High Frequency Dk & Df Test Methods Comparison
High Density Packaging User Group (HDP) Project

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Abstract

The High Density Packaging (HDP) user group has completed a project to evaluate the majority of viable Dk (Dielectric Constant)/Df (Dissipation Factor) and delay/loss electrical test methods, with a focus on the methods used for speeds above 2 GHz. A comparison of test methods from 1 to 2 GHz through to higher test frequencies was desired, testing a variety of laminate materials (standard volume production with UL approval, low loss, and "halogen-free" laminate materials). Variations in the test board material resin content/construction and copper foil surface roughness/type were minimized.

Problems with Dk/Df and loss test methods and discrepancies in results are identified, as well as possible correlations or relationships among these higher speed test methods.

An example of present difficulties with the variety of test methods used for the same laminate material:

a) Cavity resonator method at 10 GHz: Df = 0.008
b) SPP Df test data at 6 GHz: Df = 0.006 to 0.0075
c) IPC TM 2.5.5.5, 2-20 GHz Stripline, Panasonic Method
(3 layer stripline TV, 2x1078 dielectrics ~65% RC, 0.15 mm core):
E-Glass Foil Type P using E-glass: Df = 0.003 to 0.006
Foil Type P using NE-Glass: Df = 0.002 to 0.005
Foil Type R using E-Glass: Df = 0.004 to 0.007
Foil Type R using NE-Glass: Df = 0.003 to 0.006
d) IPC TM-650, 2.5.5.9, Laminator published data sheet [1 GHz, 54% RC]: Df = 0.002

The above shows a range of Df from 0.002 to 0.008 depending upon the test method and frequency used. Dk measurement methods have similar disparities.

Introduction

Currently, although there are many standard IPC test methods, there is no industry commonality in the actual methods used to evaluate high frequency laminate materials for dielectric loss (Df) and dielectric constant (Dk). As the industry moves to higher clock speeds, the probes used can become a significant part of the signal path and impact the accuracy of the measurements taken. This project was designed to characterize the different high frequency test methods regularly used by laminators, fabricators or OEM's, and to develop correlations for understanding the differences of each of these processes.

Project Plan

The project considered up to 18 different in-production materials, ranging in supplier advertised Dk from 3.3 to 4.7 and Df from 0.003 to 0.0180 , using all test methods designed into the test vehicle at various frequencies (2 GHz, 10 GHz, and up to 30 GHz if possible). When possible, multiple test facilities were used for the same test method to determine the repeatability.

Project goals included gaining a better understanding of the types of testing and the frequency limits of each type of test. The results of this project are not anticipated to eliminate any of the current test methods, but should allow more informed discussions between material suppliers and OEM's concerning the appropriate laminate material(s) suitable for a given high frequency board application.

The primary goal of this project was to compare the most commonly used high frequency Dk/Df and loss test methods in the industry over a wide range of laminate materials. The variety of test method coupons fit into the same bare board panel design, and the coupons for each test were depanelized prior to being shipped to the appropriate test facility. About half of the laminate materials used for this project were halogen-free. The test board construction, material resin content, copper foil type and surface roughness were kept constant or very similar across all laminate materials. As much as practical, all other variables were carefully controlled to facilitate the determination of accurate correlation(s) between the various test methods. After baking, the tested dry samples compared with as-received test coupons had a very slight reduction in Dk, and about a 10 to 15 percent reduction in Df when dry.

Test Board Design

The test board construction had six layers total, inner layers half-oz RTF copper foil, and finished test board thickness of 0.0313 +/- 0.0022 inches thickness glass-glass. For test coupons with traces, the trace width was either 0.0055 inches or slightly adjusted to meet 50 ohms characteristic impedance, depending upon the location (one of each per test board). For this project, two printed circuit board manufacturers shared in building the high frequency test boards, each making more than half of the different laminate materials selected for these test board builds.

Twelve different test method coupons were all made to fit into the same test vehicle, to ensure the most direct comparisons of test methods. These included:

EBW (IPC 2.5.5.12, Method A); coupon 0.35" x 5.0", GND via area free of solder mask
Split Post Dielectric Resonator cavity; coupon 2.0” x 8.0”, free of solder mask
SPP (IPC 2.5.5.12, Method C); coupon 1.4” x 3.3”, no solder mask coating
Stripline Test at X-Band (IPC 2.5.5.5.1); coupon 2.0” x 2.75”
Tri-Plate Resonator (JPCA TM0001); coupon 2.0” x 8.0”, no solder mask coating
Custom 4-Port VNA testing (Intel); coupon 4.7” x 0.6”, no solder mask coating
DC Resistance testing; coupon 3.5” x 1.5”
S-3 (CISCO), Stripline S-Parameter Sweep, 40 GHz; coupon 1.5" x 15.0"
Bereskin Stripline (Isola); coupon 1.5" x 5.0", no solder mask coating
SET2DIL (IPC 2.5.5.12, Method D); coupon 0.6"x 4.7", no solder mask coating
SPC Resonator (NIST); coupon 100mm x 100mm, no solder mask coating
SUM-DISK (Fujitsu); coupon 50mm x 50mm, no solder mask coating

Standard Laminator IPC 2.5.5.5 and/or 2.5.5.9 Dielectric Sheet data Propagation Delay Testing was not included.

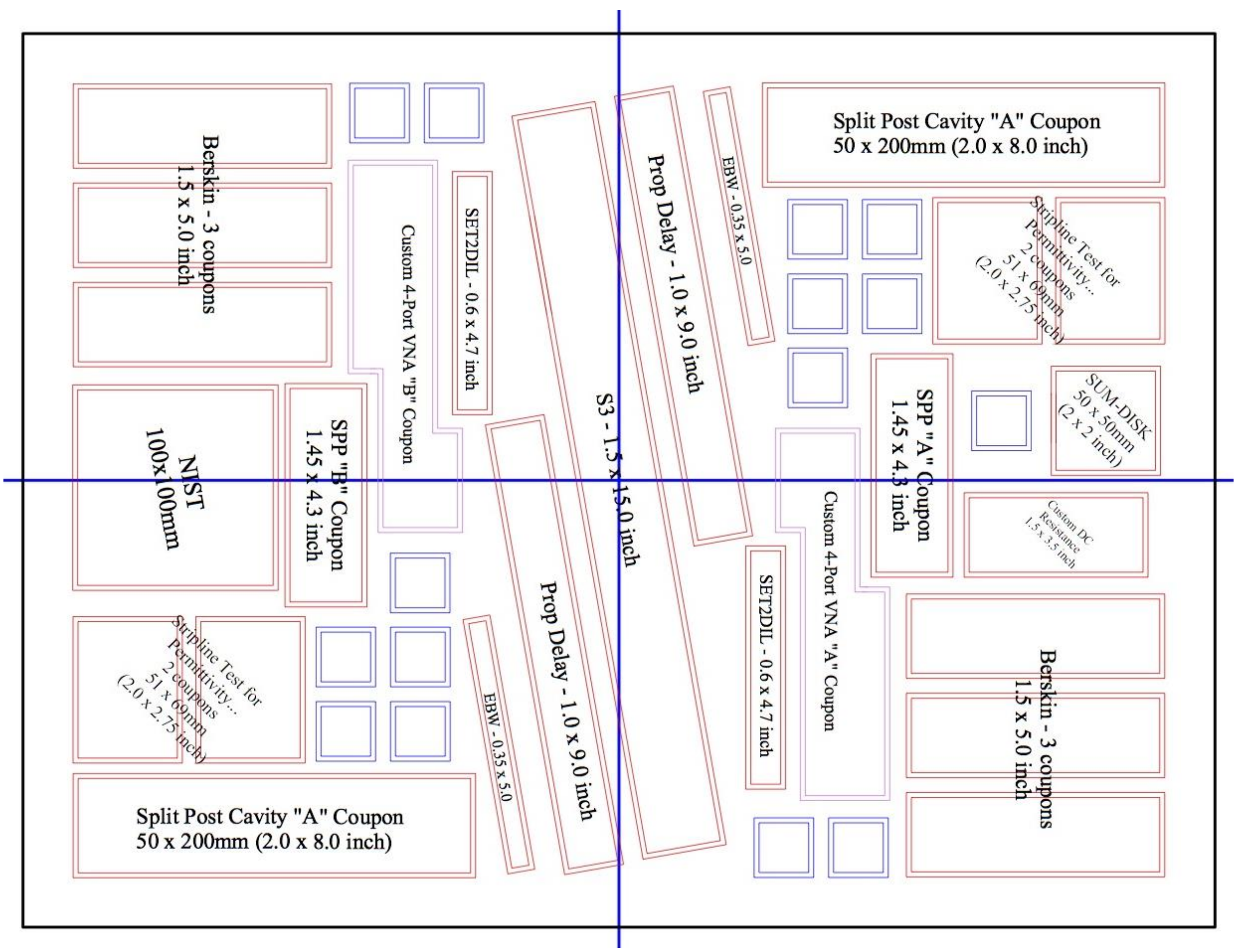


Figure 1 – Initial Test Board Layout

Experimental

When the Dk/Df and loss testing first began, it was found that some test boards had solder mask and/or silkscreen legend marking on the coupon areas required to be free of solder mask and marking materials. This issue was fixed on all subsequent builds. The IPC Stripline Test coupon however (IPC 2.5.5.5.C) was missing the test traces themselves, and therefore this test method was dropped.

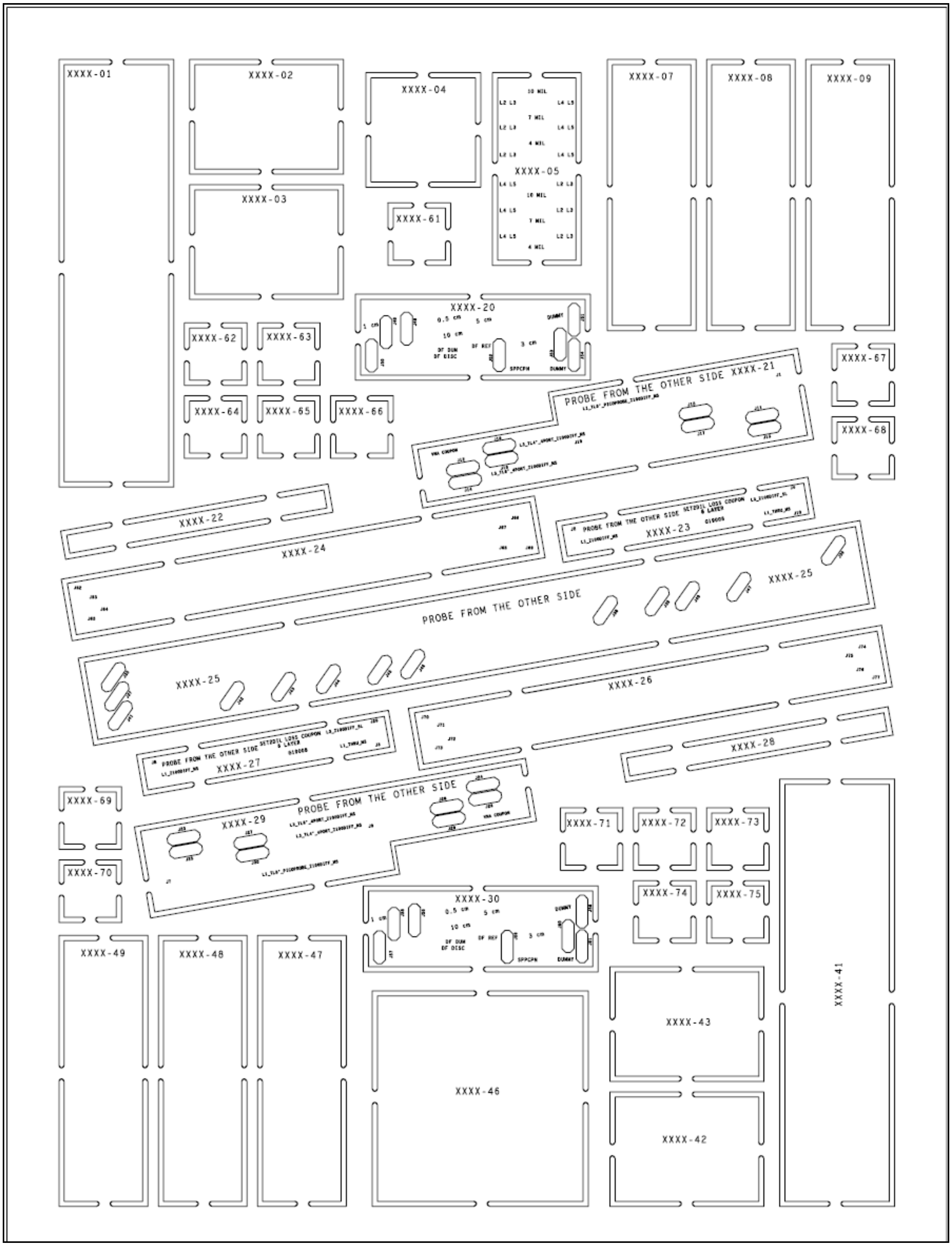


Figure 2: Final Test Board Layout

Experimental, cont.

The probes used for higher speed testing can be a significant part of the signal path and impact the accuracy of the measurements taken. Calibration before testing was required. Particularly for trace/conductor based test methods, a defective or contaminated coupon can significantly damage a probe in a single application, and/or significantly affect the results.

During the testing phase, participating member S. Kikuchi of Fujitsu Advanced Technologies, Fujitsu Ltd., provided the following classification for the high frequency test methods. As illustrated in figure 3 for a single material example, the Z-Direction type test coupons tend to give the lowest Dk values for a laminate material. The test method coupons with patterns inside them like SPP and S-3 tend to measure higher Dk values. The In-Plane type coupons give the highest Dk values in a Dk versus frequency graph.

* Z-Direction Test Coupons (Dk/Df extraction)
    Tri-plate Resonator, 2.0" x 8.0"   JPCA TM001
    Bereskin Stripline, 1.5" x 5.0" or 1.25" x 4.0"   Isola
    SUM-DISK, 50 mm x 50 mm (up to 67 GHz)   Fujitsu

* Trace/Conductor Based (Dk/Df extraction, 50 ohms SE impedance)
    SPP, 1.4" x 4.3" (3.94, 1.97, 1.18, 0.40, 0.20 inches) IPC 2.5.5.12 (1.3, Method C)
    S-3_Cisco 1.5" x 16.0" (trace lengths: 14.0, 9.5, 2.176, 0.872, etc. inches)
    4-Port VNA, 0.6" x 4.7" (long trace: 6.0005", short trace: 4.0002")

* In-Plane Test Coupons (Dk/Df extraction)
    Split Post Dielectric Resonator (up to 20 GHz)
        Transverse Electric (calibration, sample position & TE mode critical)
        Transverse Magnetic – QWED, Agilent (3x150mm)   EMC

* Trace/Conductor Based (overall delay or loss only)
    EBW, 0.35" x 5.0" (trace lengths 4.019, 3.961 inches)   IPC 2.5.5.12 (1.1, Method A)
    SET2DIL, 4.0" x 7.0" (trace length: L1,3=8.01"; L2=7.89")   IPC 2.5.5.12 (1.4, Method D)

Reference:
    Signal Loss on Printed Boards   IPC 2.5.5.12
    Propagation Delay by TDR   IPC 2.5.5.11
    Split Post (Resonant) Cavity (up to 20 GHz)   IPC 2.5.5.6
    Stripline Resonator, 2.0" x 8.0" (up to 30 GHz)   IPC 2.5.5.5.1
    Parallel Plate Capacitance (up to 1.5 GHz)   IPC 2.5.5.9
    Cavity Resonator Perturbation (up to 20 GHz)   JIS C-2565

This classification has proven helpful in explaining the statistical correlations between the test methods which have been found. Figure 3 shows how the Dk/Df extraction test methods may be grouped.

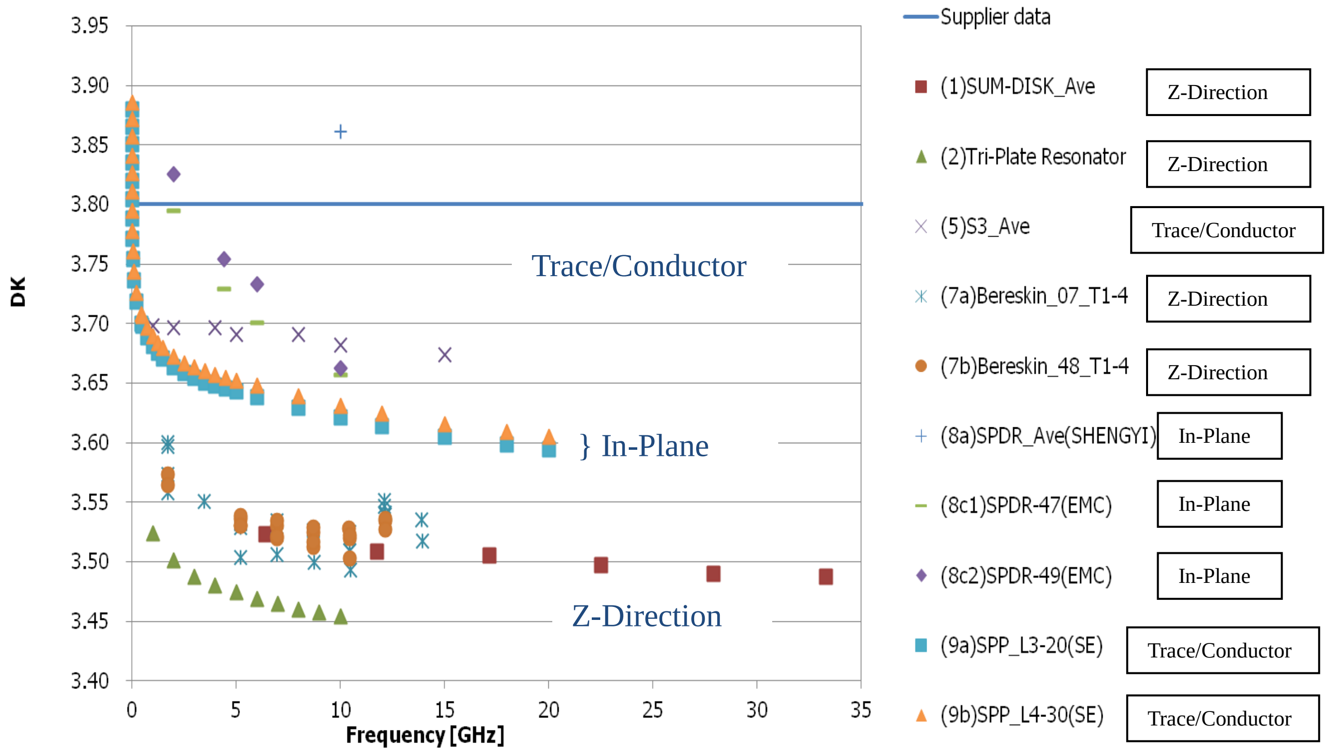


Figure 3 – Comparison of Dk Results by Test Method (for single material)

The Dk/Df extraction test results shown in Figure 3 show Z-Direction measurements all lower than the Dk/Df extraction Trace/Conductor measurements. Also the In-Plane measurements are all higher than these Trace/Conductor measurements.

Laminate Materials

A variety of laminate materials were considered for testing using the various high frequency test methods. Of these, 17 were selected to cover a wide but still representative range of Dk and Df values for the test methods to measure. In order to best compare the high frequency test methods, the test coupons would be made as much as possible with the same board construction and copper foil types.

The following table (figure 4) shows the actual dielectric constructions used for each laminate material. Some laminate material core constructions could not be made exactly the same. The F1 and F2 column indicates the two different fabricators of the test boards.

	Laminate Materials	Core Construction	% Resin Content - Core	Prepreg Construction	% Resin Content-Prepreg	Cu Foil	50 ohm L4 Impedance Trace Width
F2	L01	2x1080	64	2x1080	63	.5/.5 RTF	4.2
F2	L02	2x1080	64	2x1080	63	.5/.5 RTF	4.5
F1	L03	1080/3313	56	2x1080	64	.5/.5 DSTF	5.2
F2	L03	1080/2113	56	2x1080	66	.5/.5 RTF	4.3
F2	L04	2x1080	63	2x1080	63	.5/.5 RTF	5.3
F2	L05	2x1080	62	2x1080	62	.5/.5 RTF	5.3
F2	L06	2x1080	63	2x1080	63	.5/.5 RTF	5.2
F2	L07	2x1080	64	2x1080	64	.5/.5 RTF	6.0
F2	L08	2116	54	2x1280	64	.5/.5 RTF	4.7
F1	L09	2x1080	63	2x1080	63	.5/.5 HVLP	6.0
F2	L09	2x1080	63	2x1080	64	.5/.5 RTF	3.8
F2	L10	2x1280	62	2x1280	62	.5/.5 RTF	3.7
F1	L11	2x1080	64	2x1080	65	.5/.5 RTF	6.9
F1	L12	2x1080	63	2x1080	65	.5/.5 RTF	6.5
F1	L13	2x1080	64	2x1080	64	.5/.5 HTE Elong	5.0
F1	L14	2x1080	63	2x1080	65	.5/.5 RTF	5.8
F1	L15	2x1080	64	2x1080	64	.5/.5 RTF	5.3
F1	L16	1506	44	2x1080	65	.5/.5 RTF	5.0
F1	L17	1501	46	2x1080	65	.5/.5 RTF	5.0
F1	L17	1501	46	2x1080	65	.5/.5 RTF	5.0

Figure 4 – Comparison of Laminate Material Board Constructions

The following figure 5 plot shows the Dk and Df as listed on laminate material supplier's own data sheets for the laminate materials used in this testing. The work of manufacturing the test boards was divided between two fabricators, with each having about the same spread of low versus high Dk/Df materials.

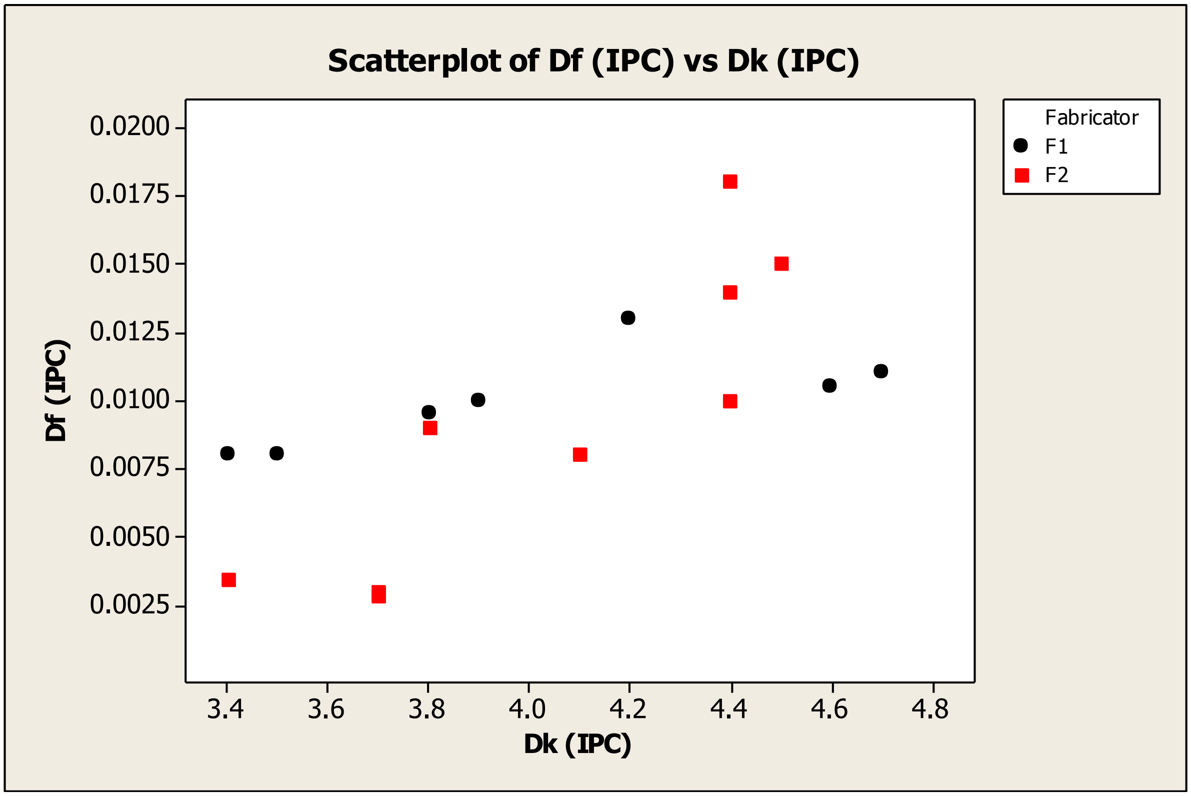


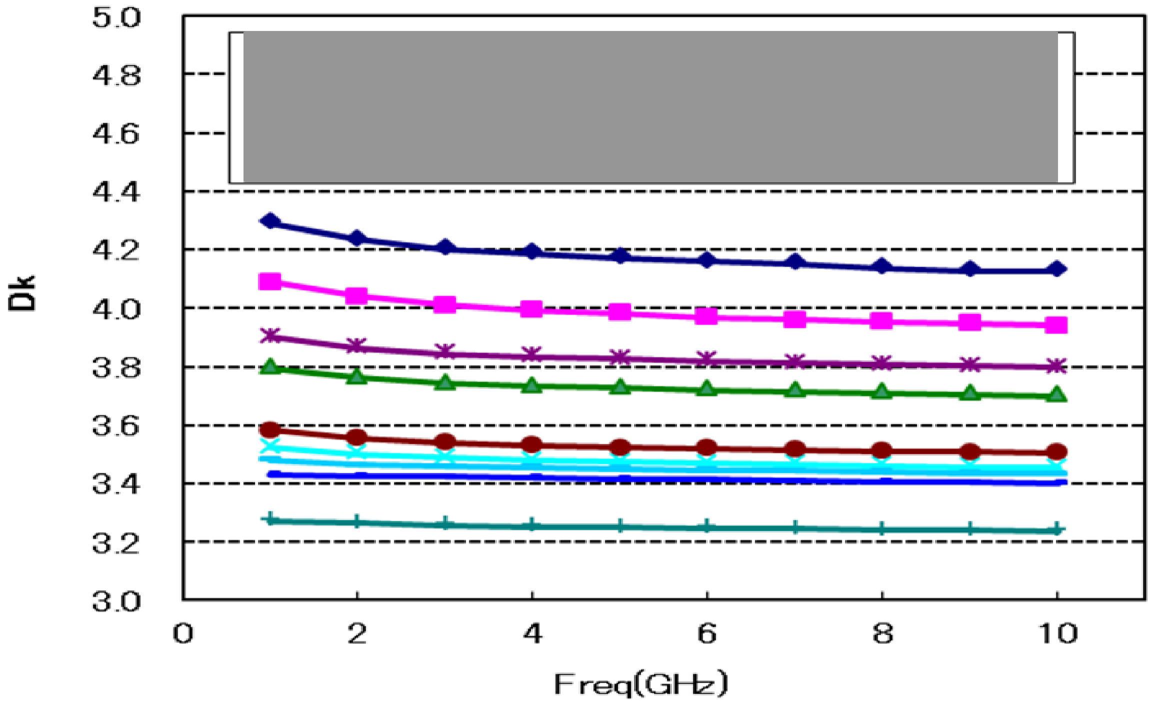
Figure 5 – Scatterplot of laminator data sheet Dk and Df for each material

Sample Preparation

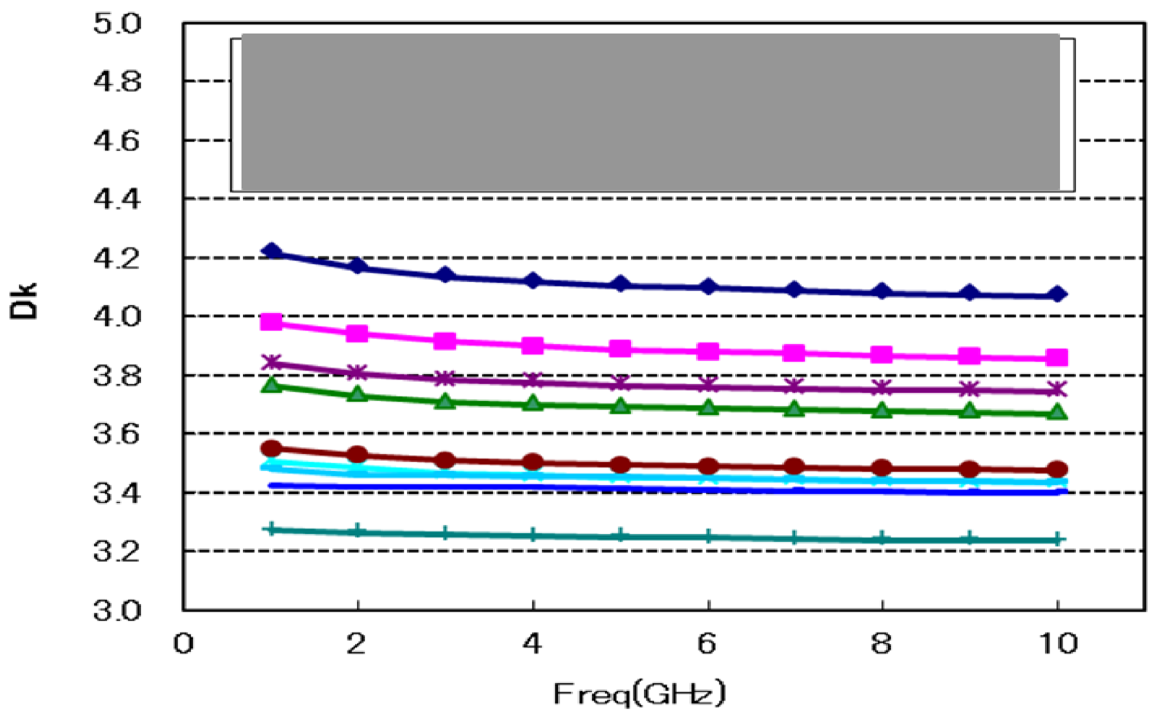
Two test coupons were used for most test methods. For trace/conductor based test methods, one coupon was maintained at a constant trace width and spacing and the other required trace width and spacing adjustments depending upon the laminate material Dk to achieve the 50 ohms single-ended and 85 ohms differential pair impedance specified.

Results

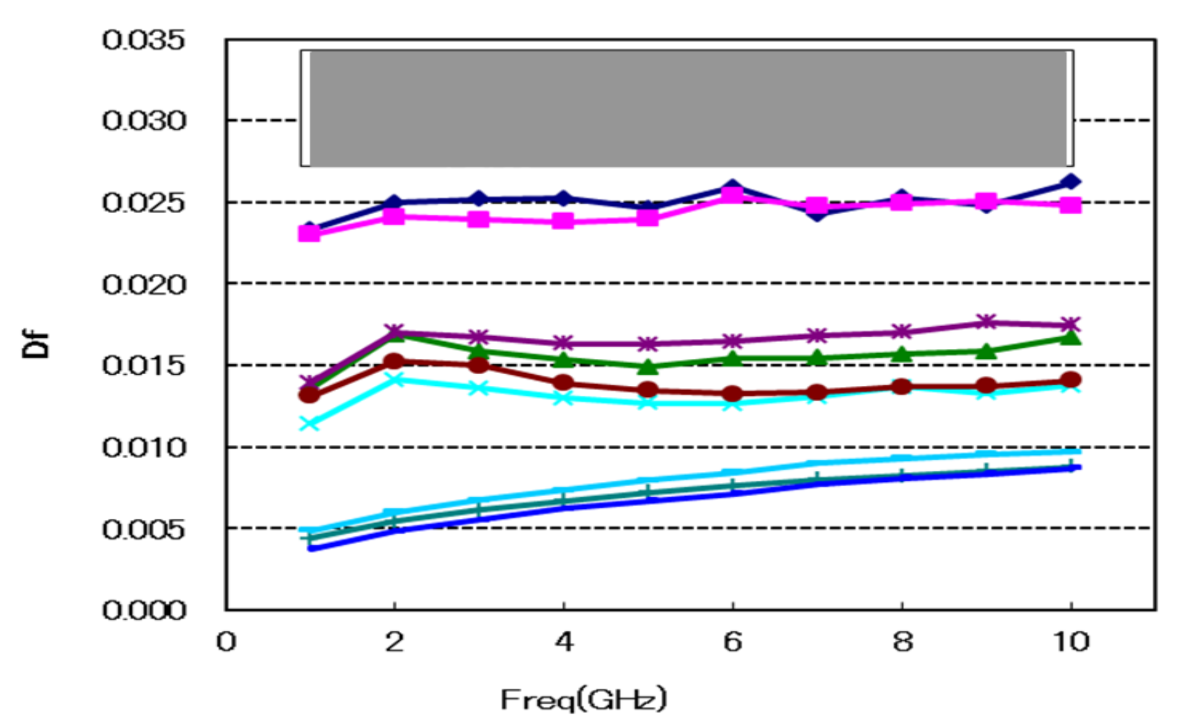
All coupons were tested in the as-received condition. Some coupons were also tested after baking until dry. The baked dry coupons measured Dk ranging from none to 3 percent lower compared with the As-Is test coupons. The baked dry coupons measured Df ranging from none to 20 percent lower compared with the As-Is test coupons. The following Tri-Plate Resonator (JPCA TM001) test results (figures 6-9) show how the amount of moisture present in a laminate material can affect Dk and Df test results.



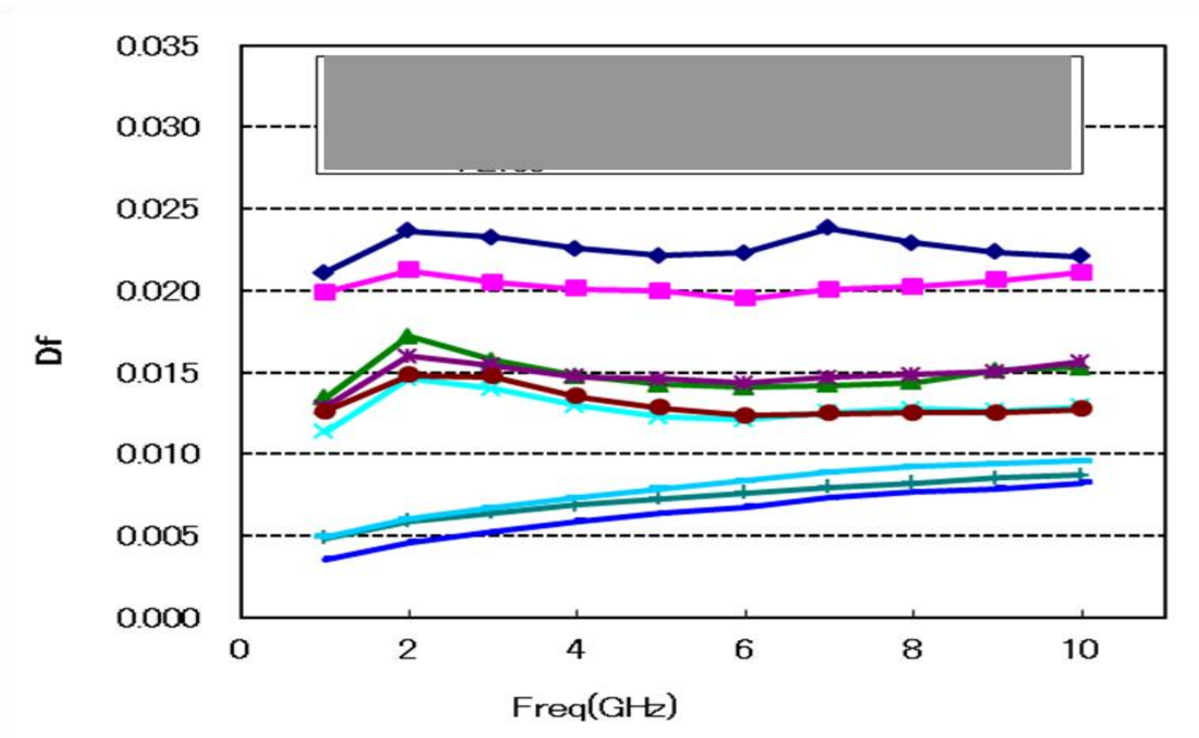
Dk as Received (Figure 6)



Dk after Bake Dry (Figure 7)

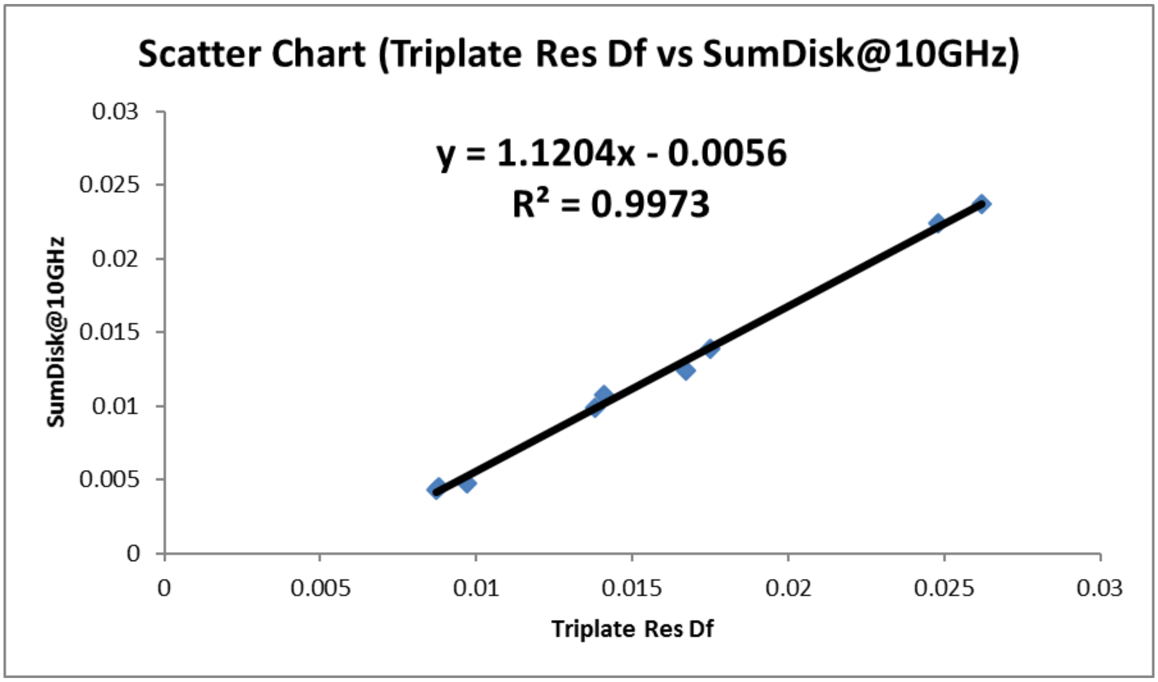


Df as Received (Figure 8)



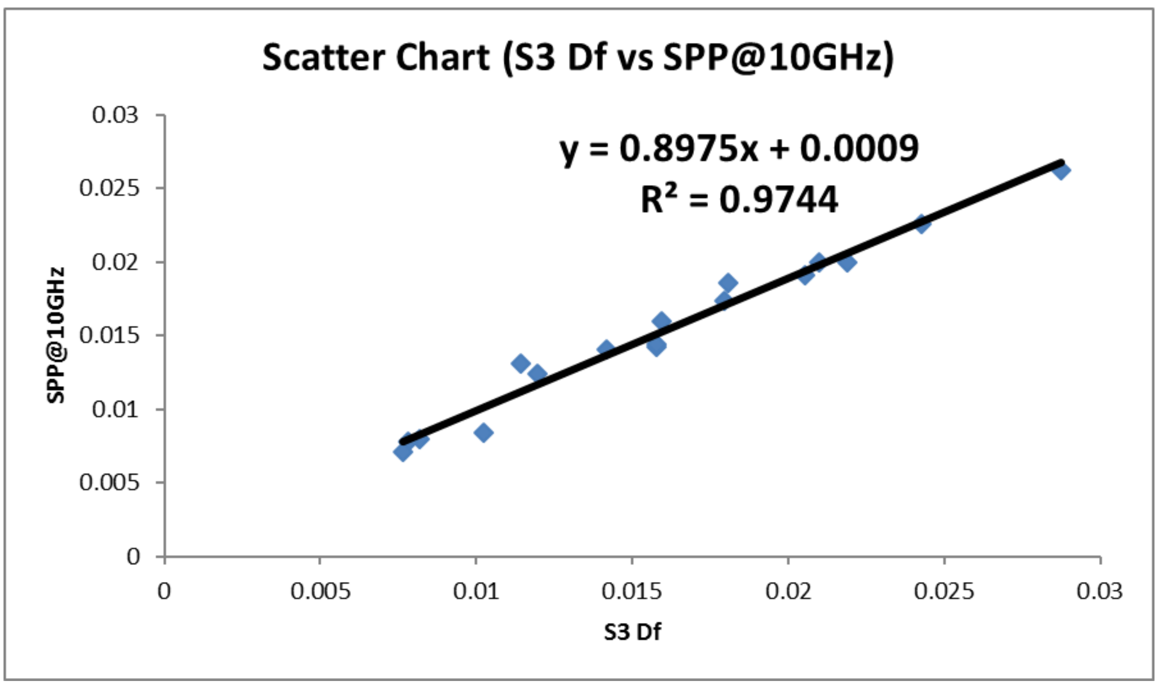
Df after Bake Dry (Figure 9)

The Dk/Df extraction trace/conductor based test method Dk and Df results tended to fall between those test methods measuring Dk and Df primarily in the Z or vertical direction (SUM-DISK) and those measuring Dk and Df primarily in the X-Y plane (Split-Post Dielectric Resonator). The Z-Direction test methods showed very good correlation, even for Df (see Figure 10).



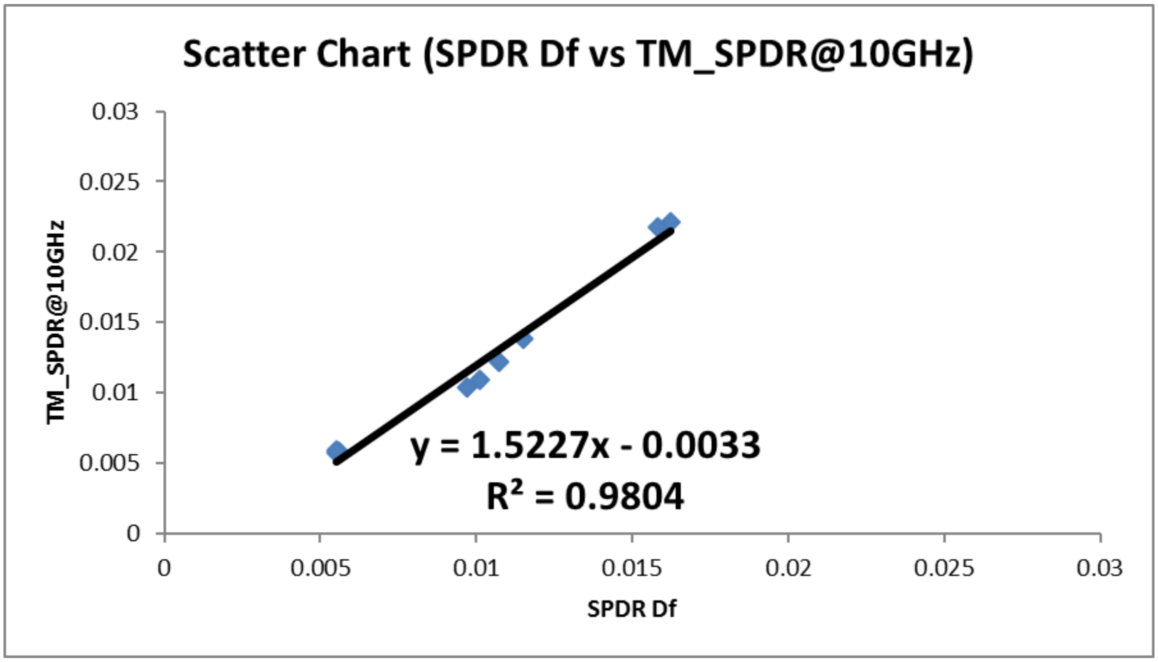
Z-Direction Test Method Df Correlation (Figure 10)

The SPP and S-3 Trace/Conductor test methods showed good correlation (see Figure 11).



Trace/Conductor Test Method Df Correlation (Figure 11)

The In-Plane Test Coupon test methods showed very good correlation, even for Df (Figure 12).



In-Plane Test Coupon Test Method Df Correlation (Figure 12)

In comparison, the correlations of the various test methods had considerably more variation when compared with each laminate material suppliers' published Dk and Df values (Figures 13 and 14).

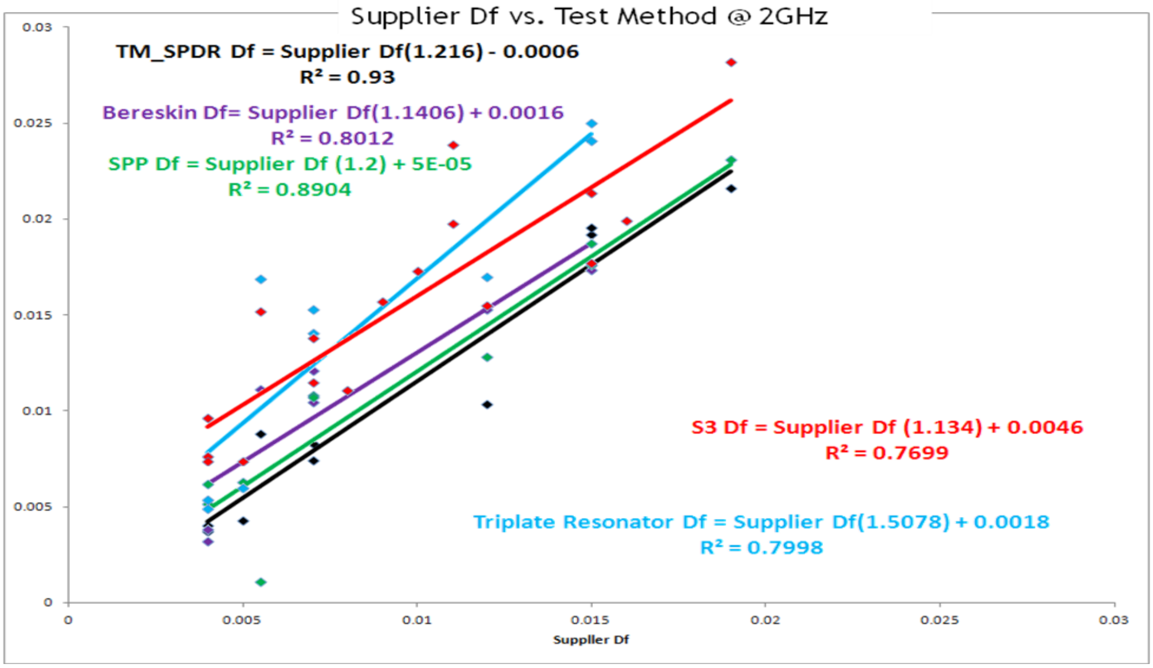


Figure 13

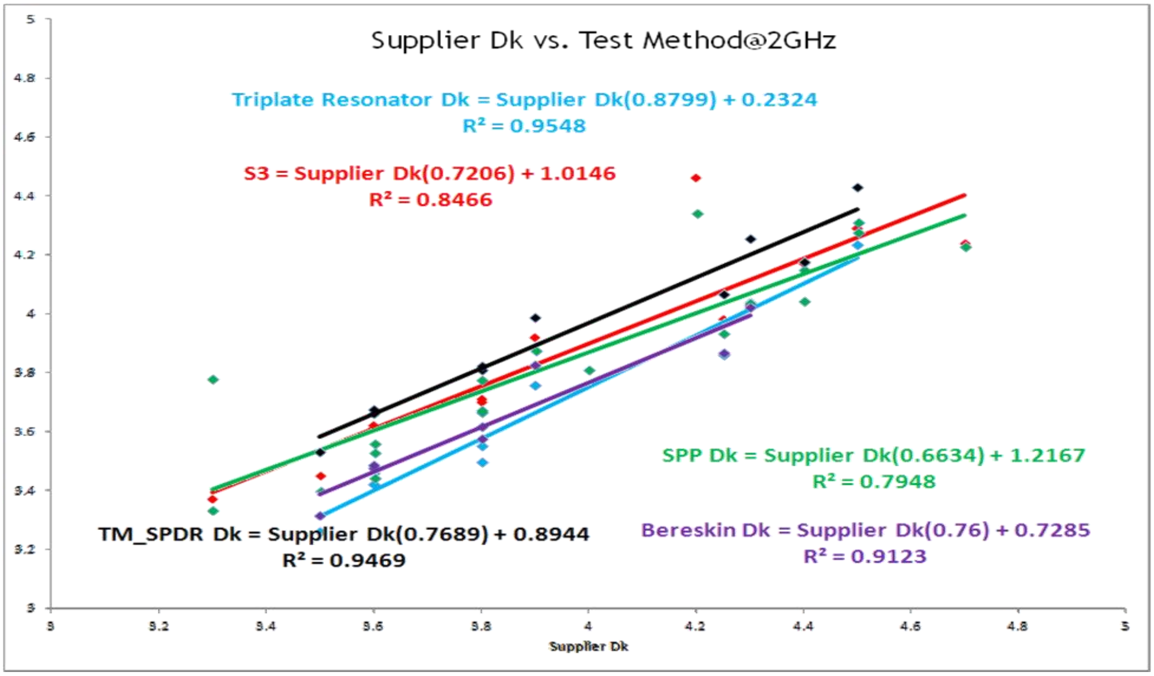


Figure 14

The two overall trace/conductor delay/loss test methods did not correlate as well (Figure 15).

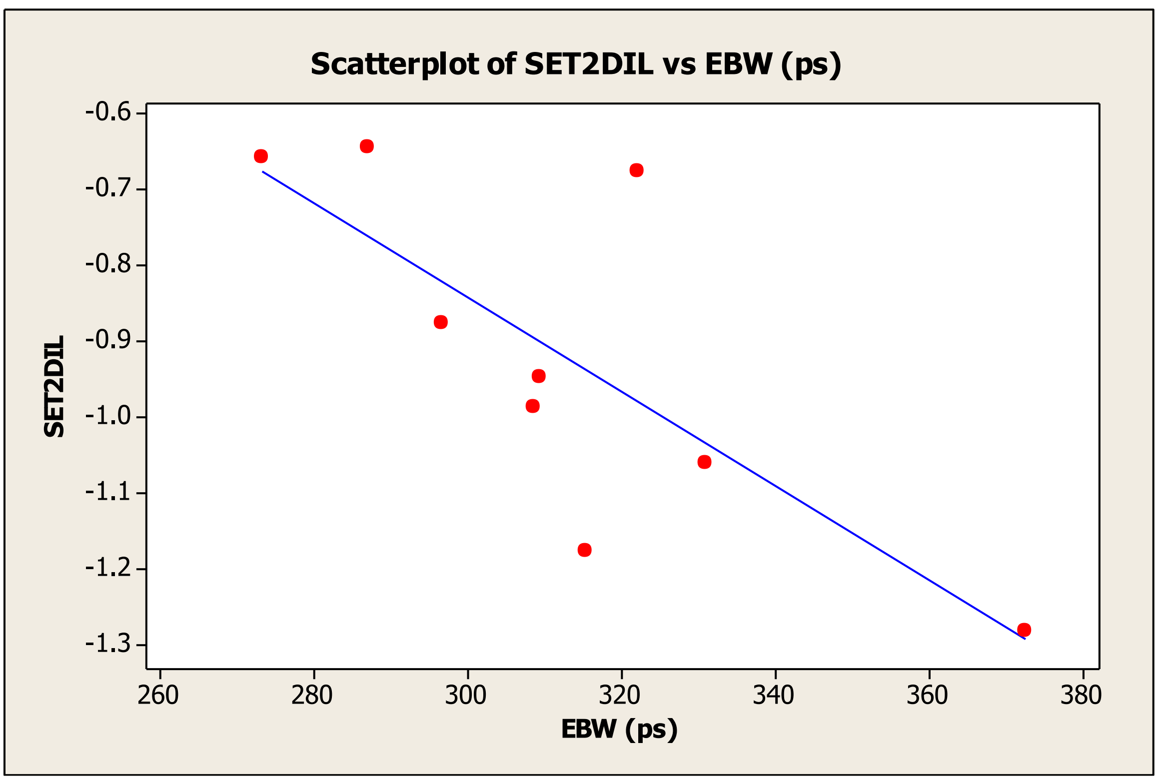


Figure 15

Conclusions – Dk/Df Extraction Test Method Pros & Cons

SUM-DISK (Z-Direction, Low measured Dk)

Pro: One resonator for several frequencies, from 5 GHz up to 67 GHz

Unwanted higher modes are well suppressed
Conductor loss can be separated precisely
Etched roughness effect of Cu Disk perimeter is calibrated
Fringing field effect of disk perimeter calibrated by mode matching method

Con: Not suitable below 5.0 GHz
Accuracy is poor if material Df is greater than 0.020
Special tool and skill is needed for exact centering of the copper disk

BERESKIN (Z-Direction, Low measured Dk)

Pro: Correlates well with other Dk test methods up to 20 GHz (Resonant Re-Entry, MIT waveguide technique, IPC-TM-650 2.5.5.3, 5, 6).
Small sample size (two 1.1625 x 4.0 inches) allows all three X/Y/Z axes.
Different fixture lengths can be used for testing at lower frequencies.

Con: Minimum 0.011 inches thickness can be tested due to fringing length addition to the center copper strip. Uses 50 ohm impedance probe lines.
Testing is dependent upon the copper strip used, and is a destructive test.

TRI-PLATE RESONATOR (Z-Direction, Low measured Dk)

Pro: Network analyzer measures attenuation constant, S21, and Dk and Df up to 20 GHz to 30 GHz depending upon the material tested.
Material specimen is simple with no fabrication of multilayer board required.
Suitable for temperature and humidity dependency testing.

Con: Df measurements do not include conductor loss or Cu surface roughness.
Skill is needed for the exact positioning of the coaxial cables.

S-3_CISCO (Patterns Inside, Mid-range measured Dk)

Pro: Standing wave test method is more representative than resonator (incorporates copper surface roughness loss and same Z-axis E-field)
Tuned launch via with upper and lower shields reduces Z variation
Dk/Df/Attenuation up to 40 GHz
Antipad diameter is tuned to minimize via L and C
Backdrilling minimizes parasitic effect of the via stub
Calibration by TRL structures on board to de-embed launch vias
No external calibration modules (50 GHz VNA)
Many individual data points (up to 40 GHz in 50 MHz steps)

Con: Requires 2.4 mm SMA bolt-on connectors and 50 GHz coaxial cable
Sensitive to PCB fabricator facility oxide-type treatment process
Sensitive to PCB fabricator facility etched line width variation
Differential pair measurements are susceptible to fiber weave effects

SPP (Full SPP with extraction, Patterns Inside, Mid-range measured Dk)

Pro: Requires about $110K USD worth of equipment and microsection capability.
Uses properly configured test coupon with SMA connectors, depending upon the test frequency requirements.
Propagation constant (attenuation), Dk, Df up to 60 GHz.
Full 2D model generated for interconnect and verified with measurements.

Con: Requires coupon microsections, DC line resistance, and LCR meter measurements. Modeling software required.

SPDR – TRANSVERSE ELECTRIC (In-Plane, High measured Dk)

Pro: Easy step-by-step operation with commercial standard fixture
Testing can be done under viable temperature conditions (-125 to 110 C)
If width/thickness of sample is consistent, then very accurate and repeatable:
- Dk range 1 to 30, accuracy +/- 1 percent
- Df range 0.05 to 0.0001, accuracy +/- 5 percent

Con: Need a separate dedicated resonator for each frequency tested
No resonators available for over 20 GHz
Tested Dk and Df value may not represent Dk and Df on actual boards since test specimen does not include copper.

SPDR – TRANSVERSE MAGNETIC (In-Plane, high measured Dk)

Pro: Easy step-by-step operation
If width of sample is consistent, then very accurate and repeatable:
Dk range 1 to 30, accuracy +/- 1 percent
Df range 0.05 to 0.0001, accuracy +/- 5 percent

Con: Need a separate dedicated resonator for each frequency tested
No resonators available for over 18 GHz
Very tight control of sample width is required for consistency (4.0 mm)
Tested Dk and Df value may not represent Dk and Df on actual boards since test specimen does not include copper.

Conclusions – Overall Trace/Conductor Delay/Loss Test Method Pros & Cons

EBW (overall trace/conductor delay/loss)

Pro: Easy and quick to operate for production testing and monitoring.
Impedance and propagation delay measurements data gathered at same time.
Simple coupon design for measuring Dk/Df/Attenuation up to 50 GHz

Con: Min. 5.0 cm test trace length in order to measure degradation in rise time.
Does not measure absolute loss in dB, nor does it separate loss components
Can use standard passive TDR probe or connector (SMA).

SET2DIL (overall trace/conductor delay/loss)

Pro: This test is relatively quick with about $70K USD worth of equipment and a properly configured test coupon up to 20 GHz (accurately configured probe pads and locating holes means 15 to 30 seconds per trace measured for impedance using good probe technique).
Coupons can contain multiple traces for testing
Est. $150 setup charge and $35 per trace tested
Probe is reusable >1000X if the coupon is good, but each probe costs about $1800. Cables are subject to wear (about $100 each).
Can be implemented as a Delta L method (two line lengths).

Con: Need high-end fast rise time TDR (TEK or Agilent) and special software to extract the SET2DIL information from the TDR reflections.

SPP (Quick, not done as part of this project)

Pro: Requires about $90K USD worth of equipment and test coupon with microprobe lands.
Measures overall loss/attentuation up to 50 GHz. IPC 2.5.5.12 Method C.

Con: SPP coupons with microprobe lands require about 2 minutes for either SE or DIFF. Est. setup charges $25 per SE trace and $50 per DIFF trace tested.
Like all test methods measuring only total attenuation/propagation delay loss, is not applicable to determining the laminate or dielectric material loss.

PROPAGATION DELAY BY TDR

Pro: TDR (time domain reflectometry) minimizes probe errors.
Measures intra pair skew very accurately.

Con: Accuracy depends upon the rise time of the pulse sent (signal edge).
Requires fast pulse generator (e.g. 20 GHz scope), and TDR passive probes.
Only measures overall combination of effects of dielectric loss, dielectric thickness, trace width, and copper surface roughness.

Conclusions & Comments

The high frequency Dk/Df extraction test methods considered can be categorized into three types; Z-Direction, Trace/Conductor, and In-Plane. This work has also shown that laminate material supplier data sheet values and higher frequency (above 2 GHz) Dk and Df test method results for the same laminate material can vary significantly. However, this project work found strong correlations between Dk and Df test method results when the same board construction is used and when these test methods are of the same type.

The quick overall trace conductor loss test methods used for ongoing production monitoring are not suitable for evaluating a specific laminate material due to the effects of other complicating factors on overall loss including dielectric thickness, trace width, treatment used, and copper surface roughness.

Recommendations

1) Industry to agree on two standard laminate material construction stack-ups for higher frequency laminate material testing for Dk/Df extraction, such as:

High Resin Content = all 1080 or 1086 or 1078, 65-70 percent resin content

Low Resin Content = all 2113 or 3313 or 2116, 50-55 percent resin content

2) Industry agree on always identifying the Dk/Df test method type if not the specific test method used, and the moisture content of the samples tested.

3) More work is needed to identify all the variables that can affect the higher frequency trace/conductor type test method results.

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Mike Freda, Stephanie Moran of Oracle Corp.
Jack Fisher of HDP

Appendix: IPC Test Methods (courtesy of TTM)

Standard	Common Name	Frequency Range	Specified Instruments	Stimulus/Measurement
IPC 2.5.5	Dielectric Constant	1MHz	capacitance bridge, signal generator & null detector	continuous application DC/capacitance measurement
IPC 2.5.5.1	Permittivity & Loss Measurement at 1MHz, (Contacting Electrode Systems)	-	-	-
	Method A	1MHz	1 MHz three terminal capacitance bridge, 100-1000 PF	continuous application DC/capacitance measurement
	Method B	1MHz	1 MHz capacitance bridge, two or three terminal test fixture	continuous application DC/capacitance measurement
	Method C	1MHz	Q meter with 1 MHz capability Q Coils	continuous application DC/Q resonance
	Method D	1MHz	1 MHz three terminal capacitance bridge, 100-1000 PF	continuous application DC/capacitance measurement
IPC 2.5.5.2	Dielectric Constant and Dissipation Factor of Printed Wiring Board Material - Clip Method	1MHz	1 MHz Digital LCR Meter (coaxial termination)	continuous application DC/capacitance, loss measurement
IPC 2.5.5.3	Permittivity and Loss Tangent of Materials (Two Fluid Cell Method)	1MHz	1 MHz Capacitance Bridge, 0-200 (or 0-100) pf	continuous application DC/capacitance measurement
IPC 2.5.5.4	Dielectric Constant and Dissipation Factor of Printed Wiring Board Material-Micrometer Method	22kHz to 70MHz	Q meter with suitable frequency coils or VNA/PNA	continuous application DC/Q resonance

IPC 2.5.5.5	Stripline Test for Permittivity and Loss Tangent (Dielectric Constant & Dissipation Factor) at X-Band	X - Band (8GHz-12.5GHz)	HP (Agilent) reference test set: • Sweep Frequency Generator Mainframe 8350B • RF Plug-In, 83592A, 0.01 to 20 GHz • Power Splitter 11667A • Automatic Frequency Counter 5343A • Source Synchronizer 5344A (interconnected assembly with counter) • Coaxial cables and adapters • 10 dB Attenuator, 8491B - or- VNA & peripherals of equivelent capability	multi-mode frequency sweep input/resonant frequency measurement
IPC 2.5.5.5.1	Stripline Test for Complex Relative Permittivity of Circuit Board Materials to 14 GHz	1GHz-14GHz		
IPC 2.5.5.6	Non-Destructive Full Sheet Resonance Test for Permittivity of Clad Laminates	20GHz to microwave band	HP (Agilent) reference test set: • Sweep Oscillator 835OB-Option 908 • RF Plug-in 0.01-20 GHz83592A Option 002 • Microwave Frequency Counter 5343A • Source Synchronizer 5344S, Options 043, 908 • Power Meter 436A • Power Sensor 848A • Power Splitter 11667A - or- VNA & peripherals of equivelent capability	multi-mode frequency sweep input/resonant frequency measurement
IPC 2.5.5.7	Characteristic Impedance of Lines on Printed Boards by TDR	variable, designed for appropriate spectral content	TDR or TDR/TDT of suitable frequency range	Voltage pulse, 10-500ps
IPC 2.5.5.8	Low Frequency Dielectric Constant and Loss Tangent, Polymer Films (two fluid method)	10kHz-1MHz	1 MHz Digital LCR Meter (coaxial termination)	continuous application DC/capacitance, loss measurement

IPC 2.5.5.9	Permittivity and Loss Tangent, Parallel Plate, 1 MHz to 1.5 GHz	1MHz-1.5GHz	Hewlett-Packard (Agilent) model 4291A Impedance Analyzer or equivelet	frequency sweep over +/- 5% of target frequency (typically 1MHz-1.5GHz)
IPC 2.5.5.10	High Frequency Testing to Determine Permittivity and Loss Tangent of Embedded Passive Materials	100MHz-12GHz NB - 18GHz max with use of appropriate techniques & algorithms	VNA, 100MHz - 18GHz minimum bandwidth, Agilent 8720D or equivalent	S-11, 100MHz-12 or 100MHz-18GHz sweep
IPC 2.5.5.11	Propagation Delay of Lines on Printed Boards by TDR	100MHz-60GHz (hardware dependant)	TDR or TDR/TDT of suitable frequency range	selected for appropriate spectral content
IPC 2.5.5.12	Test Methods to Determine the Amount of Signal Loss on Printed Boards	-	-	-
	Method A - (EBW) Effective Bandwidth	100MHz-60GHz (hardware dependant)	TDR	Selected for appropriate spectral content
	Method B - (RIE) Root Impulse Energy	100MHz-60GHz (hardware dependant)	TDR/VNA	250 ps or specified
	Method C - (SPP) Short Pulse Propagation	100MHz-60GHz (hardware dependant)	TDT	11-35 ps
	Method D - (FD) Frequency Domain	100MHz-60GHz (hardware dependant)	VNA/TDR	300 KHz to 10 GHz or as specified
2.5.5.13	Relative Permittivity and Loss Tangent Using a Split-Cylinder Resonator	2-40GHz	VNA/PNA orfsuitable frequency range	2GHz-40GHz (10GHz resonator)
-	Split-Post Dielectric Resonator (SPDR)	2-20GHz	VNA/PNA of suitable frequency range	2-20GHz sweep

High Frequency Loss Test Methods For Laminate Materials Comparison

High Density Packaging User Group (HDPUG) Project

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Santa Clara, CA

Joe Smetana
Alcatel-Lucent
Plano, TX

High Frequency Loss Test Methods Project

Introduction:

Currently a large variety of higher frequency Dk/Df extraction and overall loss test methods are being used at frequencies above 1 GHz. Depending upon the laminate material, different Dk and Df values are reported depending upon the test method used. Consequently, determining the electrical performance of laminate materials is difficult.

If a common test board design and construction stack-up could be developed containing all varieties of high speed test coupon designs, then it may be possible to establish some correlations between these test methods using a variety of laminate materials.

High Frequency Loss Test Methods Project

Background: Megtron-6 example

Cavity resonator method (10 GHz)	Df = 0.008
SPP (6 GHz)	Df = 0.006 to 0.0075
IPC TM 2.5.5.5, 2-20 GHz, Stripline	
E-Glass, VLP Cu Foil	Df = 0.003 to 0.006
NE-Glass, VLP Cu Foil	Df = 0.002 to 0.005
E-Glass, RTF Cu Foil	Df = 0.004 to 0.007
NE-Glass, RTF Cu Foil	Df = 0.003 to 0.006
IPC TM 2.5.5.9, Parallel Plate	Df = 0.002

High Frequency Loss Test Methods Project

Objectives:

1) Develop a high frequency test board construction stack-up that is able to support most high speed test coupon design and test sample thickness requirements.
2) Test a variety of laminate materials using most high frequency Dk and Df test methods using this common test board design and construction.
3) Analyze the results to determine the rank ordering and any correlation among the variety of test methods used.
4) Document the characteristics of each test method, and any test method specific problems or issues related to obtaining consistent and timely results.

High Frequency Loss Test Methods Project

High Frequency Test Method Coupons:

• Split Post Dielectric Resonator*	up to 20 GHz
• SET2DIL, IPC 2.5.5.12, Method D	up to 20 GHz
• SPP, IPC 2.5.5.12, Method C	up to 20 GHz
• Bereskin, Isola	up to 20 GHz
• Stripline Test at X-Band, IPC 2.5.5.5.1	up to 20 GHz
• 4-Port VNA	up to 25 GHz
• Tri-Plate Resonator, JPCA TM001	up to 25 GHz
• Split Cylinder Resonator	up to 40 GHz
• S-3, CISCO	up to 40 GHz
• EBW, IPC 2.5.5.12, Method A	up to 60 GHz
• SUM-DISK, Fujitsu	up to 67 GHz

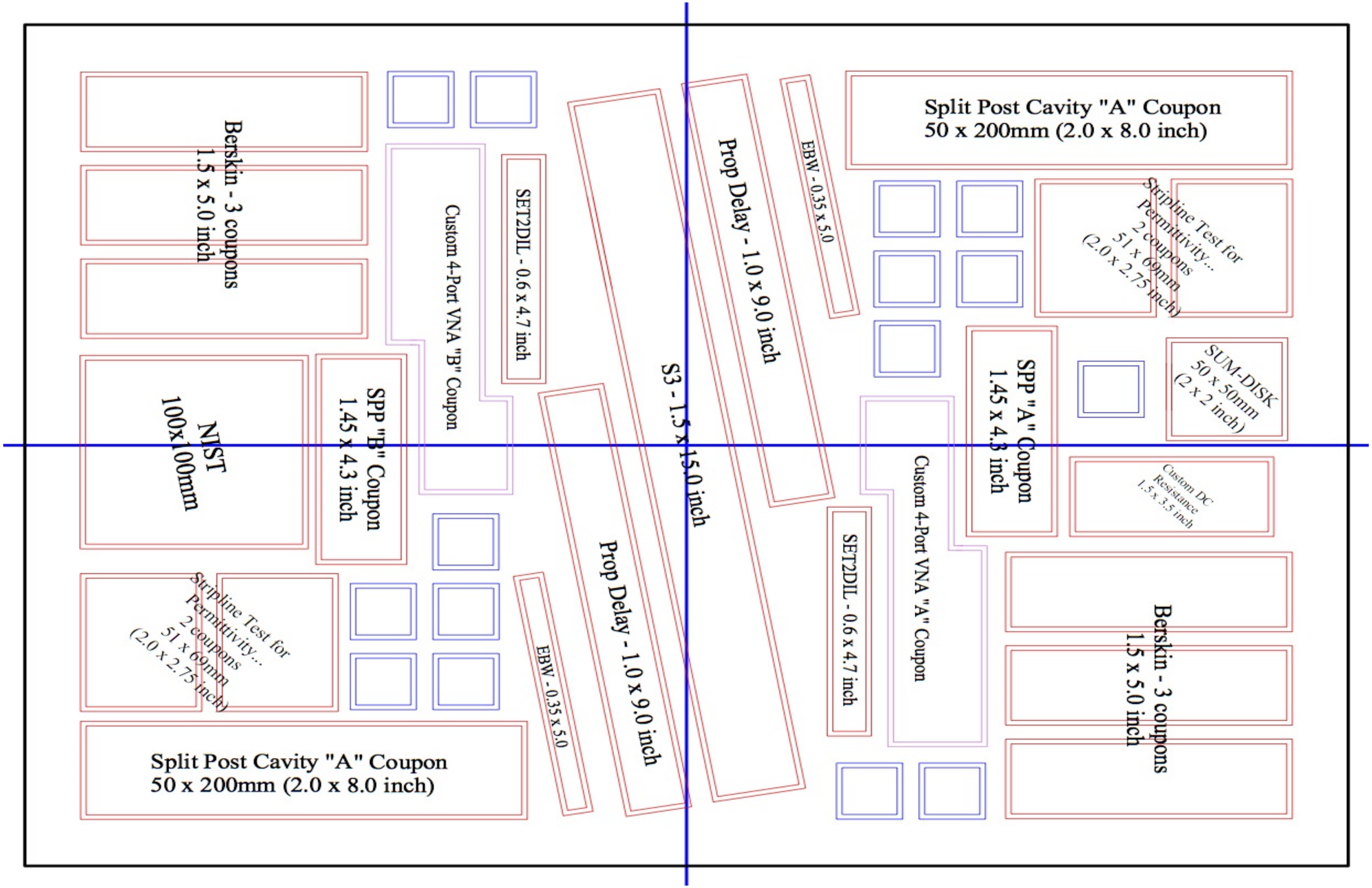
- Prop Delay and DC Resistance testing (for control/monitor)

High Frequency Loss Test Methods Project

Test Board Construction:

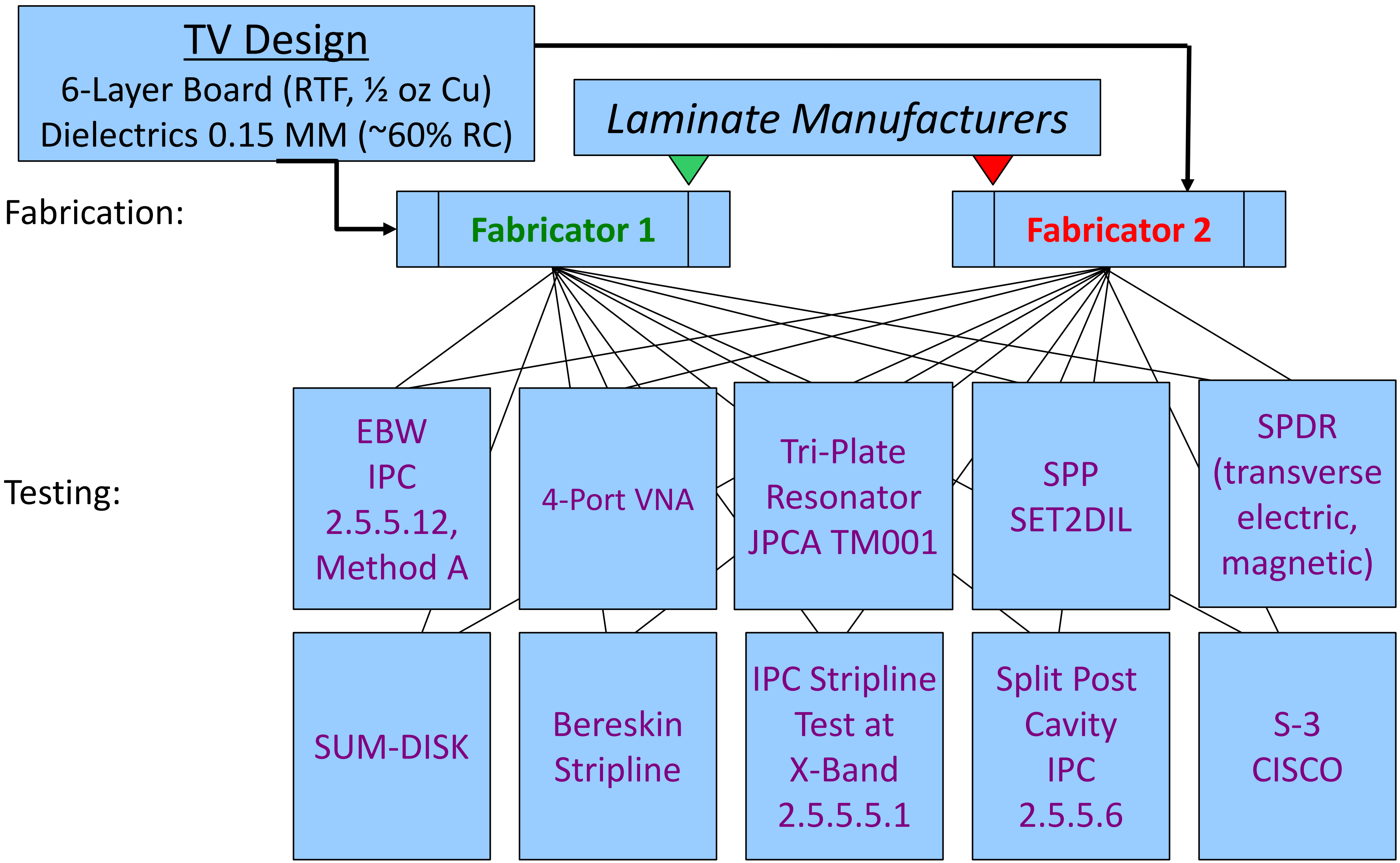
1) Six layers, ½ oz. copper inner layers, 0.031 inches thick
2) Trace/conductor test methods have one coupon with fixed 0.0055 inches trace width, and a second coupon on same test board adjusted to 50 ohms impedance as needed for the each specific laminate material used.
3) Thirteen different test method coupons were all made to fit into the same test board vehicle design, to ensure the most direct comparisons of the test methods.
4) Test methods requiring thicker samples have multiple coupons designed in so that, after stacking the coupons, the required dielectric thickness for testing is met.

High Frequency Loss Test Methods Project

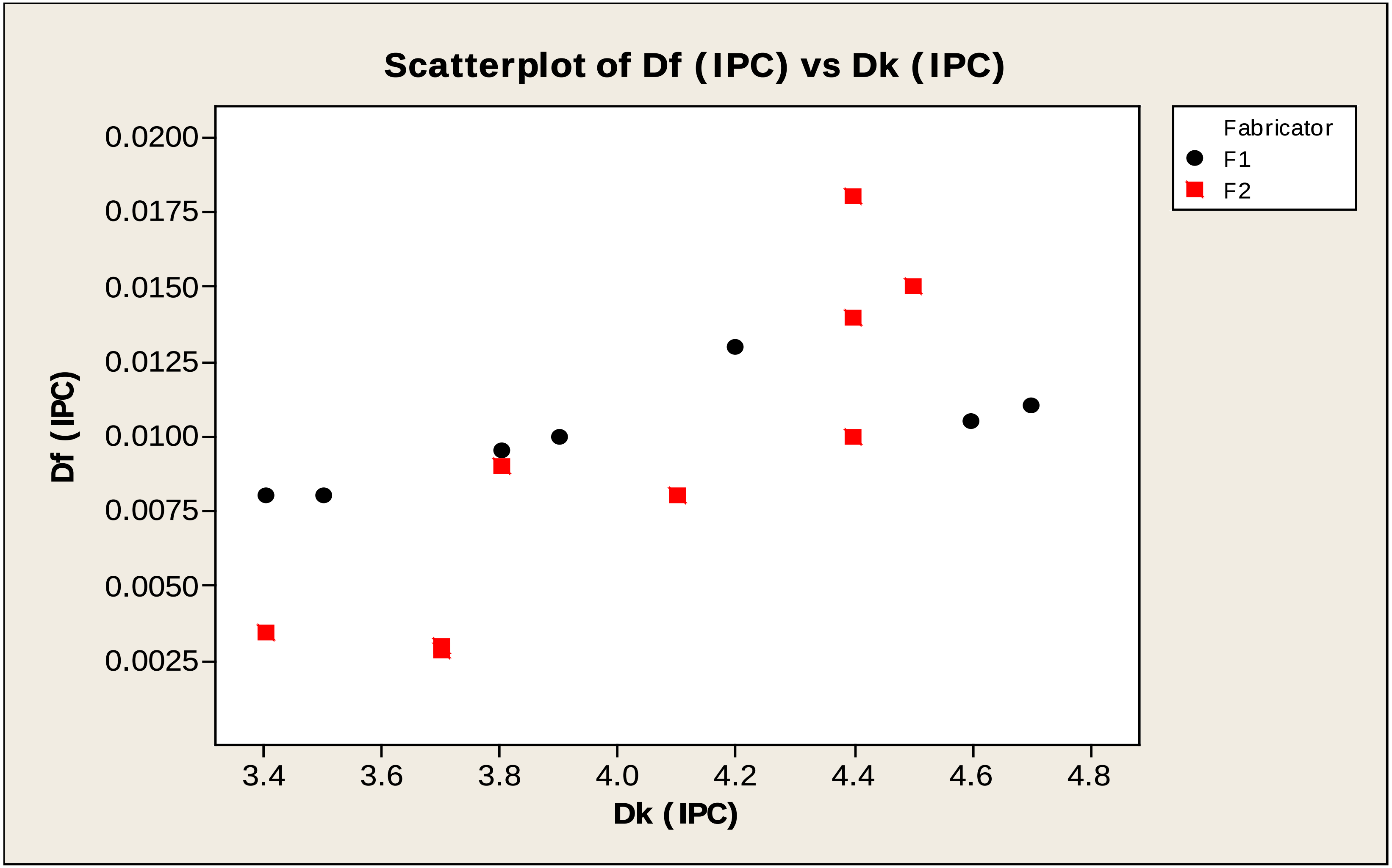


High Frequency Loss Test Methods Project

	Laminate Materials	Core Construction	% Resin Content - Core	Prepreg Construction	% Resin Content-Prepreg	Cu Foil	50 ohm L4 Impedance Trace Width
F2	L01	2x1080	64	2x1080	63	.5/.5 RTF	4.2
F2	L02	2x1080	64	2x1080	63	.5/.5 RTF	4.5
F1	L03	1080/3313	56	2x1080	64	.5/.5 DSTF	5.2
F2	L03	1080/2113	56	2x1080	66	.5/.5 RTF	4.3
F2	L04	2x1080	63	2x1080	63	.5/.5 RTF	5.3
F2	L05	2x1080	62	2x1080	62	.5/.5 RTF	5.3
F2	L06	2x1080	63	2x1080	63	.5/.5 RTF	5.2
F2	L07	2x1080	64	2x1080	64	.5/.5 RTF	6.0
F2	L08	2116	54	2x1280	64	.5/.5 RTF	4.7
F1	L09	2x1080	63	2x1080	63	.5/.5 HVLP	6.0
F2	L09	2x1080	63	2x1080	64	.5/.5 RTF	3.8
F2	L10	2x1280	62	2x1280	62	.5/.5 RTF	3.7
F1	L11	2x1080	64	2x1080	65	.5/.5 RTF	6.9
F1	L12	2x1080	63	2x1080	65	.5/.5 RTF	6.5
F1	L13	2x1080	64	2x1080	64	.5/.5 HTE Elong	5.0
F1	L14	2x1080	63	2x1080	65	.5/.5 RTF	5.8
F1	L15	2x1080	64	2x1080	64	.5/.5 RTF	5.3
F1	L16	1506	44	2x1080	65	.5/.5 RTF	5.0
F1	L17	1501	46	2x1080	65	.5/.5 RTF	5.0
F1	L17	1501	46	2x1080	65	.5/.5 RTF	5.0


TV Design
6-Layer Board (RTF, ½ oz Cu)
Dielectrics 0.15 MM (~60% RC)
Laminate Manufacturers
Fabrication:
Fabricator 1
Fabricator 2
Testing:
EBW IPC 2.5.5.12, Method A
4-Port VNA
Tri-Plate Resonator JPCA TM001
SPP SET2DIL
SPDR (transverse electric, magnetic)
SUM-DISK
Bereskin Stripline
IPC Stripline Test at X-Band 2.5.5.5.1
Split Post Cavity IPC 2.5.5.6
S-3 CISCO

High Frequency Loss Test Methods Project



High Frequency Loss Test Methods Project

S. Kikuchi of Fujitsu Advanced Technologies, Fujitsu Ltd., provided the following classification of high frequency Dk/Df extraction test methods.

* Z-Direction Test Coupons

Tri-plate Resonator, 2.0” x 8.0”	JPCA TM001
Bereskin Stripline, 1.5” x 5.0” or 1.25” x 4.0”	Isola
SUM-DISK, 50 mm x 50 mm (up to 67 GHz)	Fujitsu

* Trace/Conductor Based (Dk/Df extraction, 50 ohms SE impedance)

SPP,	1.4” x 4.3”	IPC 2.5.5.12 (1.3, Method C)
S-3,	1.5” x 16.0”	Cisco
4-Port VNA,	0.6” x 4.7”	TBD

* In-Plane Test Coupons (Dk/Df extraction)

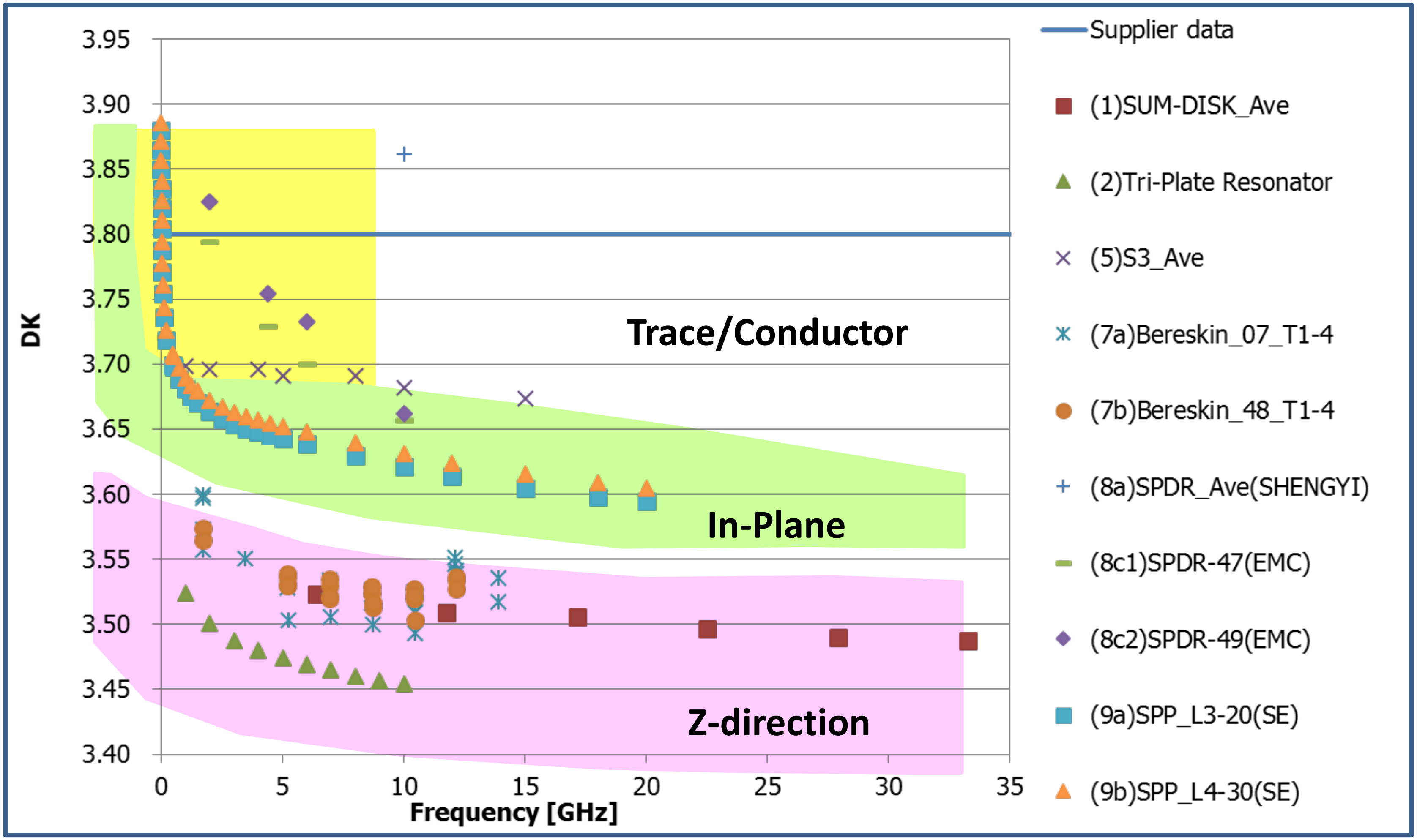
Split Post Dielectric Resonator (up to 20 GHz)

Transverse Electric (calibration, sample position & TE mode critical)

Transverse Magnetic – QWED, Agilent (3x150mm) EMC

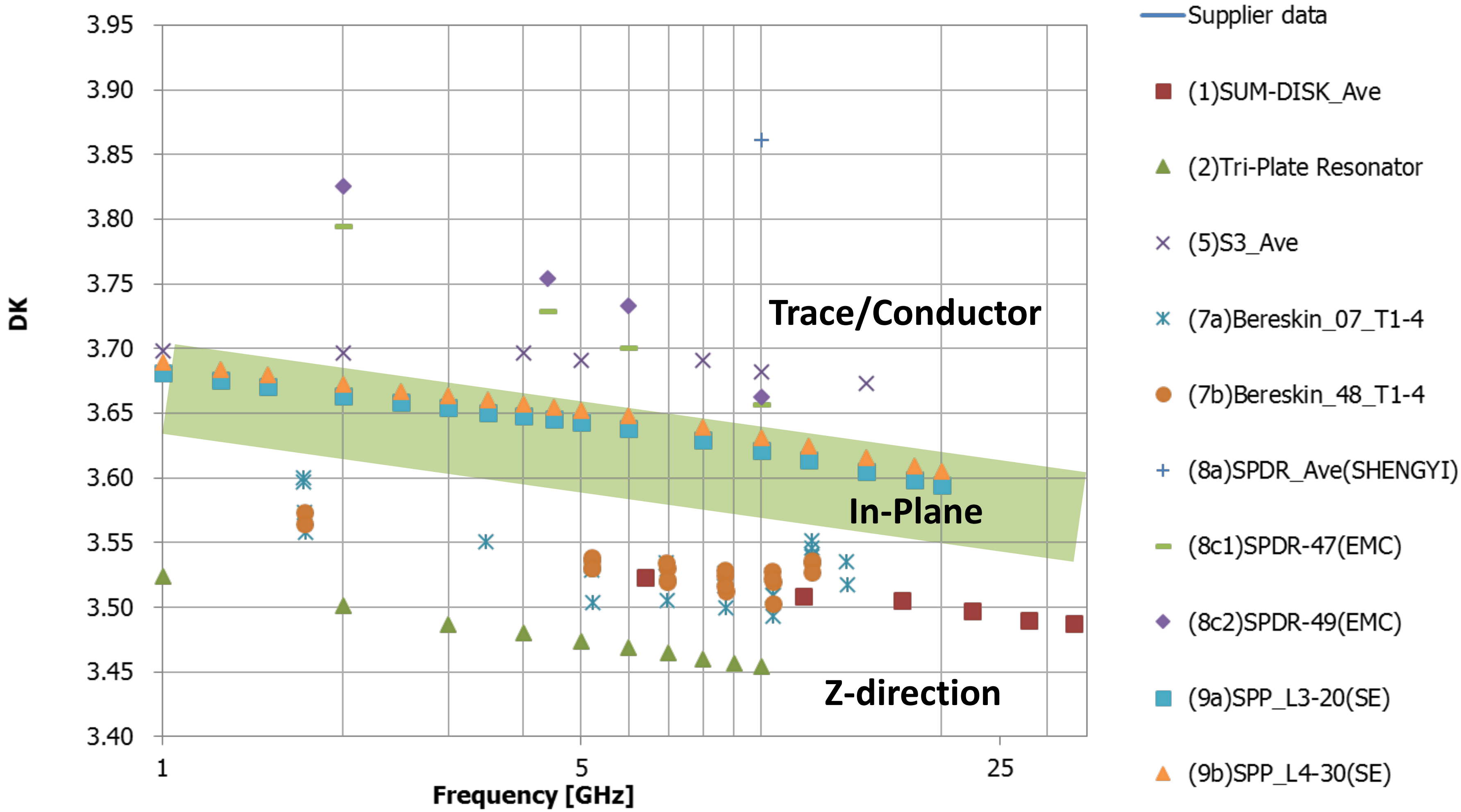
High Frequency Loss Test Methods Project

Comparison of Dk/Df Extraction Results by Test Method (for single material)



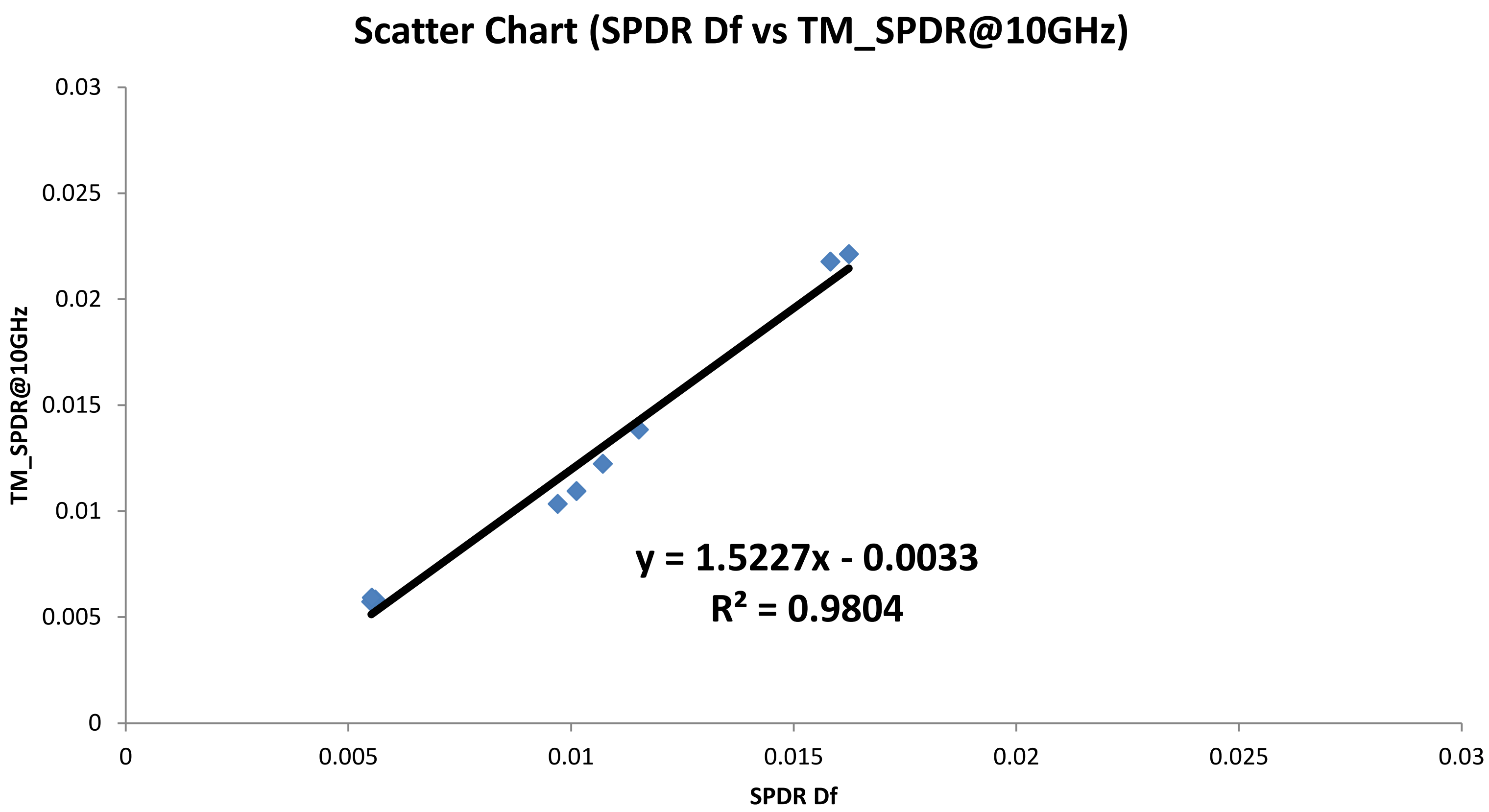
High Frequency Loss Test Methods Project

Comparison of Dk/Df Extraction Results by Test Method (for single material)



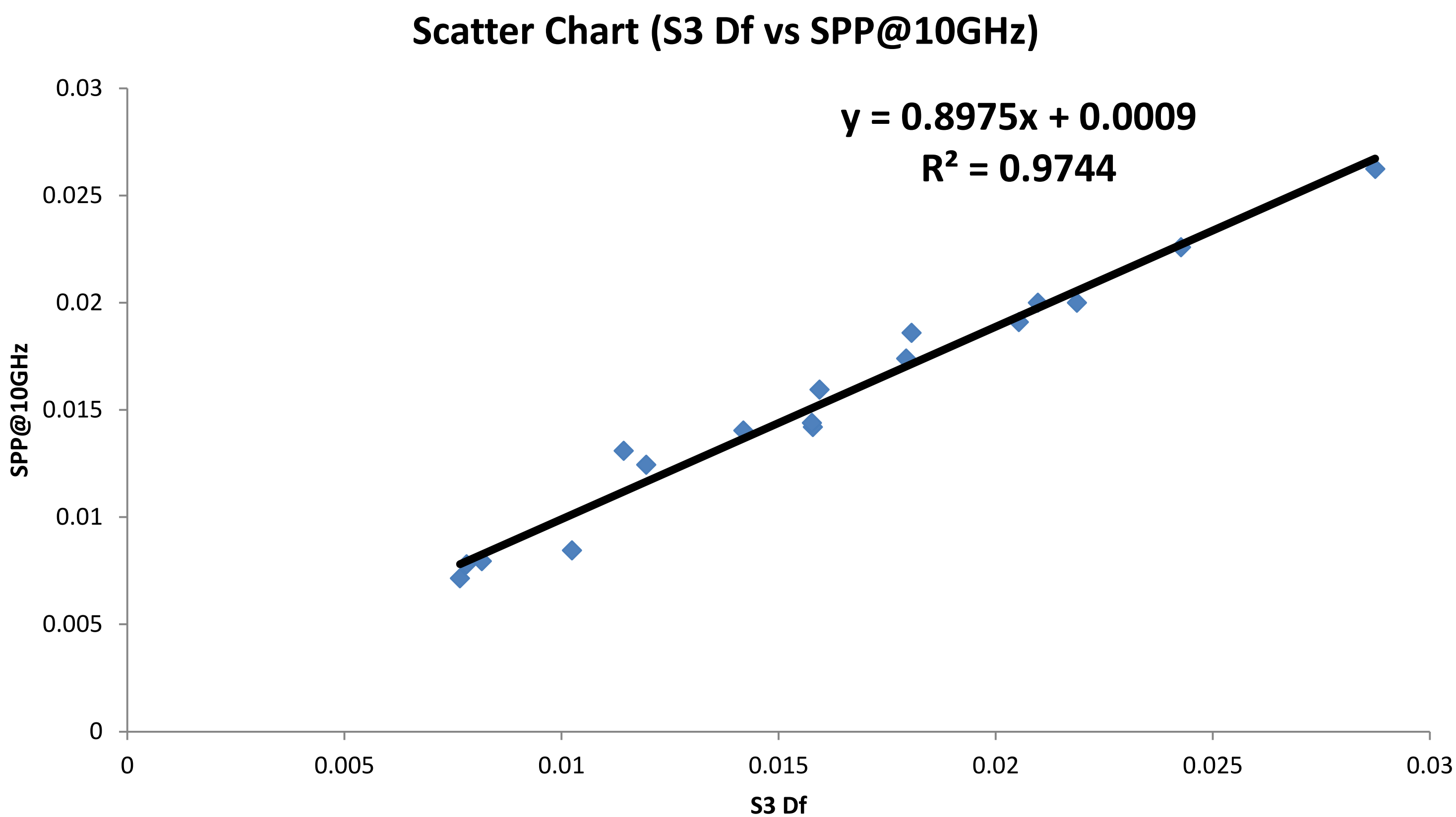
High Frequency Loss Test Methods Project

The In-Plane test methods showed very good correlation, even for Df.



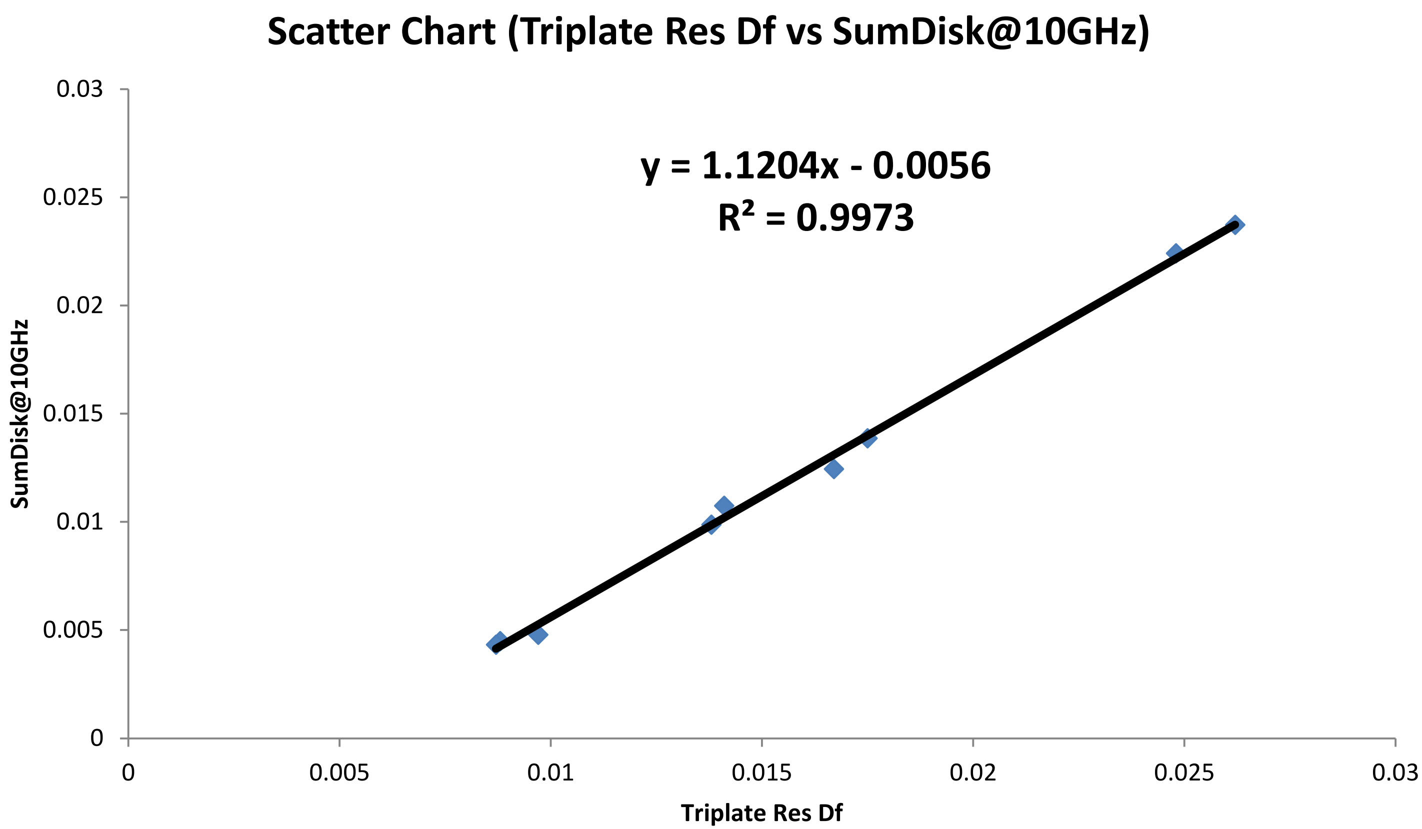
High Frequency Loss Test Methods Project

The SPP and S-3 Trace/Conductor test methods showed good correlation, even for Df.



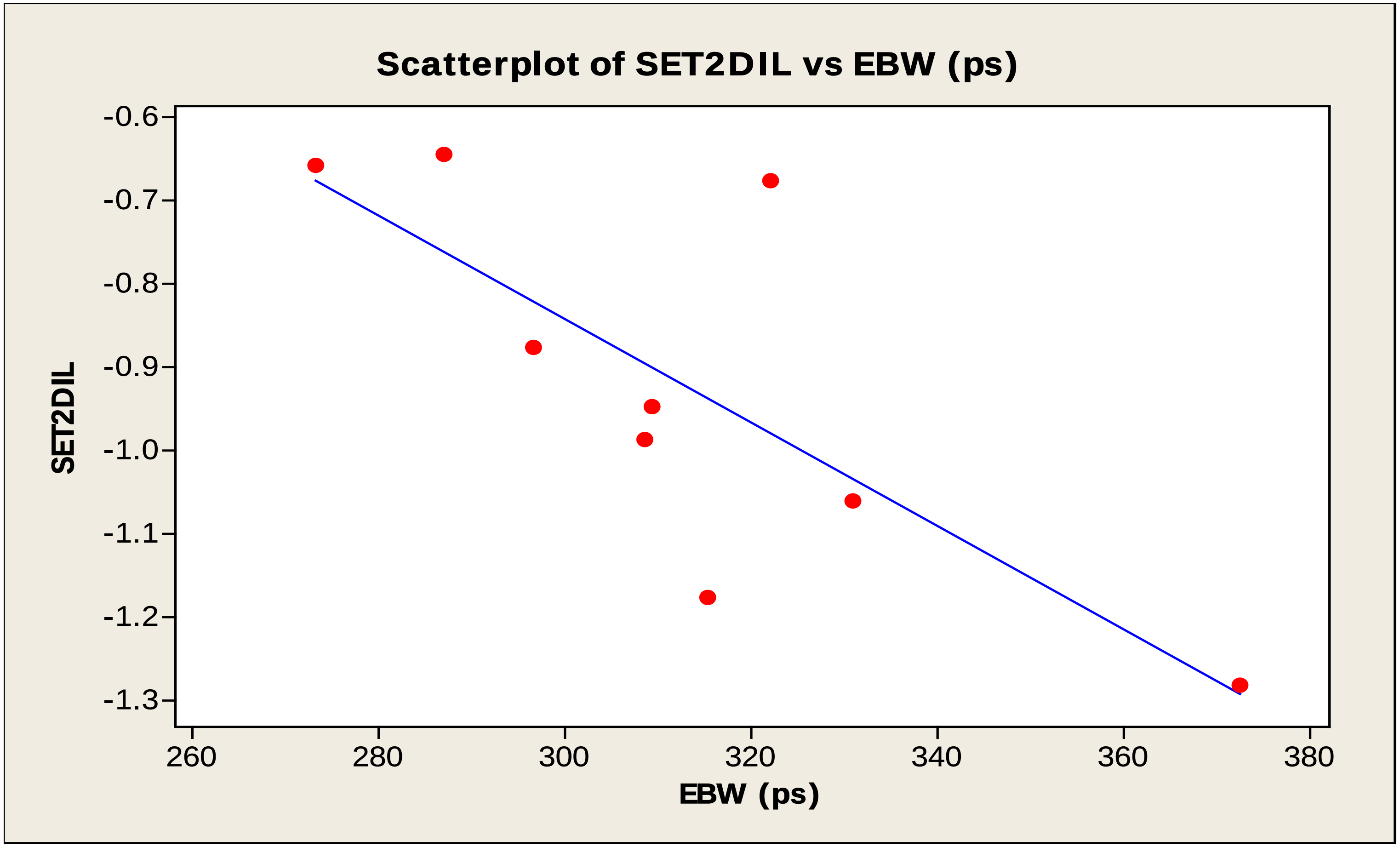
High Frequency Loss Test Methods Project

The Z-Direction Dk/Df Extraction test methods showed very good correlation, even for Df.



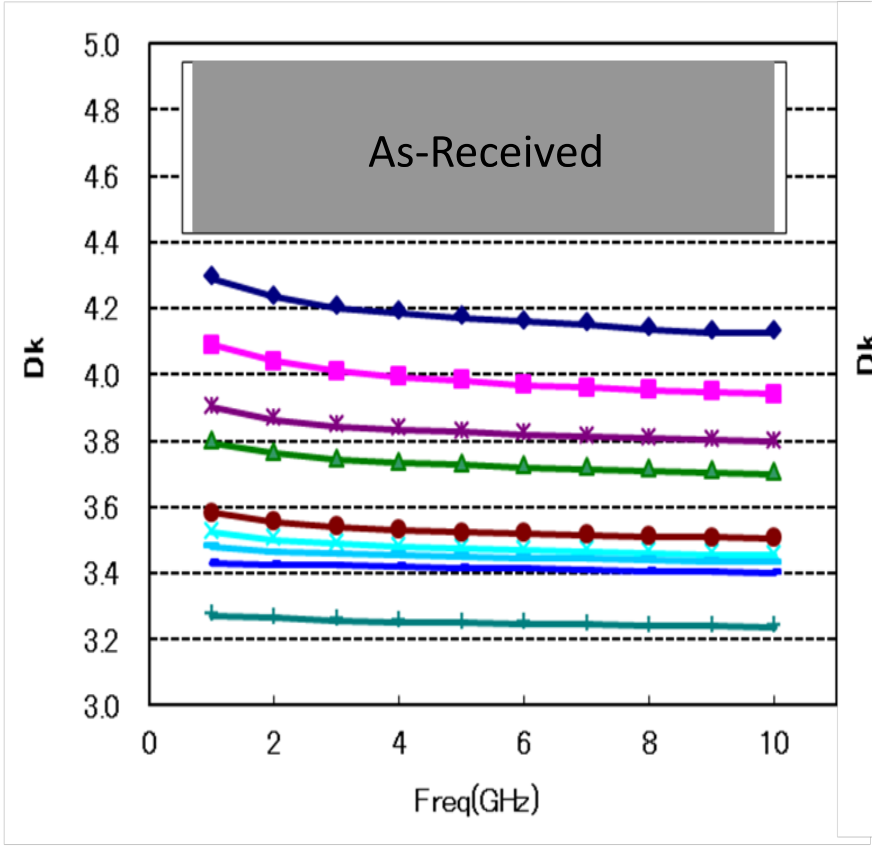
High Frequency Loss Test Methods Project

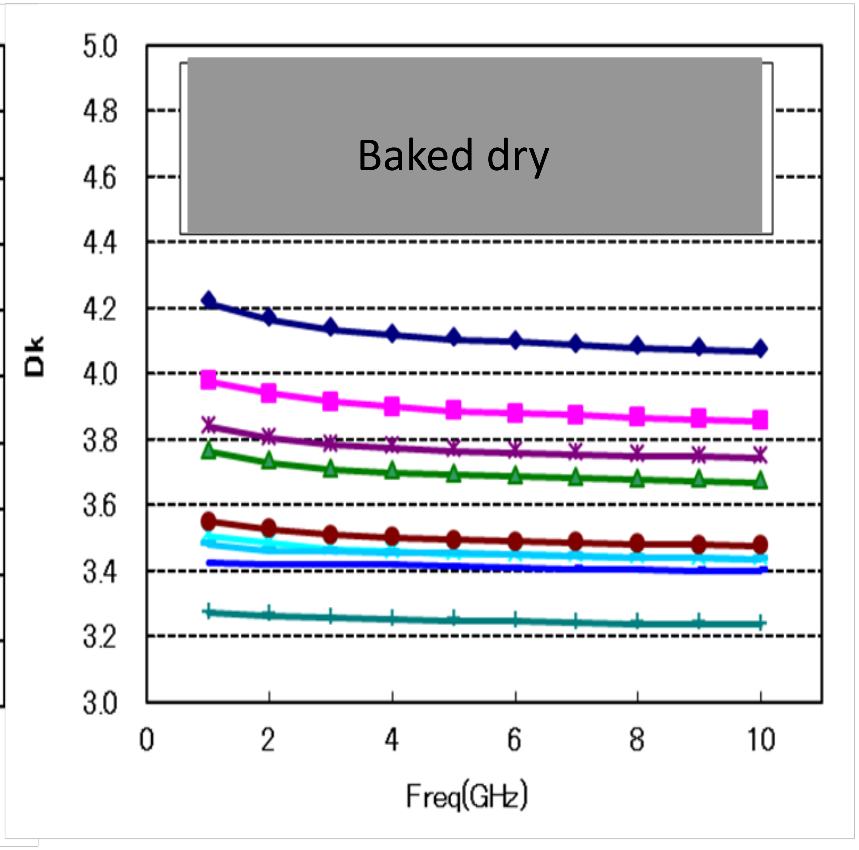
The two overall trace/conductor delay/loss test methods did not correlate well.



High Frequency Loss Test Methods Project

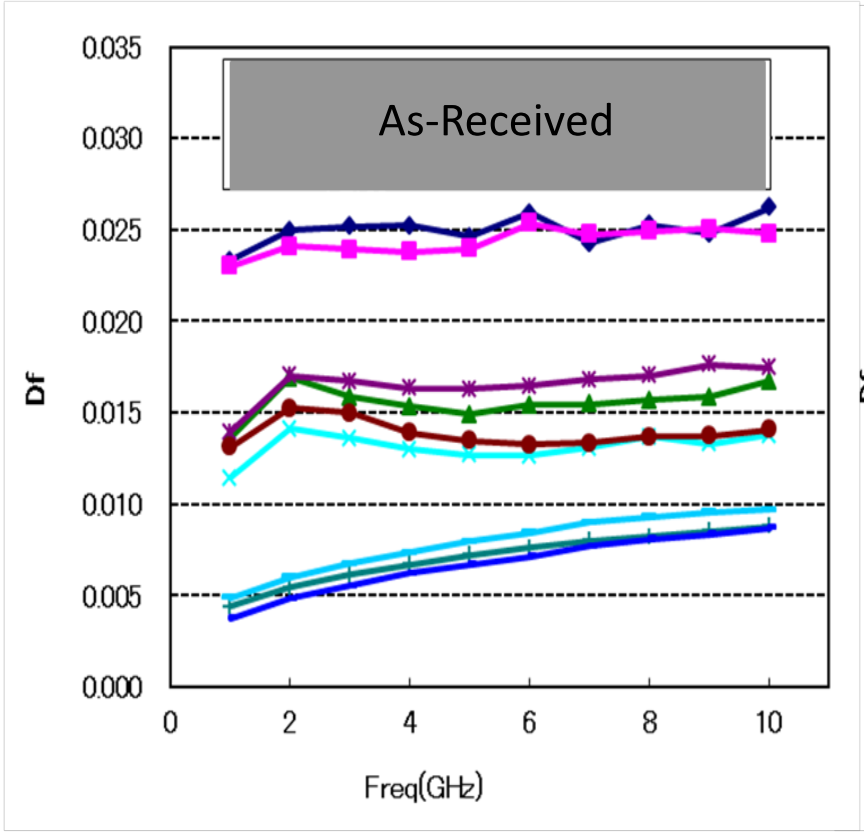
All test coupons were tested in the As-Received condition. Some coupons were also tested after baking until dry. This had an up to 3 percent impact on the measured Dk value:

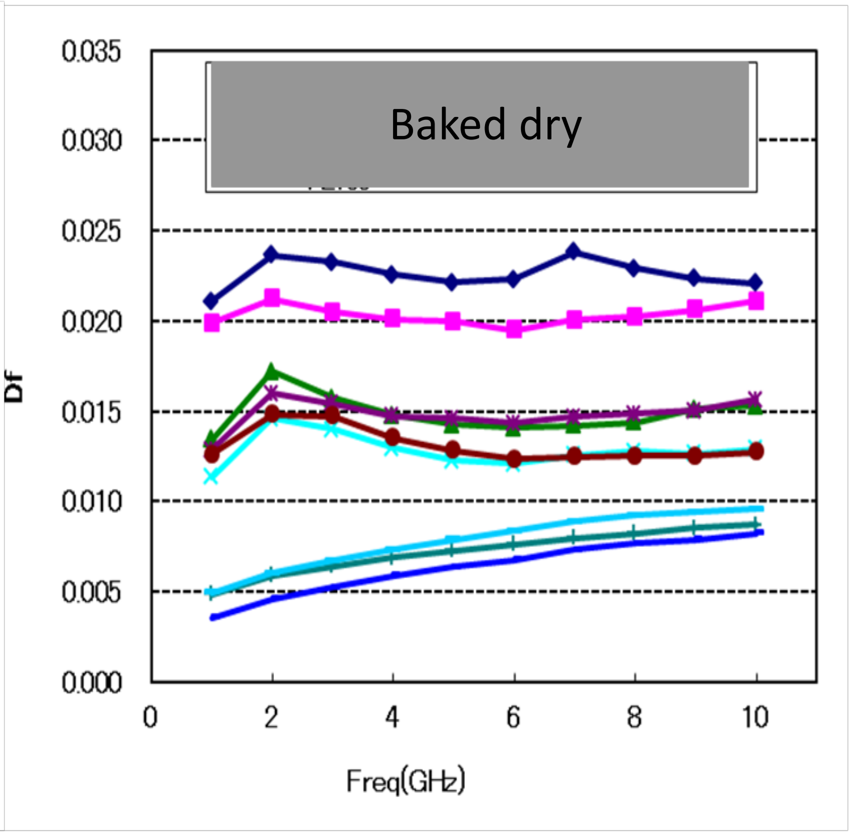




High Frequency Loss Test Methods Project

All test coupons were tested in the As-Received condition. Some coupons were also tested after baking until dry. This had an up to 20 percent impact on the measured Df value:





High Frequency Loss Test Methods Project

CONCLUSIONS: Dk/Df Extraction, Z-Direction Test Method Pros & Cons

SUM-DISK	Pro:	One resonator for several frequencies, from 5 GHz up to 67 GHz
		Unwanted higher modes are well suppressed
		Conductor loss can be separated precisely
		Etched roughness effect of Cu Disk perimeter is calibrated
	Con:	Not suitable below 5.0 GHz
		Accuracy is poor if material Df is greater than 0.020
		Special tool and skill needed for exact centering of copper disk
BERESKIN	Pro:	Correlates well with other Dk test methods up to 20 GHz.
		Small sample size allows all three X/Y/Z axes.
		Different fixture lengths allow testing at lower frequencies.
	Con:	Minimum 0.011 inches sample thickness
		Uses 50 ohm impedance probe lines.
		Testing depends on copper strip used, and is a destructive test.

High Frequency Loss Test Methods Project

CONCLUSIONS: Dk/Df Extraction, Z-Direction Test Method Pros & Cons

TRI-PLATE RESONATOR

Pro: Network analyzer measures attenuation constant, S21, Dk , Df up to 20 GHz to 30 GHz depending upon the material tested.
Simple specimen with no MLB fabrication required.
Suitable for temperature and humidity dependency testing.

Con: Df measurements only, not trace loss or surface roughness.
Skill is needed for the exact positioning of the coaxial cables.

CONCLUSIONS: Dk/Df Extraction, Patterns Inside Test Method Pros & Cons

S-3_CISCO

Pro: Standing wave test method is more representative than resonator (incorporates surface roughness loss and same Z-axis E-field).
Tuned launch via with upper and lower shields reduces Z variation.

High Frequency Loss Test Methods Project

S-3_CISCO, cont.

Pro: Dk/Df/Attenuation up to 40 GHz.
Antipad diameter is tuned to minimize via L and C.
Backdrilling minimizes parasitic effect of the via stub.
Calibration by TRL structures on board to de-embed launch vias.
No external calibration modules (50 GHz VNA).
Many individual data points (up to 40 GHz in 50 MHz steps).

Con: Requires 2.4 mm SMA bolt-on connectors , 50 GHz coaxial cable.
Sensitive to PCB fabricator facility oxide-type treatment process.
Sensitive to PCB fabricator facility etched line width variation.
Diff pair measurements are susceptible to fiber weave effects.

SPP (Full) Pro: Requires about $110K USD worth of equipment, microsection TW capability, and properly configured test coupon for test frequency.
Propagation constant (attenuation) up to 60 GHz.

Con: Requires coupon microsections, DC line resistance, and LCR meter measurements. 2D modeling software required, and verification.

High Frequency Loss Test Methods Project

CONCLUSIONS: Dk/Df Extraction, In-Plane Test Method Pros & Cons

SPDR – TRANSVERSE ELECTRIC

Pro: Easy step-by-step operation with commercial standard fixture.
Testing can be done at different temperatures (-125 to 110 C).
Very repeatable if width/thickness of sample is consistent.
- Dk range 1 to 30, accuracy +/- 1 percent
- Df range 0.05 to 0.0001, accuracy +/- 5 percent

Con: Need a separate dedicated resonator for each frequency tested.
No resonators available for over 20 GHz.

High Frequency Loss Test Methods Project

PDR – TRANSVERSE MAGNETIC (In-Plane, high measured Dk)

Pro: Easy step-by-step operation.
Very repeatable if width of sample is consistent
  Dk range 1 to 30, accuracy +/- 1 percent
  Df range 0.05 to 0.0001, accuracy +/- 5 percent

Con: Need a separate dedicated resonator for each frequency tested.
No resonators available for over 18 GHz.
Tight control of sample width needed for consistency (4.0 mm).

CONCLUSIONS: Overall Conductor Loss Test Method Pros & Cons

EBW (overall trace/conductor delay/loss)

Pro: Easy and quick to operate for production testing and monitoring.
Impedance & propagation delay data gathered together up to 50 GHz.

Con: Test trace is more than 5.0 cm in length, SMA connectors required.
Does not measure absolute loss in dB or separate loss components.
Can use standard passive TDR probe or connector (SMA).

High Frequency Loss Test Methods Project

SET2DIL (overall trace/conductor delay/loss)

Pro: Test is relatively quick with about $70K USD worth of equipment and a properly configured test coupon up to 20 GHz.
Est. $150 setup charge and $35 per trace tested
Probe is reusable >1000X if the coupon is good.

Con: Assumes conductor width (not measured).
Need high-end fast rise time TDR (TEK or Agilent) and special software to extract the SET2DIL information.
Each probe costs about $1800, and cables are subject to wear.

<u>CONCLUSIONS</u>

High frequency Dk/Df extraction test methods can be categorized into three types; Z-Direction, Trace/Conductor, and In-Plane. There are strong correlations between Dk and Df test method results for most test methods of the same type, when the same board construction is used. This work has also shown that laminate material supplier data sheet values at higher frequency (above 2 GHz) Dk and Df test method results for the same laminate material can vary significantly.

High Frequency Loss Test Methods Project

The quick overall trace conductor loss test methods used for ongoing production monitoring are not suitable for evaluating a specific laminate material due to the effects of other complicating factors on overall loss including dielectric thickness, trace width, treatment used, and copper surface roughness.

RECOMMENDATIONS

1) Industry to agree on two standard laminate material construction stack-ups for higher frequency laminate material testing for Dk/Df extraction, such as:
   High Resin Content = all 1080 or 1086 or 1078, 65-70 percent resin content
   Low Resin Content = all 2113 or 3313 or 2116, 50-55 percent resin content

2) Industry to agree on always identifying the Dk/Df test method type if not the specific test method used, and the moisture content of the samples tested.

3) More work is needed to identify all the variables that can affect the higher frequency trace/conductor type test method results.

High Frequency Loss Test Methods Project

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