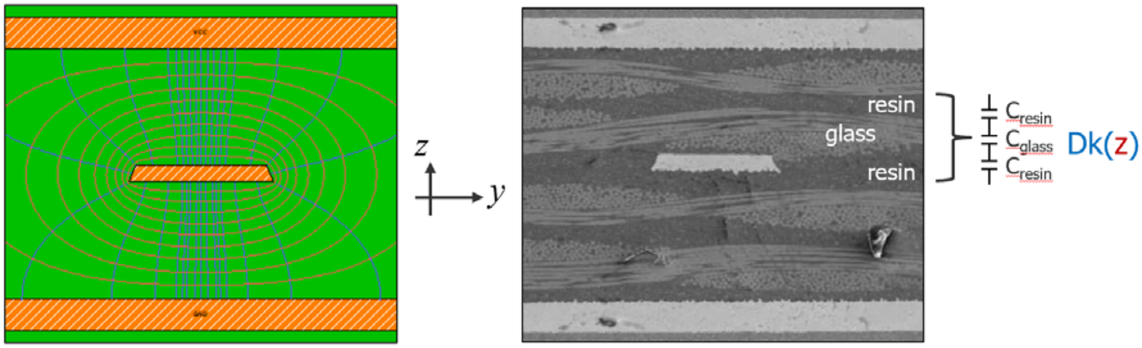

Figure 3: The predominant E-field direction for a transmission line is "out of plane," or in the z-direction. A signal will "see" the capacitance of the layered resin and glass combination in series, as shown, resulting in an effective Dk(z).

Dielectric characterization methods today are split between "in-plane" methods and the "out-of-plane" method noted above. Figure 4 shows a glass-weave layer that would include resin above and below it, as noted above. In-plane dielectric characterization methods would analyze the capacitance of resin and glass elements in parallel, resulting in Dk(xy) and Df(xy).

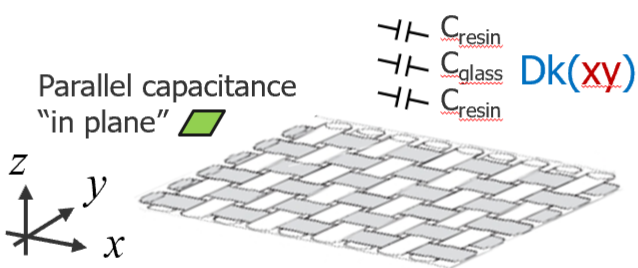

Figure 4: "In-plane" dielectric characterization sees the relative capacitance of the resin-glass-resin combination in parallel, as shown, resulting in an effective Dk(xy). In-plane Dk and Df do not physically represent what a high-speed signal will "see."

Dk and Df Measurement Methods used in Laminate Tables

For glass-reinforced, high-layer count (HLC) digital designs, example laminate suppliers include Elite Materials Corporation (EMC, Taiwan), Doosan (Korea), Isola (US), ITEQ (Taiwan), Nanya Plastics (Taiwan), Panasonic (Japan), Park Electrochemical (US), Shengyi Technologies (China), and Taiwan Union Corporation (TUC, Taiwan). A significant cross section of these suppliers are represented in this study. (For the purposes of this paper, we are specifically excluding non-reinforced, microwave materials such as PTFE-based materials.)

To make matters even more confusing, laminate manufacturers may use:

- One test method for datasheets and another for their Dk/Df tables.
- One test method at 1 GHz and another test method above 1 GHz.
- One test method for Dk and another test method for Df.

All of the above variants are spread across eight or nine high-layer count, digital laminate manufacturers as well as a subset of the 12 different IPC test methodologies. Table 1 summarizes how most of these laminate manufacturers characterize their product lines:

CCL Manufacturer	Datasheet Test Methods (IPC-TM-650)		Dk/Df Tables	
	Dk	Df	Dk	Df
Doosan	2.5.5.9	2.5.5.9	2.5.5.13	
EMC	2.5.5.9	2.5.5.9	2.5.5.13	
Isola	2.5.5.9	2.5.5.9	Bereskin Stripline	
ITEQ	2.5.5.13	2.5.5.13	2.5.5.13	
Nanya	2.5.5.9	2.5.5.9	2.5.5.13	
Nelco	2.5.5.5	2.5.5.13	2.5.5.5	2.5.5.13
Panasonic	2.5.5.9	2.5.5.9	2006 IEEE Conference Procedings	
Shengyi	2.5.5.5	2.5.5.5	2.5.5.13	
TUC	2.5.5.13	2.5.5.13	2.5.5.13	

Table 1: Standard test methods for dielectric testing, by laminate manufacturer.

A summary of the most-commonly used dielectric-characterization methods in the table are shown in Figure 5 below.

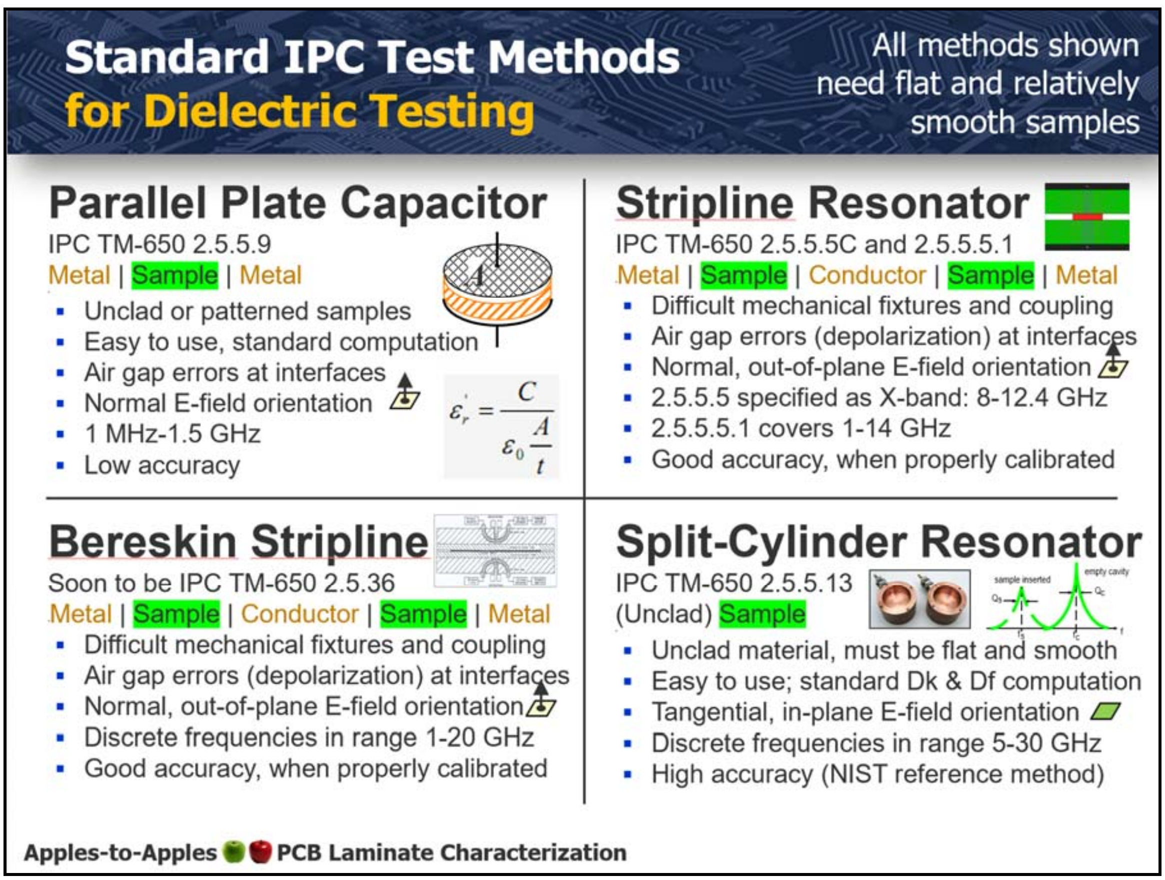

Figure 5: Summary of common dielectric test methods employed by laminate manufacturers.

Dielectric-Only Characterization Methods

For the highest-accuracy permittivity measurements for very-low-loss materials, resonant techniques are used. The common frequency range for these techniques are in the 1-20 GHz range, although higher-frequency resonant fixtures are available. The methods noted in the table above are described in more detail below.

- IPC-TM-650 2.5.5.5.1, the Stripline Resonator Test for Complex Relative Permittivity, is used to measure relative permittivity (ε_r) and dissipation factor (Df) or loss tangent (tan δ) of circuit board substrates under stripline conditions.[2] Measurements are made by measuring resonances of a length of stripline over a wide frequency range from 1-14 GHz. The method permits a wide variety of specimen configurations, varying in dielectric thickness, width of center conductor, and use of clad or laid up conductor foil. Sensitivity to differences in tan d are enhanced by the ability to adjust the degree of coupling to the resonator by adjusting an air gap between probes and the resonator ends. Many of the principles used in IPC-TM-650, Method 2.5.5.5 are applied in this method, which reports out-of-plane Dk and Df—with the same electric-field orientation that a high-speed signal will see. This method is highly accurate and a reasonable alternative for low-loss laminates for frequencies ranging from 1-14 GHz.
- IPC-TM-650 2.5.5.5, the Stripline Test for Permittivity and Loss Tangent, is a stripline test method that is used quite a bit in the microwave industry. This approach employs two specimen halves that are etched free of copper and placed on either side of a thin resonator card. This method reports out-of-plane Dk and Df—with the same electric-field orientation that a high-speed signal will see. The Stripline Test is highly accurate, and a reasonable alternative for low-loss laminates—for frequencies ranging from 8-12.4 GHz.[3]
- IPC-TM-650 2.5.5.9, the Parallel Plate Capacitor method, provides Dk and Df results between 1 MHz and 1.5 GHz following the basic technique of the ASTM D-150 standard.[4] Five laminate manufacturers report Parallel Plate Capacitor measurements at 1 GHz in datasheets. Here, an AC voltage is applied to parallel plates on each side of the dielectric specimen, and capacitance is measured using an impedance analyzer. Knowing the electrode geometry and dielectric thickness, the measured capacitance and dissipation factor are converted to Dk and Df values for the material. An advantage for the parallel plate method lies in the fact that it's an easy test. The biggest disadvantages lie in the fact that it does not extend above 1.5 GHz, and accuracy is limited above 1 GHz. Another concern lies in the fact that the surface roughness of the sample(s) can act to lower the reported Dk. Consequently, the Dk measurements tend to be biased low for CCL materials due to the natural surface of the material.
- IPC-TM-650 2.5.5.13, the Split Cylinder Resonator (SCR) method, is commonly used by six different Asian laminate manufacturers, in particular, for construction of Dk and Df tables that are passed on to OEMs and fabricators for use with stackup design.[5] This method was written by researchers at NIST for the IPC TM-650 manual. Sample preparation is easy and the method is highly accurate. NIST also computes the measurement uncertainty for this method, so it can act as

a solid reference technique. However, this method only measures the dielectric with an electric field that is tangential (in-plane) with the specimen surfaces. NIST and others[7] have shown that for common CCL material, the in-plane Dk values will be 5-20% higher that the out-of-plane Dk values. Since SI engineering relies on a dominant out-of-plane electric field, data sheets showing Dk from SCR measurements will not be useful to design. The SCR method uses a VNA, with a resonant cavity fixture connected between two ports. Software then calculates Dk and Df from VNA measurements of the resonant frequency and Quality (Q) Factor of the split cylinder resonator with the sample inserted.

- Between 6-40 GHz, Panasonic uses a balanced circular disk resonance methodology developed by Yoshio Kobayashi and presented at the 2006 IEEE Conference.[6] Since the Megtron 4/6/7 series has been popular in high speed, high layer count design, we are interested in understanding how this methodology compares with IPC standards and our measurements.
- The Bereskin Clamped Stripline Resonator method—soon to be represented as IPC-TM-650 2.5.5.15 or .16—measures out-of-plane Dk and Df, with accurate results between 2-15 GHz. The resonator is the clamped copper strip. As noted in Table 1 above, Isola uses this method exclusively. The Bereskin and Stripline Resonator methods agree when fixtures are properly calibrated. Without calibrating the fixture, Dk and Df results may contain significant measurement errors.

Summaries of the above test methodologies, comparing material-loss categories on the vertical with and frequency (horizontal) is shown in Figure 6 below.

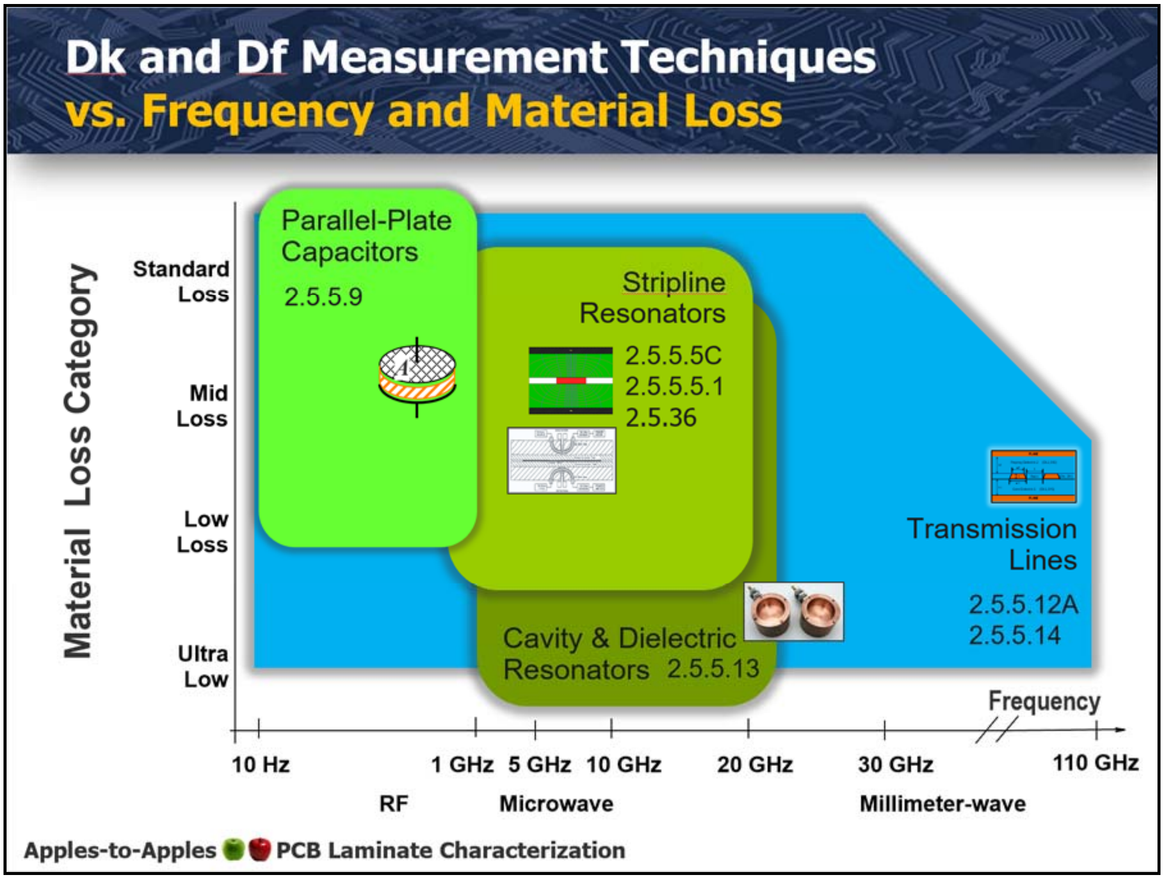

Figure 6: IPC Dk and Df measurement techniques
vs. frequency and material-loss categories.

Transmission-line Based Insertion-Loss Tests

Worth mentioning, but intentionally beyond the scope of the present study are the various copper-clad dielectric-testing methodologies, including the following:

- Short-Pulse Propagation (SPP) is an IBM-created methodology for characterizing insertion loss, Dk, and Df, from 1 GHz to as much as 40 GHz with the proper equipment. SPP, a fairly-involved procedure, is captured as Method C in IPC-TM-650. 2.5.5.12.[8]
- SET2DIL is a TDR-based, Intel-created methodology for characterizing differential insertion loss, from which Dk and Df are extracted. Captured as Method D in IPC-TM-650.2.5.5.12. Developed initially with the hope that fabricators could monitor loss in production. Removing launch artifacts proved to be a challenge.[9]
- Delta-L is an updated Intel methodology that eliminates the launch artifacts from the SET2DIL methodology. As of this writing, the IPC D-24d group is almost ready to release 2.5.5.14, which is the evolutionary endpoint of Intel’s efforts. Essentially, this would supersede Method D from 2.5.5.12 (SET2DIL).[9]

PCB Fabricator Practices

Some PCB fabricators use first-order equations as a framework for using the above transmission-line methods to estimate Dk or Df, respectively, from the above methodologies. It's clear why this practice is employed: it's relatively easy to do. But it cannot be considered as a reliable design methodology, so we will not give it further consideration here.

Advantages of the Proposed Methodology

We present a direct approach to acquiring and using Dk and Df parameters that puts engineers in control. This "apples-to-apples" approach allows the same test method to be used throughout design and supply chain monitoring, eliminating confusion due to varying test methods, copper effects, data sources, and vendor practices.

Engineers can make quick, broadband permittivity tests on their own bench and test a number of materials in a short amount of time. The data comes from the same test system and the same operator; designers and PCB fabricators can eliminate the question of data source when selecting PCB materials.

Further, it is quite easy to test a number of CCL specimens from a production sample. This provides expectated values for Dk and Df over a number of observations along with the variance of each parameter.

The test method provides out-of-plane dielectric constant and loss tangent values. This removes an important source of test-method confusion, which will be discussed further below. It also means that the electric-field orientation during permittivity testing closely matches the dominant electric-field orientation considered in signal integrity and power integrity simulation.

Presently, the permittivity test methodology covers frequencies in the range 1-20 GHz, and the method provides Dk and Df values as functions of frequency, not just single points.

In this paper we demonstrate this quick and direct method of acquiring and utilizing actual dielectric constant and loss tangent values from a variety of materials. In practice, these would be the materials used by a PCB fabricator and the measurement data could be utilized in signal-integrity simulations. This approach replaces guesswork and trust with actual Dk, Df, and variance data acquired at a known test bench. It also ensures that Dk and Df data from all measured materials can be compared on an "apples to apples" basis, as the paper title suggests.

With this as background, we will now outline the details of this study.

Experimental Design (DOE)

Our goal was to compare the following:

- Published CCL vendor table values for Dk(f), Df(f).
- Dk(f), Df(f) for an uncured prepreg. Of course, there's no such thing as an uncured prepreg in a circuit board. Our purpose was simply to pull some data from the prepregs that were sent to us before temperature-curing them to show why you should never try to predict any finished Dk and Df values from uncured prepreg.
- Dk(f), Df(f) for an identical temperature-cured prepreg.
- Dk(f), Df(f) for a similar single-ply core. (With copper etched away.)
- Dk(f), Df(f) for a similar dual-ply core. (With copper etched away.)

Test Specimens

In support of our DOE, our goal was to obtain:

- An uncured prepreg panel; e.g., 1078 glass; ideally around 4 mils.
- A similar construction (material, glass style, resin content) in unclad single-ply core.
- A 2-ply core construction with the same material, glass style, and resin content with the copper etched away.
- Coupon Size: 3.000 x 3.0 in, which we cut into three 1-inch wide strips
- Thickness: 4-30 mils (preference for 4-5 mils, since these are common)

Measurement Setup

For the purpose of our testing and data collection, we developed an automated Dk and Df test system based on a stripline resonator, similar in most respects to IPC TM-650-2.5.5.5.1, but with some notable improvements over 2.5.5.5.1 that allow accurate Dk and Df characterization up to 20 GHz. Attributes of the measurement setup are further summarized below, and the test setup is shown in Figure 7:

- E-field measurements: out-of-plane (z-direction, for SI applications)
- Frequency range: 1-20 GHz
- Thickness measurements: USB micrometer
- Calibration: verified with national lab data
- Measurement resolution: Dk ±0.03, Df ±0.001, Thickness ±0.001 mm
- Simplified specimen insertion into fixture

Note: we were not able to get perfect glass style and resin content alignment from our material sources. This narrowed the sample size for resolving some of our study questions noted below.

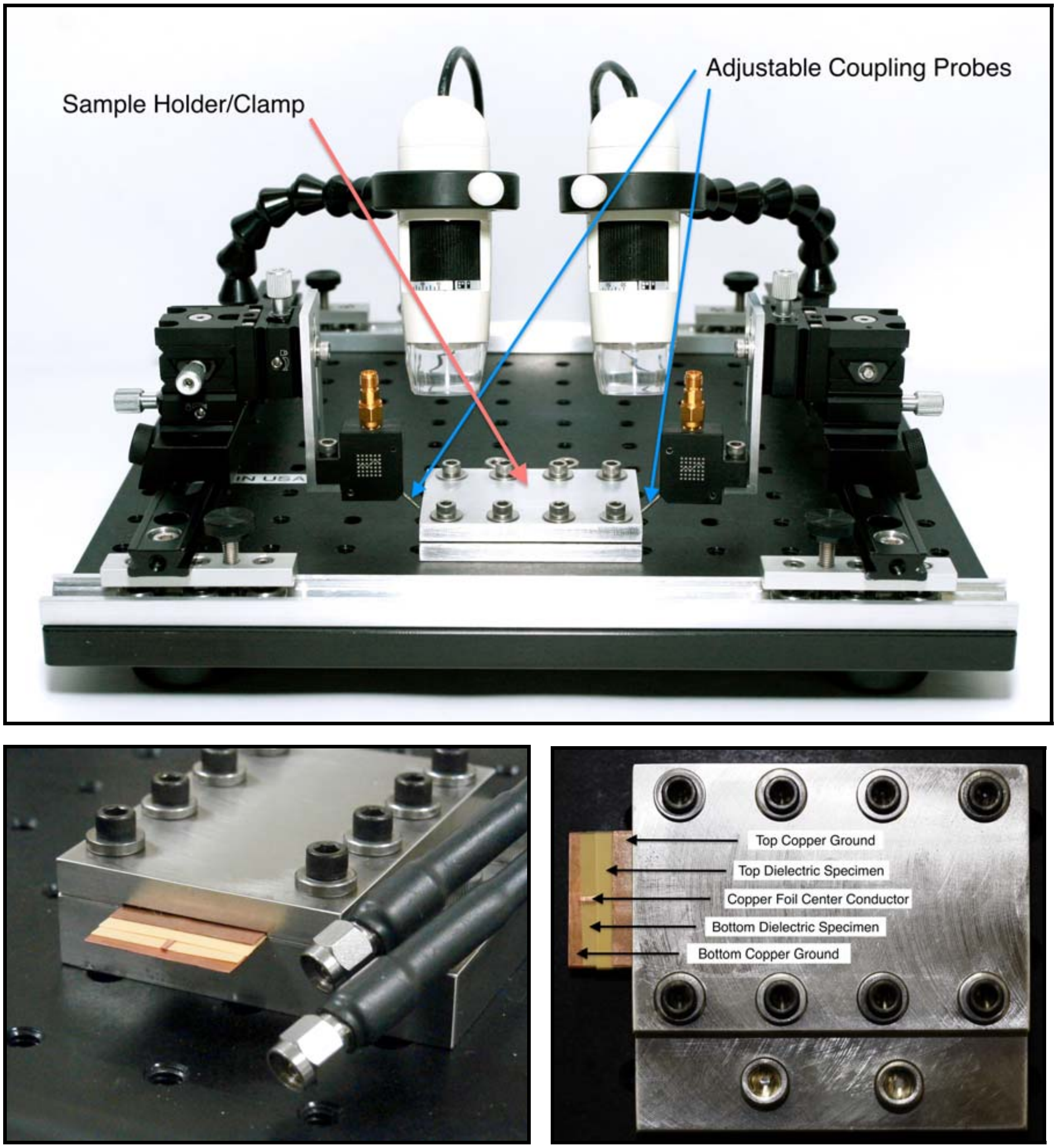

Figure 7: Stripline resonator test setup.

Details of the Stripline Resonator Test Method

The stripline resonator test fixture used in testing the CCL permittivity uses two 25 x 76.20 mm (1 x 3 in.) sheets of the dielectric material under test to form a "Type A" stripline resonator specimen.[2] The Type A stripline resonator specimen is a stack of:

1) bottom copper foil ground sheet
2) lower sheet of unclad material under test
3) copper foil center conductor strip
4) upper sheet of unclad material under test
5) top copper foil ground sheet, using rolled copper with no surface treatment

We used an automated digital micrometer to make five measurements of material thickness along the 76.2 mm (3 inch) length of a test specimen. The mean value was used in the Dk and Df computations. We did not test pieces where the thickness varied by more than 5% along the length.

To test, we slid the Type A specimen stack into the stripline resonator fixture and clamped the stack together with a 2000N force.

The IPC method is further modified in our method to correct the published IPC algorithm for copper loss. The stripline resonator fixture is calibrated using known materials with traceable Dk and Df values to remove the electromagnetic losses of the copper conductors from the total resonator losses. In this way, our stripline resonator method reports a corrected Df of only the dielectric region of the test specimen and is not influenced by the Ohmic losses of the conductors, though we acknowledge that the observed dielectric losses may be influenced by surface pits impressed into the dielectric when treated copper (rough copper) was first laminated onto the material under test.

A coaxial probe is used to capacitively couple a stimulus signal to the stripline at one end of the Type A specimen stack, and a second capacitively-coupled probe is used at the other end to measure the signal transmitted by the stripline. The probes are connected to a network analyzer that provides the stimulus signal and measures the transmission parameter S21 as a function of frequency. When set to a broadband sweep of 0.5-20 GHz, the network analyzer records the position of a number of half-wavelength resonances that fall on a grid that is approximately 1 GHz. For this study we selected resonances near 1, 10, and 20 GHz.

To measure the dielectric constant and loss factor at each resonant frequency, the measurement system adjusts the network analyzer frequency to sweep a narrow band centered on each resonant mode of interest. CCN's DkSLR software first acquires the center frequency and quality (Q) factor from the S21 sweep, then computes Dk and Df using the material thickness and the calibration data. This is repeated to obtain Dk and Df measurements at all resonances of interest.

Since we often cannot measure at exactly the frequency points of interest, we fit the measurements made to a wideband Debye model to interpolate our measurements from the resonant peaks closest to the desired test frequency.[10] We have shown that this fitting does not increase the measurement uncertainty beyond the measurement uncertainty calculated at the nearest resonant frequencies.

To estimate a bound on measurement repeatability, we disassembled the fixture and specimen stack and repeated the measurement process to obtain many independent measurements of Dk and Df. Over the materials tested here, we find a 1-sigma repeatability of 0.05 in Dk and 0.0005 in Df.[11]

Measurement Process

The measurement process was as follows:

1. Prepare coupon—including curing prepreg materials in a vented lab oven (no vacuum) with a light plate pressure of 2,000 N/m^2. A thermocouple measured the temperature of the top pressure plate, and the following temperature profile was used:
    a. Ramp-up: 25-205C in 90 minutes
    b. Ramp-down: 205-90C in 60 minutes
    c. Rapid Cool: 90-25C in 30 minutes
    (Internal consistency checks showed this process to be sufficient for emulating PCB fabricator press cycles, where prepregs are cured.)
2. Measure thickness at 5 points or more on coupon using USB micrometer to automatically record readings
3. Insert coupon into test fixture
4. Run Dk and Df measurements at 1, 10, and 20 GHz
5. Repeat Steps 3-4 at least three times per coupon
6. Repeat Steps 1-5 for each coupon in sample
7. Compute average values and standard deviations over sample
8. Compare results to published CCL-vendor values

Measurement Accuracy

A critical objective for this paper was to create an easy to use measurement technique for out-of-plane dielectric properties with high repeatability and accuracy. To assess whether the accuracy and repeatability requirements were met, results were compared against national lab data. For repeatability, we made 24 independent measurements over an eight-day period, computing the mean and standard deviations for both Dk and Df parameters.

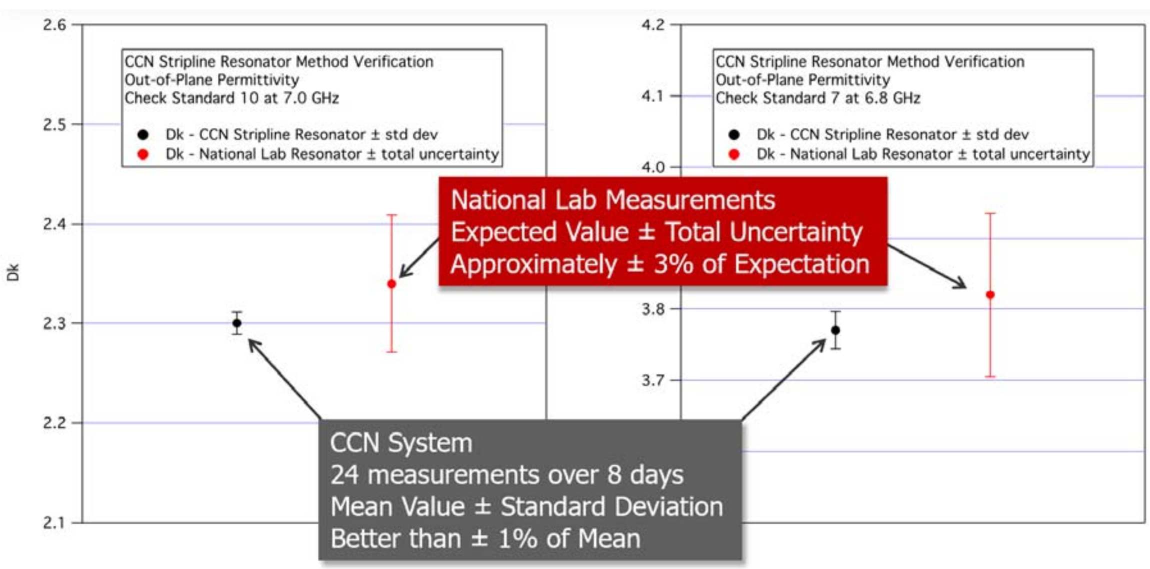

Figure 8: Measurement uncertainty between our test method and national lab measurements for dielectric constant.

Figure 8 shows a favorable comparison between our Dk measurement results and national lab data. Figure 9 shows our Df measurement resolution and repeatability in comparison to national lab data.

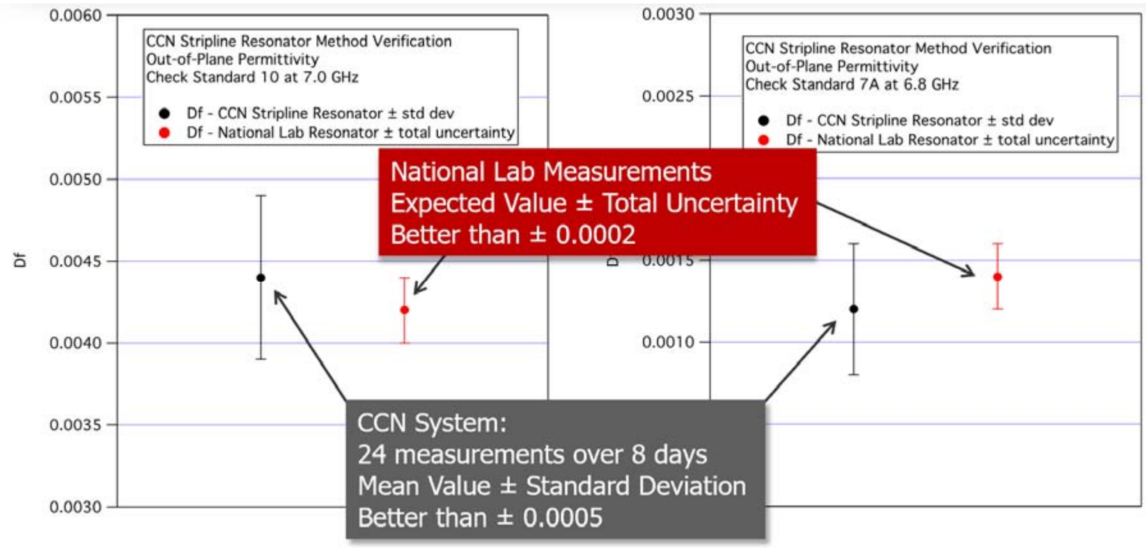

Figure 9: Measurement uncertainty between our test method and national lab measurements for dissipation factor (loss tangent).

These uncertainty comparisons are made periodically between 1-20 GHz, ensuring measurement stability and accuracy.

Published CCL Data

Our purpose with this paper is to benefit the design process, so we were not interested in highlighting or emphasizing one manufacturer versus another. In line with this goal, we gave code names to our samples and only the presenters know what these materials map to.

The nomenclature developed for this study starts with a one or two-digit number corresponding to the testing sequence, which was simply tied to when the material was received.

- Cores were designated with a “C”
- Prepregs were designated with a “P.”
- Single-ply cores were preceded with a “1”
- Dual-ply cores were preceded with a “2.”
- Uncured prepregs use the letter “U.”

Using the above nomenclature system, *published* laminate parameters for Dk and Df at 1, 10 and 20 GHz—for the materials used in this study—are shown in Table 2 below.

ID	Dk 1GHz	Dk 10GHz	Dk 20GHz	Df 1GHz	Df 10GHz	Df 20GHz
01-C2	3.50	3.49	3.49	0.0057	0.0059	0.0059
02-C1	3.50	3.49	3.49	0.0057	0.0059	0.0059
03-P	3.50	3.49	3.49	0.0057	0.0059	0.0059
04-C2	3.65	3.57	3.55	0.002	0.004	0.005
05-C1	3.49	3.41	3.40	0.002	0.004	0.005
07-P	3.47	3.39	3.38	0.002	0.004	0.005
08-C2	3.46	3.38	3.37	0.002	0.004	0.005
09-C2	3.46	3.35	3.32	0.006	0.007	0.008
10-C2	3.57	3.53		0.005	0.008	
11-C1	4.10	4.08	4.06	0.0045	0.0071	0.0075
12-C2	4.10	4.08	4.06	0.0045	0.0071	0.0075
13-C2	3.35	3.50	3.50	0.0012	0.0042	0.0047
14-C2	3.19	3.19	3.19	0.0007	0.0022	
15-C1	3.93	3.9	3.86	0.005	0.007	0.008
16-C2	3.76	3.72	3.68	0.005	0.007	0.008
17-C2		3.28			0.0077	
18-C2		3.21			0.003	
19-C2	3.89	3.86	3.82	0.005	0.007	0.008

Table 2: *Published* laminate parameters for Dk and Df at 1, 10 and 20 GHz—for the materials used in this study.

Using this nomenclature system, published laminate parameters for Dk and Df at 10 GHz and 60 percent resin content—for the materials used in this study—are shown in Figure 10 below.

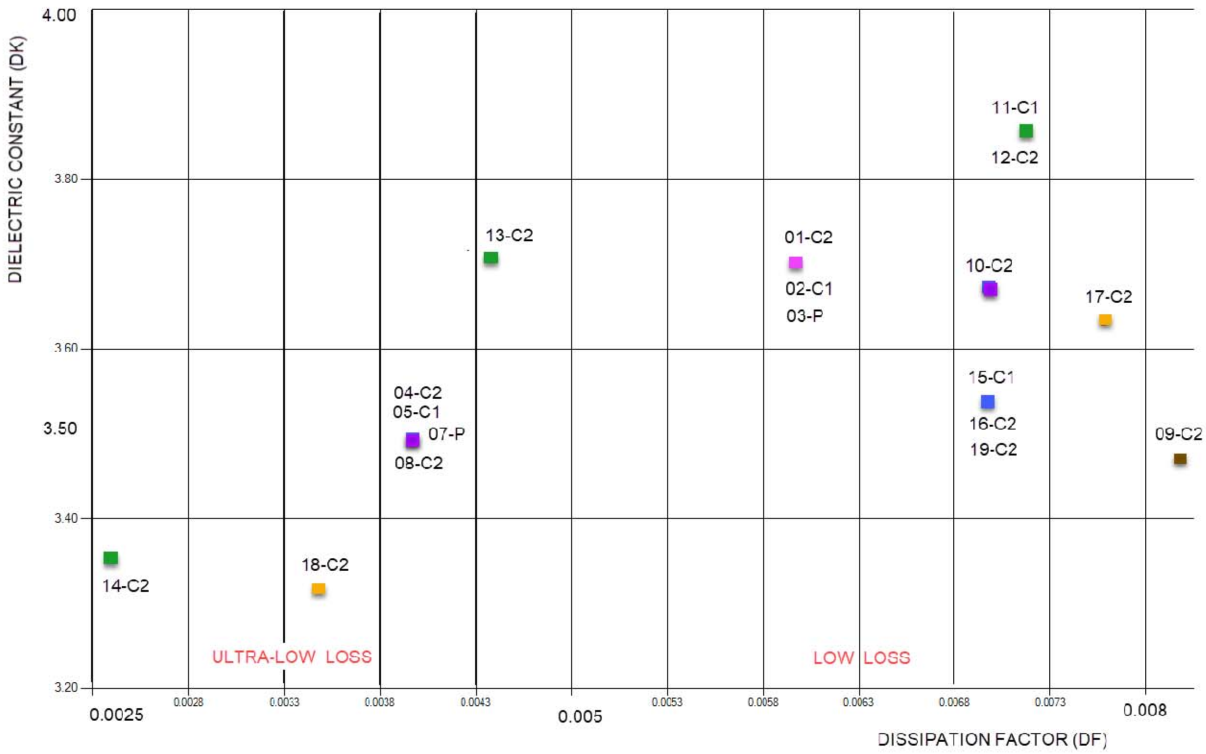

Figure 10: The same nomenclature system is applied to the Z-zero Z-planner Material Mapper, showing published laminate parameters for Dk and Df at 10GHz and 60 percent resin content for the materials used in this study.

Questions and Expected Results

Our goal was to seek answers to the questions noted below:

1) **How closely do published CCL vendor table values for Dk(f) and Df(f) correlate to our calibrated measurements?**
   a) Is there a pattern to the relationship between our *measured* and *published* results?
   b) Is the relationship different at different frequencies?
2) **Dk(f), Df(f) for a similar single-ply core—with copper etched away.** Would a similar construction and resin content—as compared to a cured prepreg—produce similar or identical results?
3) **Dk(f), Df(f) for a similar dual-ply core—with copper etched away.** Would an identical construction and resin content in a dual-ply core—as compared to a single-ply core—produce identical results?
4) **Dk(f), Df(f) for an uncured prepreg.** Of course, there's no such thing as an uncured prepreg in a circuit board, so this question was academic in nature. Our purpose was simply to pull some data from the prepregs that were sent to us before temperature-curing them.
   a) Our expectation was that Dk's for uncured prepregs would generally be higher than cured prepregs, and that Df's would be higher for uncured prepregs, as compared to their cured counterparts.
   b) Another question was whether the relationship between cured/uncured prepregs was consistent across laminate vendors and frequency.

c) A final question—as a potential shortcut for analyzing material characteristics—was to understand how closely uncured prepregs compared to temperature-cured pregs. We weren't optimistic about this one, but thought we would let the data speak for itself.

Measurement Results

As mentioned above, our goal was to learn how different test methodologies align with our calibrated results—with hopes of answering the questions noted below.

The first thing to note is the fact that both *published* and *measured* Df data show relatively little variation within a specific laminate resin system. Changing resin content (%) affects Dk much more significantly than it affects Df. To a lesser extent, the same is true for frequency. As frequency increases, Dk decreases. Df, on the other hand, increases with frequency, though not to the same degree that Dk decreases.

How Closely do Published CCL Vendor Table Values for Dk(f) and Df(f) Correlate to our Calibrated Measurements?

Within specific vendors, there's a consistent pattern in the relationship between published and measured Dk and Df data. We did find *one laminate vendor* whose published Dk and Df data was *relatively closer* to our measurement results, as shown in Table 3 below.

		Dk(f)			Df(f)		
ID	**Source**	**Dk** 1GHz	**Dk** 10GHz	**Dk** 20GHz	**Df** 1GHz	**Df** 10GHz	**Df** 20GHz
17-C2	Published		3.28	No data		0.008	No data
	Measured	3.51	3.47	3.46	0.007	0.007	0.007
	% Difference		5.8%			-12.5%	
18-C2	Published		3.21	No data		0.003	No data
	Measured	3.20	3.19	3.18	0.003	0.003	0.003
	% Difference		-0.6%			0.0%	

Table 3: One CCL vendor's published results were closer to our stripline resonator results than the other vendors—particularly for dissipation factors.

Across all materials and measurements, measured Dks were +/-10% from published values—a 20 percent range—with some vendors and frequencies being closer than others. Transmission-line impedance varies inversely with the square root of Dk. For signal-integrity purposes, it would be advantageous to remove this additional source of uncertainty—both during NPI/prototyping activities and in volume production. Table 4 below shows a CCL-vendor's results that were consistently below our measurements.

		Dk(f)		
ID	**Source**	**Dk** 1GHz	**Dk** 10GHz	**Dk** 20GHz
11-C1	Published	4.10	4.08	4.06
	Measured	3.77	3.73	3.72
	% Difference	-8.0%	-8.6%	-8.4%
12-C2	Published	4.10	4.08	4.06
	Measured	3.77	3.74	3.72
	% Difference	-8.0%	-8.3%	-8.4%
13-C2	Published	3.35	3.50	3.50
	Measured	3.27	3.26	3.25
	% Difference	-2.4%	-7%	-7.1%
14-C2	Published	3.19	3.19	3.19
	Measured	3.12	3.11	3.10
	% Difference	-2.2%	-2.5%	-2.8%

Table 4: These results show that this particular CCL vendor's published Dk results were consistently below our stripline resonator results. For example, 11-C1 Dk(10GHz)-published is 8.6% above our Dk(10GHz)-measured.

To provide an idea of the impedance implications for accurate Dk values, we mocked up a symmetrical stripline model with 5-mil thick dielectrics and a 5-mil wide trace in the Z-zero Field-Solver Sandbox™ software using the HyperLynx® field solver. Using the measured Dk value at 1 GHz for material 12-C2 above, the stripline impedance was 49 Ohms. Using the published Dk of 4.1 produced a 47 ohm impedance. Your design may be able to survive a 2 ohm difference, but this difference will be in addition to other tolerances and manufacturing variations, which can pose problems if all of the variance works in the same impedance direction. Our view is that giving away this accuracy when it's so easily avoidable is a bad design practice.

One of the more significant findings from this study is the degree to which published Df values—across all but one CCL vendors—diverged from our stripline-resonator results. These differences varied in magnitude, but always in the same direction: vendor-published values were always substantially below our measurements. The Df differences were particularly striking at 1 GHz—ranging from 33% for material 09-C2 to 200% for material 14-C2, as shown in Table 5 below.

To get an idea of the propagation-loss implications for underestimating Df, we'll use the same stripline configuration noted above for Material 04-C2. Including loss due to copper, assuming copper foil with Rz=5 um roughness, the *published* Df data results in propagation loss of 0.15 dB/inch. The same stripline with the measured Df (0.004) results in an insertion loss of 0.16 dB/inch. Perhaps even more important than the propagation-loss implications is the fact that there is significant price variation between materials with different dissipation factors. If simulations show that actual Dfs at frequencies of interest provide acceptable performance, designers can save a good bit of money by ensuring that laminate alternatives are compared on an "apples-to-apples basis.

Df(f)

ID	Source	Df 1GHz	Df 10GHz	Df 20GHz
14-C2	Published	0.001	0.002	No data
	Measured	0.003	0.003	0.003
	% Difference	200%	50%	
09-C2	Published	0.006	0.007	0.008
	Measured	0.008	0.008	0.008
	% Difference	33.3%	14%	0%

Table 5: The Df data in the last few columns above show the range of differences between published and measured values—particularly at 1 GHz.

CCN, NIST and others have shown that both 2.5.5.13 and 2.5.5.5.1 are capable of Df measurements within 0.001, so it's not immediately clear where the under-reporting of published values is coming from. One possibility is that the variation may be rooted in the fact that no well-established calibration standards exist that would tell a measurement technician whether their equipment and methodology are dialed in properly. The fact that some of the published numbers are so far off, seems to imply a broader set of causes than simply calibration, however.

Since dielectric loss varies directly with dissipation factor, there's a significant risk that the loss-budgeting process can be compromised through the use of these potentially-under-reported dissipation factors. The potential problem is further exacerbated by the fact that dielectric loss also varies with the square root of the dielectric constant. Knowing these values—at the proper frequencies of interest—is critical when optimizing material choices where dielectric loss and material cost are concerned.

Measurement Variation between Similar Prepregs and Cores

For the same laminate resin system with identical constructions (i.e., the same resin system, glass style, and resin content) our measurement data showed strong similarities between cured prepregs and both single- and dual-ply cores of the same construction, as shown in Table 6 below.

Three sets of materials in this study offered the opportunity for us to make some comparisons here, grouped as Vendors A, B and C in Table 6. For the same resin system with identical constructions (including glass style and resin content), the differences between 1- and 2-ply cores wasn't statistically significant. Differences between identically-constructed cores and temperature-cured prepregs were just barely above a level of significance.

ID	Source	Dk 1GHz	Dk 10GHz	Dk 20GHz	Df 1GHz	Df 10GHz	Df 20GHz
	Similar Core/Prepreg Constructions - Vendor A						
01-C2	Published	3.50	3.49	3.49	0.006	0.006	0.006
	Measured	3.52	3.47	3.46	0.009	0.010	0.010
02-C1	Published	3.50	3.49	3.49	0.006	0.006	0.006
	Measured	3.49	3.44	3.43	0.009	0.010	0.010
03-P	Published	3.50	3.49	3.49	0.006	0.006	0.006
	Measured	3.57	3.51	3.49	0.011	0.011	0.011
	Similar Core/Prepreg Constructions - Vendor B						
04-C2	Published	3.65	3.57	3.55	0.002	0.004	0.005
	Measured	3.53	3.51	3.50	0.004	0.004	0.004
05-C1	Published	3.49	3.41	3.4	0.002	0.004	0.005
	Measured	3.53	3.51	3.50	0.004	0.004	0.004
07-P	Published	3.47	3.39	3.38	0.002	0.004	0.005
	Measured	3.49	3.47	3.46	0.004	0.004	0.004
	Similar Core/Prepreg Constructions - Vendor C						
11-C1	Published	4.10	4.08	4.06	0.005	0.007	0.008
	Measured	3.77	3.73	3.72	0.007	0.007	0.007
12-C2	Published	4.10	4.08	4.06	0.005	0.007	0.008
	Measured	3.77	3.74	3.72	0.007	0.007	0.007

Identical (01-C2, 02-C1, 03-P); Identical (04-C2, 05-C1, 07-P); Identical (11-C1, 12-C2)

Measured Dk exhibited more variation than Df between similarly-constructed cores and prepregs.

Table 6: Measured Dk and Df results across three different laminate vendors shows a strong similarity between similarly-constructed prepregs and single- and dual-ply cores. Results from similar 1- and 2-ply cores were extremely close, in fact.

Ranked by order of importance, Dk differences were primarily driven by: (1) the resin system (material name), (2) resin content (%), and (3) cores vs. prepregs.

To be thorough, it would be best to measure all constructions in use, but a measurement shortcut may be to measure one of these three constructions (i.e., identically constructed prepreg, single- and dual-ply cores with the same glass style and resin content), reusing the data. Our research indicates that the correlation within identical constructions will be closer than the correlation between our measurements and publicly available-manufacturer data.

Comparing Measurement Methodologies

Vendor-supplied Dk and Df values use multiple measurement methodologies, as noted in Table 1. The volume of data from this particular study is not sufficient for drawing statistical conclusions relative to the different test methodologies. Nevertheless, we can make some high-level comments and assessments.

Our measurement results, as compared to vendor-published results did not show a consistent pattern of Dk variation as a result of differing measurement methods. The results vary, but not necessarily in a manner that correlates to the test methodology itself.

It was, however, noted in Table 4 that one vendor's published Dks varied more widely from our results than the others, suggesting calibration as a possible concern.

Cured vs. Uncured Prepregs

One set of cured vs. uncured prepregs in our research *increased* Dk and Df with curing, while another material *decreased* Dk and Df with curing. Our measurement results, represented by Table 7 below, do not lead us to believe that there's a consistent relationship between uncured and cured prepregs that would allow designers to be able to rely upon uncured prepreg measurements for out-of-plane Dk and Df values.

ID	Source	**Dk** 1GHz	**Dk** 10GHz	**Dk** 20GHz	**Df** 1GHz	**Df** 10GHz	**Df** 20GHz
	Vendor A						
03-P	Published	3.50	3.49	3.49	0.006	0.006	0.006
	Measured	3.57	3.51	3.49	0.011	0.011	0.011
03-U	Measured	3.66	3.57	3.54	0.018	0.018	0.018
	Vendor B						
07-P	Published	3.47	3.39	3.38	0.002	0.004	0.005
	Measured	3.49	3.47	3.46	0.004	0.004	0.004
06-U	Measured	3.31	3.30	3.29	0.003	0.003	0.003

Table 7: Comparisons between measured Dk and Df results across two laminate vendors does not show a consistent, predictable relationship between uncured and temperature-cured prepregs. Uncured prepregs are annotated with a "U" in their material IDs.

Conclusions and Key Takeaways

The methodology developed in support of this paper has the potential of eliminating significant sources of uncertainty associated with the use of dielectric constant (Dk) and loss tangent values from multiple PCB laminate- and fabrication-supplier sources and test methods.

Published Dk values varied +/- 10 percent from our measurement results—a 20% range. Dk variation and uncertainty needs to be further measured and modeled for improved signal-integrity analysis. It's not immediately clear why published values for Dk differ significantly from the calibrated, in-plane results from this study. Manufacturing variation, slight formulation changes, sample size—both for published and as a matter of ongoing sampling, and measurement-equipment calibraton are all considerations. More data needed in order to draw conclusions regarding statistical significance.
This study raised serious questions regarding vendor-published Df values. Across all vendors and measurement methods, vendor-published values fell significantly below our results. Differences at 1 GHz proved to be particularly significant. Since material selection (cost vs. loss) and loss planning are both based upon Df values, this has potentially-critical implications, both for signal integrity and cost control in volume production.

Using the stripline-resonator technique highlighted in this study, the same reliable Dk and Df test method can be used for apples-to-apples comparisons during the laminate selection process, to acquire valid Dk and Df functions for design, and to monitor the supply chain during production. For a reasonable upfront and ongoing investment, the proposed solution offers laminate (CCL) vendors, PCB fabricators, ODMs and OEM design teams a means of ensuring that the electrical parameters that they're designing with are what they'll be getting in volume production, and that they're able to compare laminate properties on an "apples-to-apples" basis.

Acknowledgements

In this study, we represented a cross section of laminates and laminate manufacturers in both North America and Asia. This objective was possible through the support of both PCB fabricators and laminate manufacturers on both sides of the Pacific, including the following companies who care enough about accurate material characterization and test-methodology accuracy to contribute test samples:

- APCT in San Jose, CA (www.apctinc.com)
- Sierra Circuits, Sunnyvale, CA (www.protoexpress.com)
- Matrix Circuit Board Materials, Irvine, CA (www.matrixelectronics.com)
- Nan Ya Plastics, Taipei, Taiwan (www.npc.com.tw)
- Park Electrochemical, Fullerton, CA (www.parkelectro.com)
- Shengyi Technologies, China (www.shengyi-usa.com)

It's also important to note that many more laminate manufacturers were represented in this study than those mentioned above, and we were careful to separate specific vendors from published and measured results comparisons in this study. We are deeply grateful for the support of the companies mentioned above, as well as their commitment to moving the industry forward on the dielectric-characterization front.

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