DesignCon 2010

Technical panel:

Making Sense out of Dielectric Loss Numbers, Specifications and Test Methods

Panelists:

Don DeGroot	CCNi
Roger Krabbenhoft	IBM
Tony Senese	Panasonic Electric Works
Allen F. Horn	Rogers Corp
Istvan Novak*	SUN Microsystems

* panel organizer

Abstract

Dielectric loss has been a crucial specification item on microwave and RF printed circuit boards for decades. With the recent explosion of buses and links with gigabit speeds on digital systems, designers of digital and mixed digital-analog boards can no longer ignore dielectric losses. In fact, in contrast to many microwave and RF applications, the wide-band nature of digital signals requires a more accurate description of laminate behavior, something that was not a must in the past. In recent years new measurement methodologies have been proposed, and now IPC has a mix of methodologies. Some were developed originally for the microwave industry, and newer methodologies, targeted to understand the wide-band nature of laminates. PCB designers today have this sometimes confusing choice of test methodologies, at the same time specification numbers for seemingly the same laminate may be vastly different. This panel discussion brings together laminate-manufacturer and OEM experts to help the user to sort through laminate data, specification numbers and test methodologies.

Panelist biographies

Don DeGroot, CCNi
Dr. Don DeGroot is President of CCNi, a test and measurement business supporting high-speed electronic design. Don has 25 years experience in high-frequency measurements and design with industry, government, and academia. He currently focuses on services that add high value to design and manufacturing, including multiport TDR and S-parameter measurements, dielectric characterization, and component qualification. Don's work includes over 100 publications and presentations that have been recognized with the U.S. Department of Commerce Silver Medal and society awards.

Roger Krabbenhoft, IBM
Mr. Krabbenhoft received a BS degree in Electrical and Electronics Engineering from North Dakota State University in 1991, after which he joined IBM's Storage Division in Rochester, MN. He spent the first 9 years of his career at IBM focusing on various aspects of HDD actuator flex cable design/development, test, and failure analysis. In 2000, he transferred to IBM's Systems and Technology Group where he led a team of engineers responsible for the development and qualification of printed circuit board technologies for IBM's server family. His recent work is in the area of high speed printed circuit board solutions for next generation server applications.

Tony Senese, Panasonic Electric Works
Mr. Senese is OEM Business Development Manager for Panasonic Electric Works R&M Group. He was formerly the Vice President of Taconic-TCL in La Verne, CA. Mr. Senese started with the Mica Corporation as an engineering technician in 1979 and has worked in various engineering, quality, manufacturing, management, and marketing functions in the industry over the last 30 years. He is the current Chair of the IPC 3-11 subcommittee overseeing the IPC-4101 specification. In 2006 and 2009 he received IPC Distinguished Service Awards for his work on the B-revision and the C-revision of that document. Mr. Senese has published numerous technical papers and instructed the IPC Professional Advancement Course on Substrate materials.

Allen F. Horn, Rogers Corp.
Dr. Horn, III received a BSChE from Syracuse University in 1979, and a Ph. D. in chemical engineering from M.I.T. in 1984. Prior to joining the Rogers Corporation Luire R&D Center in 1987, he worked for Dow Corning and ARCO Chemical. He is an inventor/co-inventor on 15 issued US patents in the area of ceramic or mineral powder-filled polymer composites for electronic applications.

Istvan Novak, SUN Microsystems
Dr. Novak is Distinguished Engineer, signal and power integrity, at SUN Microsystems, Inc.
In addition to signal-integrity system design of high-speed serial and parallel buses, he is engaged in the methodologies, designs and characterization of power-distribution networks and packages for workgroup servers. Dr. Novak has 30+ years of experience with high-speed digital, RF, and analog circuit and system design and has twenty five patents. He is Fellow of IEEE for his contributions to the signal-integrity and RF measurement and simulation methodologies.

CCNi

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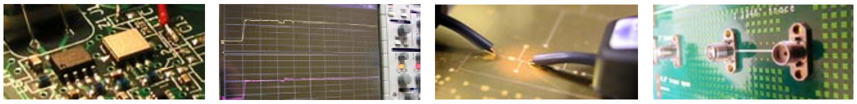


Making Sense out of Dielectric Loss

Dr. Don DeGroot

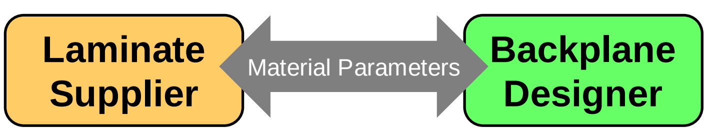
~~Holistic Center for Faith-Based Design~~
~~Santa Cruz, CA~~

CCNi, PCB Measurements (for Design)
Longmont, Colorado

Standards Empower Commerce

OEM just wants it all to work

OEM & suppliers must agree on the meaning of the specs to make it work

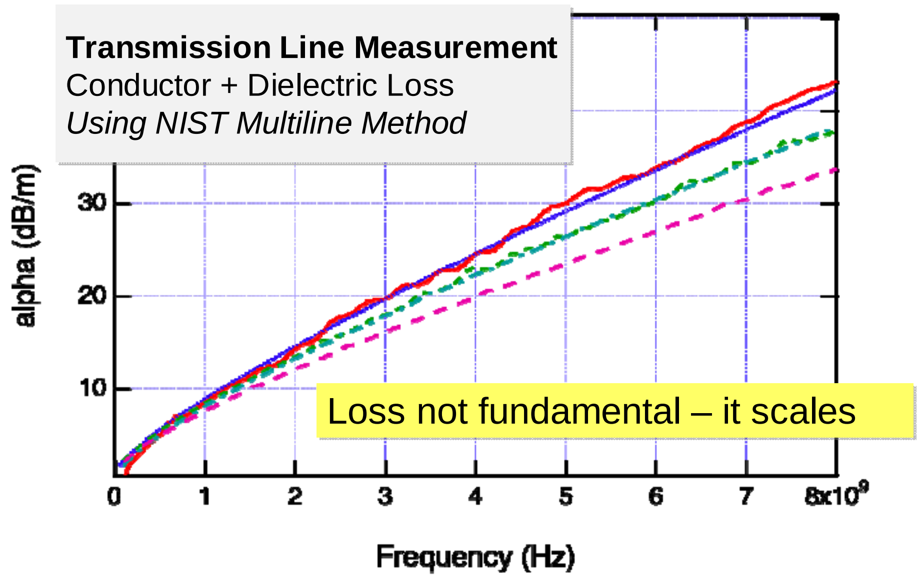


Design tools asking for **Df**(*f*) and **R**

Can we agree on how to get **Df**(*f*) & **R**?

Can we agree that we need **Df**(*f*) & **R**?

Total Transmission Line Loss Kills Speed



Material Parameters Are Fundamental

Parallel Plate Capacitor
ASTM-D150 & IPC TM-650 2.5.5.9
- Unclad or patterned samples
- Easy to use, standard computation
- Air gap errors at interfaces
- Normal **E**-field orientation
- Broadband 1 kHz < *f* < 1.8 GHz
- Low accuracy

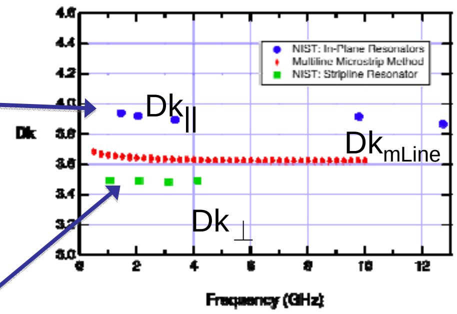
Stripline Resonator
IPC TM-650 2.5.5.5C & 2.5.5.5.1
- Metal-Sample-Conductor-Sample-Metal
- Difficult mechanical fixtures and coupling
- Air gap errors (depolarization) at interfaces
- Normal **E**-field orientation
- Discrete frequencies in range 1-10 GHz
- Good accuracy

Microstrip Resonator
End-Coupled & Ring
- Patterned microstrip resonators
- No special fixtures
- Non-standard Dk & Df computation
- Composite **E**-field, mostly normal
- Discrete frequencies in range 1-10 GHz
- Fair accuracy, depends on user & design

Split Cylinder Resonator
IPC TM-650 2.5.5.13
- Unclad material, must be flat and smooth
- Easy to use, standard Dk & Df computation
- Tangential **E**-field orientation, only
- Discrete frequencies in range 5-30 GHz
- High accuracy (NIST reference method)

We get different **Dk** answers based on method

Split Cylinder Reference
Courtesy of NIST



Stripline Resonator Reference
IPC TM 650-2.5.5.5 Courtesy of NIST

Depends on field orientation & glass weave orientation

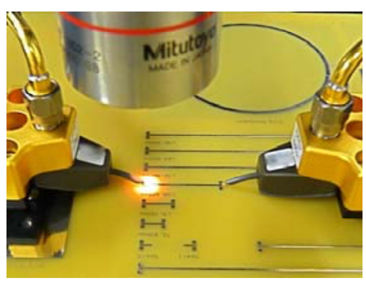
Does **Df** vary with test method?

CCNi www.PCBmeasurements.com

New IPC Test Method Activity – Multiline Dk & Df

Z measurements of conductors, then s2p with either VNA or TDNA

VNA Measurements Microstrip Coupon Probe Contacts

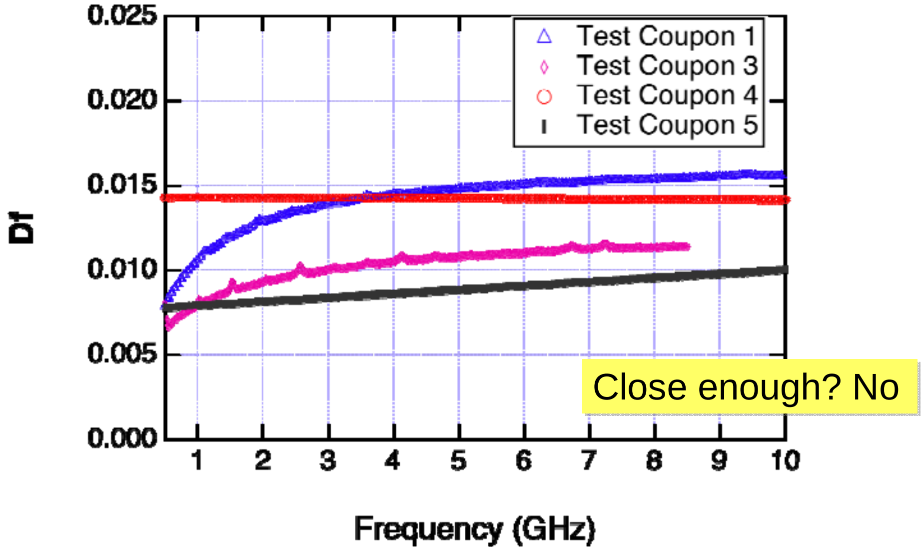


Z Measurements Short-Circuit Lines Probe Contacts

TNDA Measurements Stripline Coupon w/SMA
WaveExpert courtesy of LeCroy

Get and use low freq R & L of conductors directly!

Striplines & Microstrips give different **Df**



At the End of the Day

- Must get Dk & Df from real test coupons
- Must separate conductor & material loss
  - If we want fundamental parameters for trade
- Must improve low-*f* conductor models
  - Can measure R & L to 0.5 GHz, maybe 1 GHz
- IPC committee on two prong attack
  - Total Loss for test-coupon screening
  - Fundamental material parameters for trade

Practical Measurement of Broadband Laminate Loss Characteristics

Roger Krabbenhoft
Sr. Engineer, PCB Technology
rkrabben@us.ibm.com

Historical Laminate Electrical Property Assessment

- Varied Methods of Assessment
- Valid In Certain Frequency Ranges / Transition Not Smooth
- Does Not Account For PCB Fabricator Influence
- Resolution of Information On Internet

Electrical			
Permittivity (RC 50%)			
1MHz (LCR meter)	C-24/23/50	< 5.4	4.5
1GHz (HP4291B)	C-24/23/50	-	4.2
Loss Tangent (RC 50%)			
1MHz (LCR meter)	C-24/23/50	< 0.035	0.016
1GHz (HP4291B)	C-24/23/50	-	0.016
Volume Resistivity	C-96/35/90	> 10^6	> 10^{10} MΩ·cm
Surface Resistivity	C-96/35/90	> 10^4	> 10^8 MΩ

Practical Measurement Method

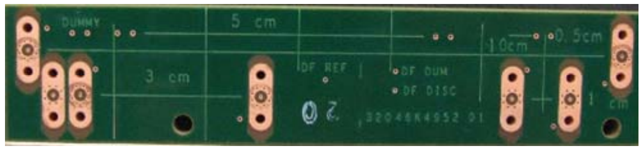
- **Short Pulse Propagation (SPP) Test Method, IPC TM650 2.5.5.12**
  - Addresses Issues Surrounding Previous Assessment Techniques
  - Allows for Broadband, Causal Characterization
    - Can Create Predictive Models, Useful To System Designers
  - Accounts For All Factors Which Influence Performance
    - Laminate Properties
    - Cu Foil Attributes
    - PCB Fab Chemistry (Adhesion Promotion)
  - Can Be Done In-Situ In Product Designs
  - Tools
    - Uses Time Domain Equipment With Which Vendors Are Familiar
    - Production Floor Employees Can Operate With Existing GUI
  - Extendable to 40+ GHz With Supporting Equipment

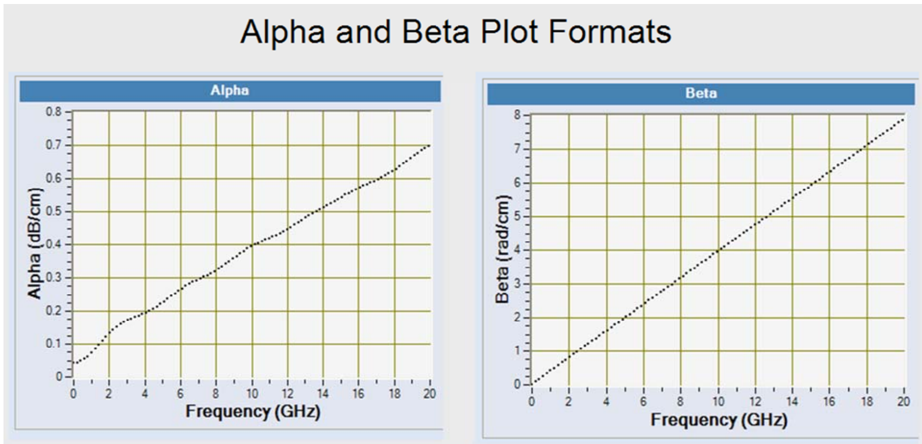
Practical Measurement Method

- **Varied Degrees of Applying The SPP Technique**
  - Output Propagation Constant Of Product Structures, Alpha/Beta
    - Production Floor, In-Situ Assessment Is Currently Available
      - Introbotics Corp., ACCU Prober With SPP
      - Facilitates Statistical Understanding of Supplier Output
  - Output ‘Effective’ Laminate Properties Of Product Structures
    - Lab Assessment
    - Use Actual Production Fabrication Processes/Materials
  - Output Laminate-Specific Properties
    - Lab Assessment
    - Facilitated Through Use of Profile-Free / Smooth Cu Foil

- **Available For Industry Wide Use**

Example Product Coupon and Data





Measuring Laminate Loss

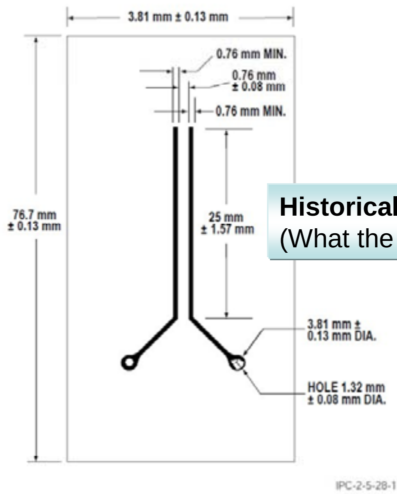
Supplier Challenges

Tony Senese
Panasonic Electric Works
Research and Marketing

Measuring Laminate Loss Supplier Challenges

- **Historical Perspective….**
- **Recent trends…**
- **Future Possibilities**

Measuring Laminate Loss
Supplier Challenges



Historical Perspective….
(What the heck is Q resonance testing for anyway?)

Measuring Laminate Loss
Supplier Challenges

Recent trends… Proliferation of methods, is that 2.5.5.5 or 2.5.5.12?

In 1980 only 3 IPC methods existed for characterizing Permittivity and Loss…

2.5.2A	Capacitance of Insulating Materials--*7/75*
2.5.5A	Dielectric Constant of Printed Wiring Materials--*7/75*
2.5.8A	Dissipation Factor of Flexible Printed Wiring Material--*7/75*

Measuring Laminate Loss
Supplier Challenges

Recent trends… Proliferation of methods, is that 2.5.5.5 or 2.5.5.12?

By 1990 we had 13 IPC methods relating to signal integrity…..

2.5.2A	Capacitance of Insulating Materials--*7/75*
2.5.5A	Dielectric Constant of Printed Wiring Materials--*7/75*
2.5.5.1B	Permittivity (Dielectric Constant) and Loss Tangent (Dissipation Factor) of Insulating Material at 1MHz (Contacting Electrode Systems)--*5/86*
2.5.5.2A	Dielectric Constant and Dissipation Factor of Printed Wiring Board Material--Clip Method--*12/87*
2.5.5.3C	Permittivity (Dielectric Constant) and Loss Tangent (Dissipation Factor) of Materials (Two Fluid Cell Method)--*12/87*
2.5.5.4	Dielectric Constant and Dissipation Factor of Printed Wiring Board Material--Micrometer Method--*10/85*
2.5.5.6	Non-Destructive Full Sheet Resonance Test for Permittivity of Clad Laminates--*5/89*
2.5.8A	Dissipation Factor of Flexible Printed Wiring Material--*7/75*
2.5.18B	Characteristic Impedance Flat Cables (Unbalanced)--*7/84*
2.5.19A	Propagation Delay of Flat Cables Using Time Domain Reflectometer--*7/84*
2.5.19.1A	Propagation Delay of Flat Cables Using Time Domain Reflectometer (TDR)--*7/84*
2.5.21A	Digital Unbalanced Crosstalk, Flat Cable--*3/84*
2.5.28A	Q Resonance, Flexible Printed Wiring Materials--*4/88*

Measuring Laminate Loss
Supplier Challenges

Recent trends… Proliferation of methods, is that 2.5.5.5 or 2.5.5.12?

We now have 23 IPC TM's to test materials Dk and Df…..

2.5.5.4	Dielectric Constant and Dissipation Factor of Printed Wiring Board Material--Micrometer Method--*10/85*
2.5.5.5C	Stripline Test for Permittivity and Loss Tangent (Dielectric Constant and Dissipation Factor) at X-Band--*3/98*
2.5.5.5.1	Stripline Test for Complex Relative Permittivity of Circuit Board Materials to 14 GHZ--*3/98*
2.5.5.6	Non-Destructive Full Sheet Resonance Test for Permittivity of Clad Laminates--*5/89*
2.5.5.7a	Characteristic Impedance Lines on Printed Boards by TDR--*3/04*
2.5.5.8	Low Frequency Dielectric Constant and Loss Tangent, Polymer Fil[illegible]
2.5.5.9	Permittivity and Loss Tangent, Parallel Plate, 1MHz t[illegible]
2.5.5.10	High Frequency Testing to Determine Per[illegible] of Embedded Passive Materials--*7/05*
2.5.5.11	Propagation Delay of Lines on [illegible]*09*
2.5.5.12	Test Methods to [illegible]ignal Loss on Printed Boards (PBs)--*5/09*
2.5.5.13	Relat[illegible]angent Using a Split-Cylinder Resonator--*1/07*
2.5.8A	[illegible] Flexible Printed Wiring Material--*7/75*
2[illegible]	[illegible]eristic Impedance Flat Cables (Unbalanced)--*7/84*
2.5[illegible]	Propagation Delay of Flat Cables Using Time Domain Reflectometer--*7/84*
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Measuring Laminate Loss
Supplier Challenges

Future Possibilities

Pick your poison and pay for it….

All testing requires investment…

- *Equipment, Methods, Personnel Etc…*

OEM's (designers) MUST drive test methods and push towards best standard test method.

Standardization saves time and $$$$$.

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Dielectric property testing: Some thoughts from a high frequency laminate supplier's point of view

Allen F. Horn, III
Associate Research Fellow
Lurie R&D Center
Rogers Corporation, Rogers CT USA

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- **Dielectric "constant"** (f(frequency, direction of travel, composition): material property related to the velocity of a fully developed EM plane wave traveling aligned with an axis of a medium of infinite extent of that material .

- **What the circuit designer really needs:**

Data that cause the model being used to design a circuit to predict the measured performance of the physical circuit

The outcome will depend on the model and how it treats conductor losses and anisotropy, as well as the material properties

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Conductor roughness effects

- A lot of recent work, both computational and experimental, has shown that conductor roughness can have a greater effect on insertion loss than previously thought

Conductor roughness effects

1. G. Brist, S. Hall, S. Clouser, & T. Liang, "Non-classical conductor losses due to copper foil roughness and treatment," *2005 IPC Electronic Circuits World Convention,* February 2005
2. T. Liang, S. Hall, H. Heck, & G. Brist, "A practical method for modeling PCB transmission lines with conductor roughness and wideband dielectric properties," IEE MTT-S Symposium Digest, p. 1780, November 2006
3. S. Hinaga, M., Koledintseva, P. K. Reddy Anmula, & J. L Drewniak, "Effect of conductor surface roughness upon measured loss and extracted values of PCB laminate material dissipation factor," *IPC APEX Expo 2009 Conference*, Las Vegas, March 2009
4. X. Chen, "EM modeling of microstrip conductor losses including surface roughness effect," *IEEE Microwave and Wireless Components Letters,* v. 17, n.2, p. 94, February 2007
5. L. Tsang, X. Gu, & H. Braunisch, "Effects of random rough surfaces on absorption by conductors at microwave frequencies, *IEEE Microwave and Wireless Components Letters,* v. 16, n. 4, p. 221, April 2006
6. R. Ding, L. Tsang, & H. Braunisch, "Wave propagation in a randomly rough parallel-plate waveguide," *IEEE Transactions on Microwave Theory and Techniques,* v. 57, n.5, May 2009
7. A. Deutsch, C. W. Surovic, R. S. Rabbenhoft, G. V. Kopcsay, and B. J Chamberlin, "Prediction of losses caused by roughness of metallization in printed circuit boards," IEEE Transaction on Adv. Packaging, v.30, n.2, May 2007

Conductor roughness effects

- Some work has shown there can be a significant effect on conductor roughness on propagation constant as well.

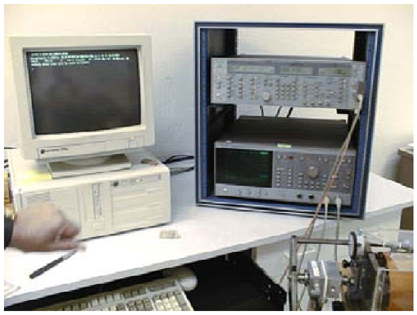
1. Deutsch, A. Huber, G.V. Kopcsay, B. J. Rubin, R. Hemedinger, D. Carey, W. Becker, T Winkel, & B. Chamberlin, p. 311, ., *IEEE Symposium on Electrical Performance of Electronic Packaging, 2002*

What the laminate manufacturer really needs:

A test to insure that a material with dielectric properties that fall within the specification limits is made.

What the laminate manufacturer really needs:

A test to insure that a material with dielectric properties that fall within the specification limits is made.



Standard IPC-4103 dielectric constant test method:
X-Band Stripline Test, 23C/50% RH

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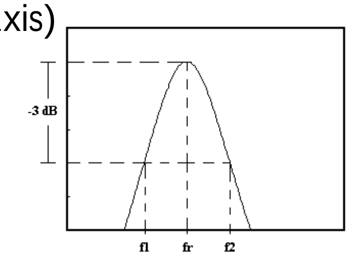
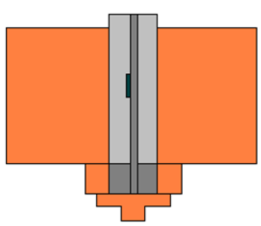
IPC-TM-650 2.5.5.5

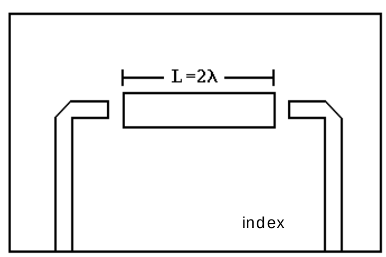
- $\varepsilon r = [nc/(2f_r\{L+\Delta L\})]^2$ (z-axis)
- $1/Q_U = 1/Q_C + 1/Q_D$
- $\tan\delta \propto 1/Q_D$

$\tan\delta = [(f_2-f_1)/f_r] - 1/Q_c$

$1/Q_c$: conductor losses







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Advantages

- homogeneous medium
- simple equations, no dispersion
- measure dielectric constant and loss tangent
- allow to measure within sheet variation
- Operator independent and very repeatable

Disadvantages

- measures one thickness only
- destructive test
- Doesn't really give an accurate DK number for rigid or high DK materials due to "air gap" from the profile of the conductor left behind when the material is etched.

- Circuit substrate manufacturers will need to assist in practical measurements of circuit performance factors, as well as continue with historical QC methods for material uniformity and process control.

Challenges of Laminate Selection and Specification

Istvan Novak, Sun Microsystems

Our Wish List…

OEMs need

- Scalable interconnect models for worst-case simulations
- Alternate laminate sources, managed by specifications

Laminate vendors want

- Advertise and trade laminates based on specifications

The Problem with Specification

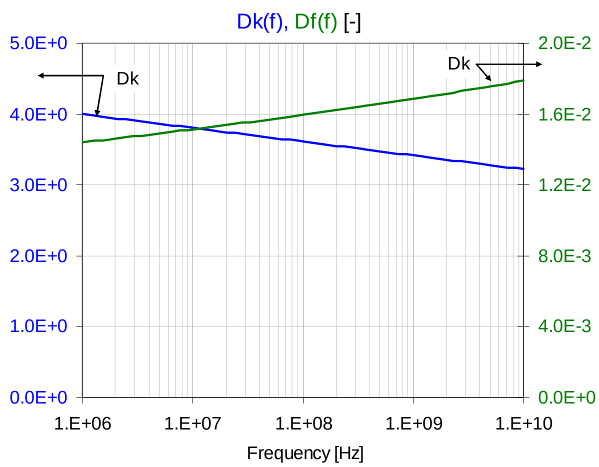
- High-speed digital applications need wide-band laminate characterization data
- System simulations need wide-band frequency-dependent laminate models (and it should be causal)

BUT

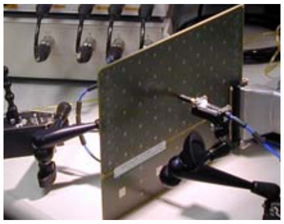
- Test methods providing continuous frequency plots are limited to lower frequencies (approx. < 1 GHz)
- High-frequency test methods yield discrete frequencies
- Field orientation may be different from usage
- Performance in finished PCB may be different

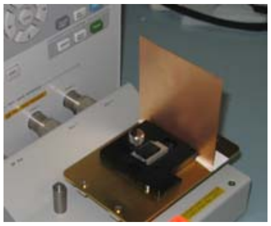
Wide-Band Causal Model

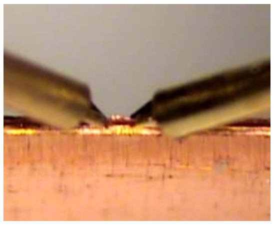
$$\varepsilon_r(\omega) = \varepsilon'_\infty + \frac{\Delta\varepsilon'}{m_2 - m_1}\ln\frac{\omega_2 + j\omega}{\omega_1 + j\omega}\frac{1}{\ln(10)}$$

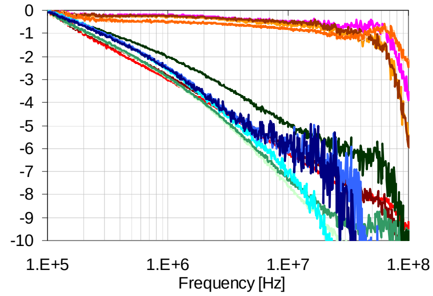


Direct Impedance Measurements









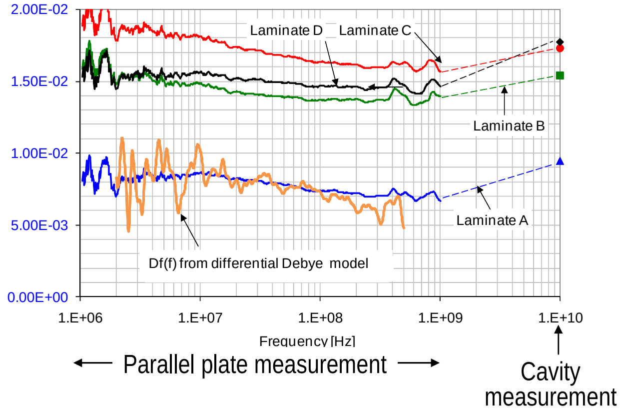
Good below the structural resonances <1GHz

Measurement vs Model

Differential Debye model:

$$Df(f) = \frac{C(f)-C(f+\Delta f)}{C(f)} \frac{a}{\ln\left(\frac{f+\Delta f}{f}\right)}; \quad a = \frac{\pi/2}{\ln(10)}$$

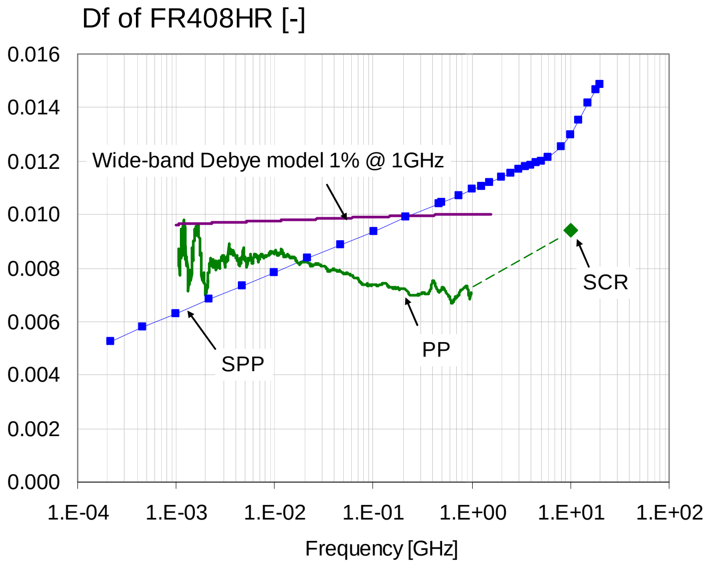
Df(f) of four different laminates



Note the negative slope of Df below 1GHz

Captured if the Debye model is applied differentially

Different Test Methods



Significant disagreement among different test methods and the wide-band Debye model

The Path Forward

- Use interconnect data measured on real-life stackup
- Fit simulation model to measured performance

BUT

- This does not necessarily allow for separate specification of laminate dielectric loss
- Laminate performance can not be evaluated independent from the copper and the PCB fabrication process details