DesignCon 2012

WHERE CHIPHEADS CONNECT

Comprehensive Analysis of Flexible Circuit Materials Performance in Frequency and Time Domains

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Outline

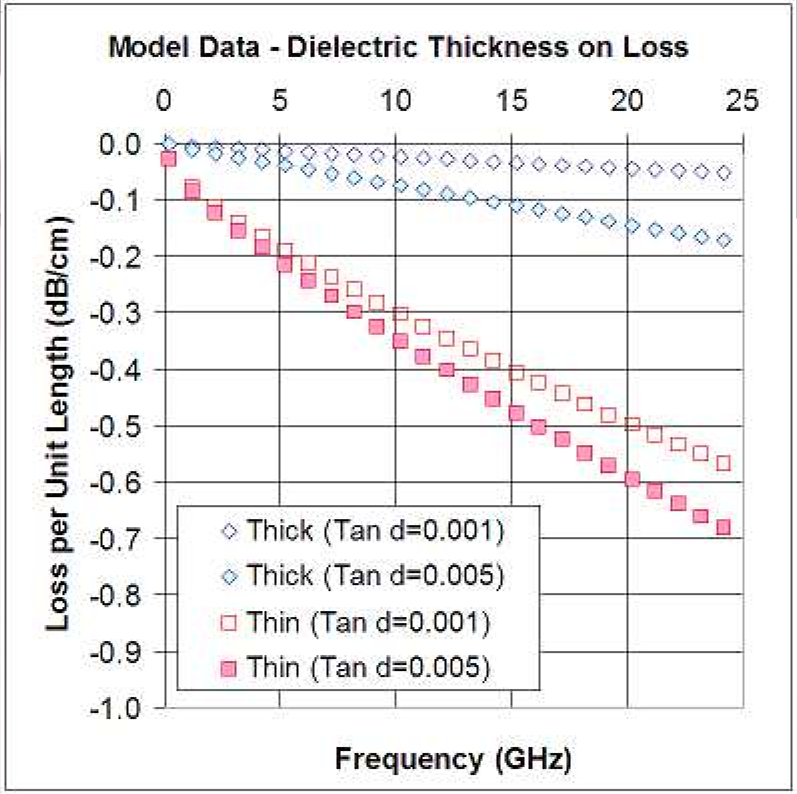
- Motivation for Work
- Overview of Testing and Analysis
  - Phase I
  - Phase II
  - Phase III
- Phase I Test Results and Analysis
- Phase II Test Results and Analysis
- Phase III Analysis
- Additional Results Compared to Phase I Baseline

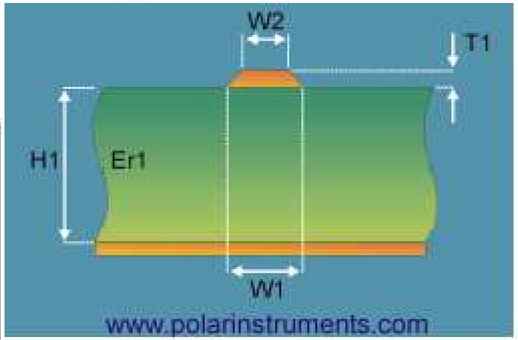
Motivation

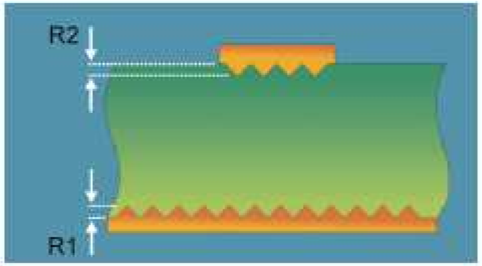
- *SOURCE: Global Mobile Data Traffic Forecast Update, 2010–2015 (www.cisco.com).
  - Mobile network connection speeds will increase 10-fold by 2015 from 2010 Levels*
  - Global mobile data traffic will increase 26-fold between 2010 and 2015*
  - Two-thirds of the world's mobile data will be video by 2015*
- Data transmission at high speeds used to involve very specialized circuitry that was concentrated near the processor.
- High speed signals are no longer restricted to thick packages. There are many more applications for thin dielectrics.

Thin vs Thick Copper Clad Laminates

- For thin transmission lines at higher frequencies, many more factors influence signal loss than simply the dielectric loss tangent.







	Thick	Thin
H1=	1600 um	50 um
Er1=	3	3
W1=W2=	3988 um	112 um
T1=	18 um	18 um
TAN D=	0.001, 0.005	0.001, 0.005
R1=R2=	0.5 um	0.5 um
Cond=	$4x10^7$S/m	$4x10^7$S/m

Each Example is 50 Ohms

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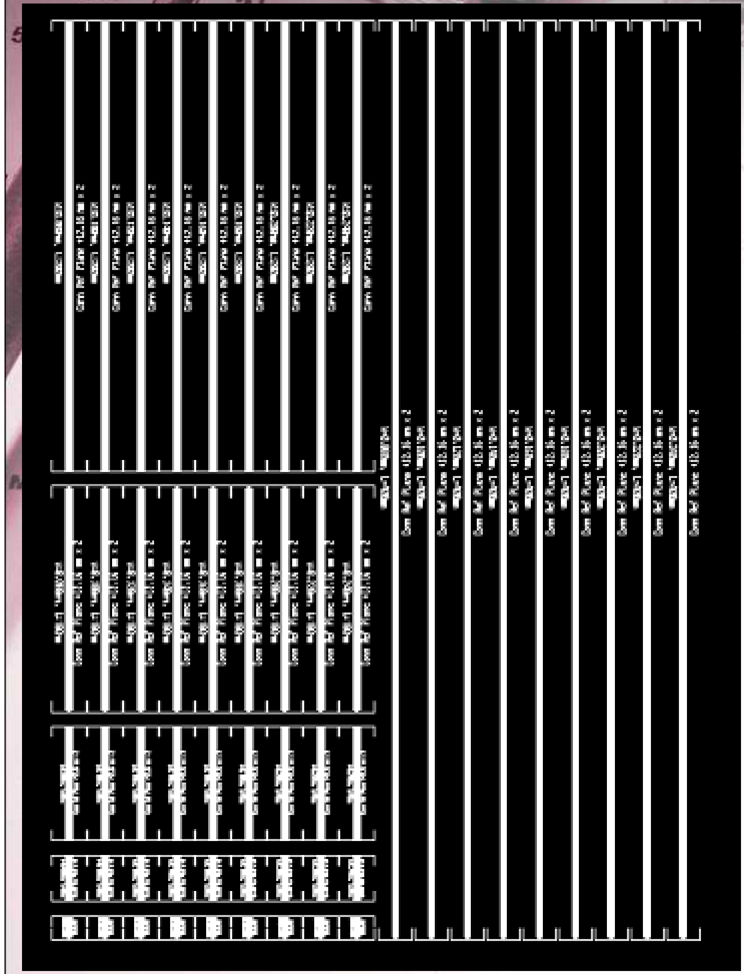
How to Evaluate Thin Dielectrics?

- Three Phase Plan:
  - Phase I – "Apples to Apples" comparison of microstrip lines made from copper clads made from 100um and 50um thick dielectrics.
    - Five Rigid Clads versus Five Flexible Clads
    - Directly Measure Impedance, S-Parameters and Eye Patterns
    - Extract Permittivity from Impedance Measurements
    - Analyze Loss Tangent from Transmission Loss Measurements
    - Evaluate Time Domain Effects from Eye Patterns
  - Phase II – Utilize specially designed connectors to obtain measured stripline results. Use Simbeor Methodology to extract parameters (Dk and Df) from stripline transmission lines.
  - Phase III – Apply extracted parameters to a PCIe-Gen3 application. Compare to parameters extracted from traditional flex used as incumbent material.

Phase I - Apples to Apples Comparisons

- All samples had 0.5 oz copper with dielectric between 50-100 um thick
- Rigid Copper Clads:
  - FR4-100 FR4 material, Standard Profile ED Cu, 100 um thick dielectric
  - M4-100 Mid-Range Glass / Epoxy, RTF Profile ED Cu, 100 um dielectric
  - M4-50 Mid-Range Glass / Epoxy, RTF Profile ED Cu, 50 um dielectric
  - M6-100 Low Loss Glass / Epoxy, Ultra Low Profile ED Cu, 100 um dielectric
  - M6-50 Low Loss Glass / Epoxy, Ultra Low Profile ED Cu, 50 um dielectric
- Flexible Copper Clads:
  - AP-100 Adhesiveless PI, Ultra Low Profile RA Cu, 100 um dielectric
  - AP-50 Adhesiveless PI, Low Profile RA Cu, 50 um dielectric
  - TK-100 Fluoropolymer/PI Composite, Ultra Low Profile RA Cu, 100 um dielectric
  - TK-75 Fluoropolymer/PI Composite, Ultra Low Profile RA Cu, 75 um dielectric
  - TK-50 Fluoropolymer/PI Composite, Ultra Low Profile RA Cu, 50 um dielectric

Phase I – Common Test Pattern



18”x12” Panel
- -Print and Etch
- -No plated finish (just bare copper)
  Black = Copper; White = Etched

Five Line Lengths
400 mm, 200 mm, 100 mm, 50 mm, 20 mm
(plus X-section samples)

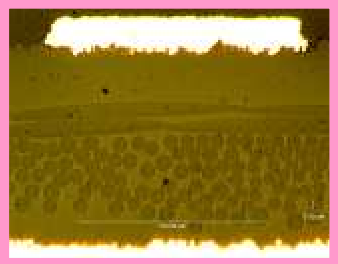
Nine Designed Line Widths (Wart):
240 um, 220 um, 200 um, 180 um, 160 um,
140 um, 120 um, 100um, 80 um

One set of lines used for cross section.

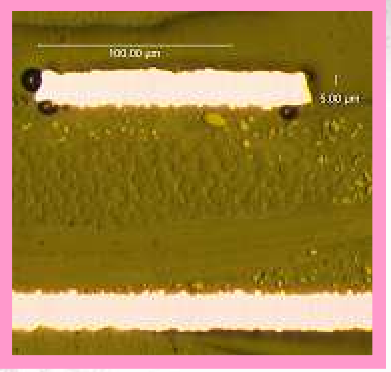
NOTE: These are ARTWORK widths, not final fabricated widths.

Representative X-Sections

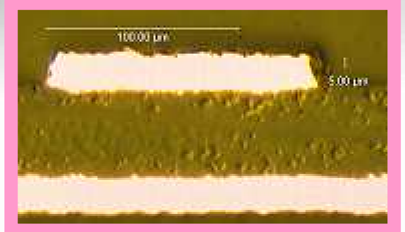
FR4-100



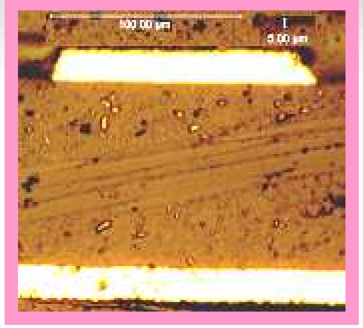
M4-100



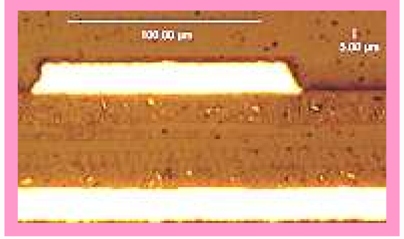
M4-50



M6-100



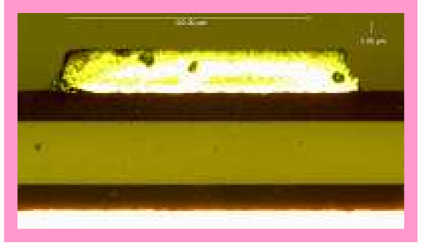
M6-50



AP-100

TK-100

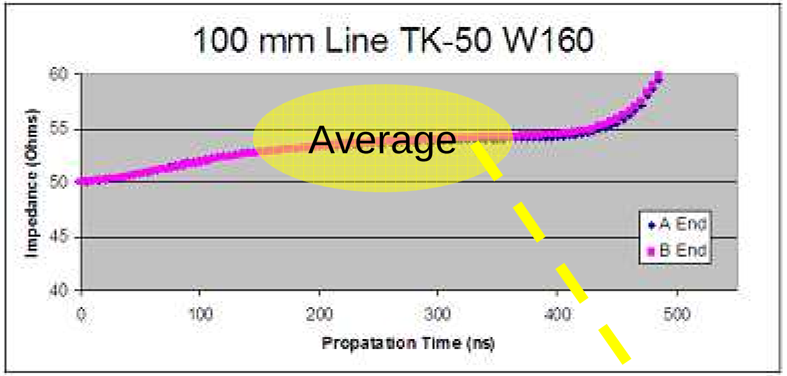
TK-50

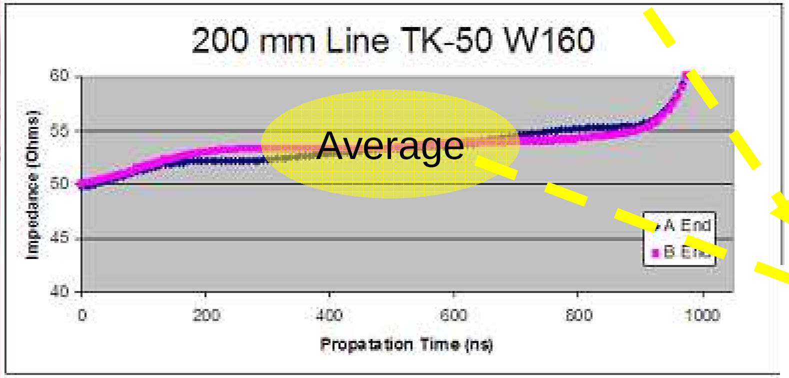


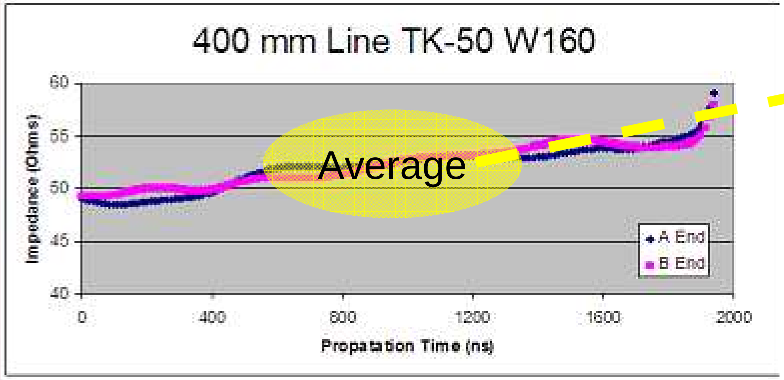
TK-75

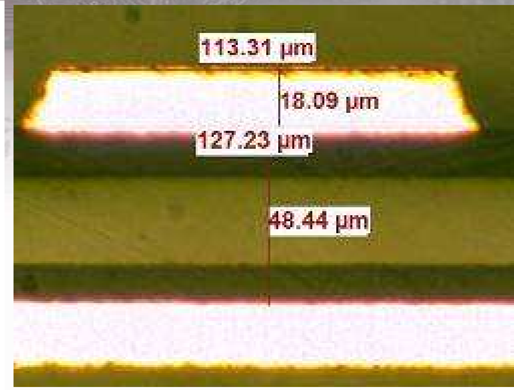
AP-50

Measure – TDR and X Section





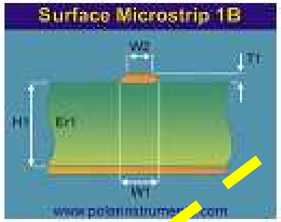




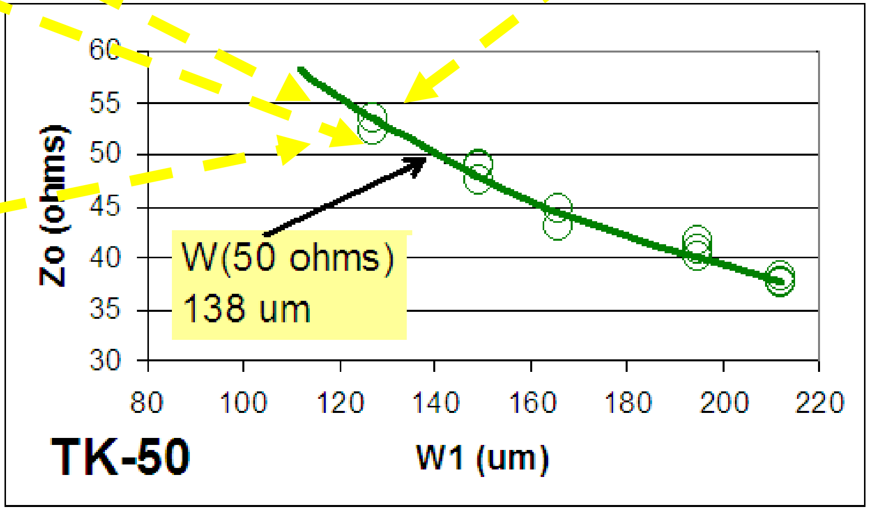
15 lines per clad (3 Lengths x 5 Widths)

This example shows measurement of one line width for one clad.

Compile 15 measurements and plot to obtain 50 ohm line width from curve-fit.



Flexible Clads (dimensions in um)					
Clad	Wart	H1	T1	W1	W2
TK-50	160	48	18	127	113
	180	50	18	149	137
	200	48	19	165	152
	220	49	18	195	182
	240	47	18	212	201



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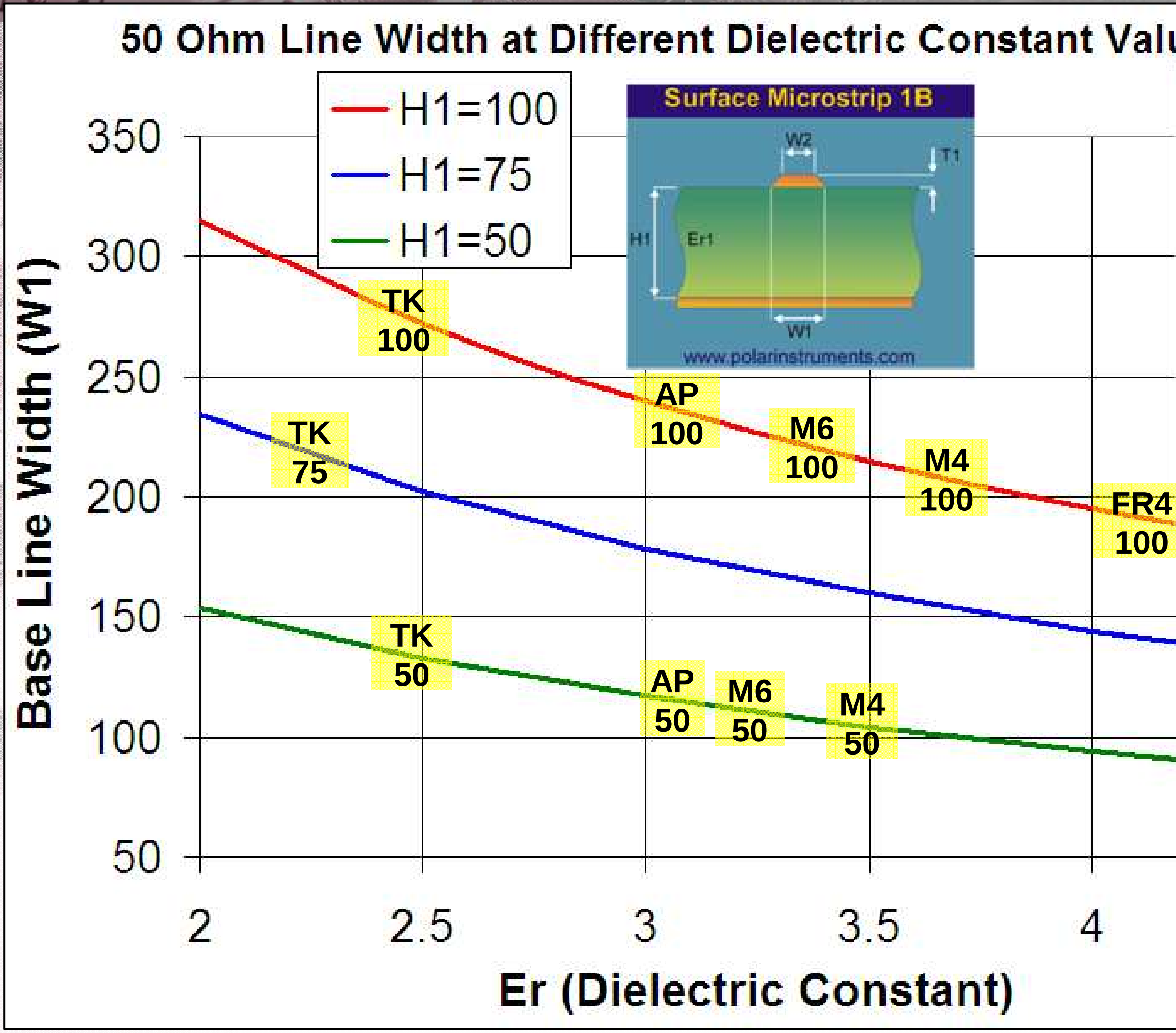
Summary of All Clads

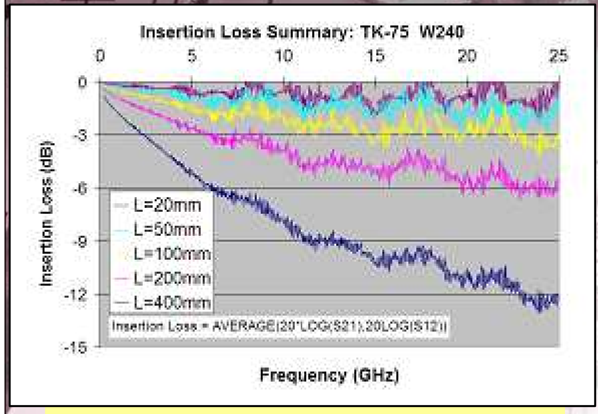


50 Ohm Line Widths from Figure 4	
Clad	W1(um)
FR4-100	191
M4-100	208
M6-100	223
AP-100	240
TK-100	276
TK-75	224
M4-50	107
M6-50	114
AP-50	119
TK-50	138

Loss Analysis Method

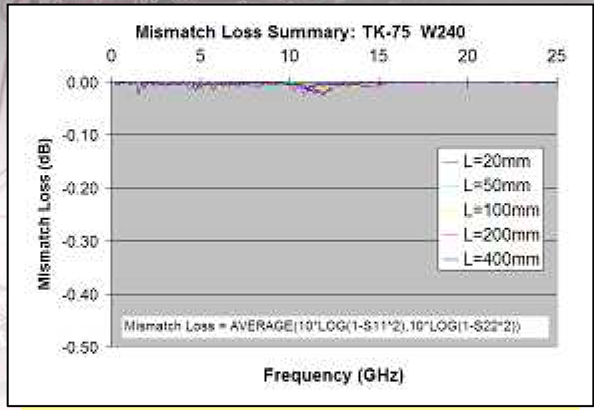
- 25 Lines Measured for Each Clad
  - 5 Lengths x 5 Widths
  - High Frequency Connectors Attached
- Vector Network Analyzer (VNA) Measurements
  - SOLT Calibration, Anritsu Lightning VNA
  - 0.2 – 25 GHz, 1601 Points
- Since all lines were not 50 ohms, mismatch loss is subtracted out to isolate only the signal loss that is due to transmission.
- Since five different lengths are measured, effects of connectors can be subtracted off by looking at the DIFFERENCE in loss divided by the DIFFERENCE in length.

From Raw to Summary Data



Insertion Loss from S21 and S12 of one width (5 lines)

-



Mismatch Loss from S11 and S22 of same lines

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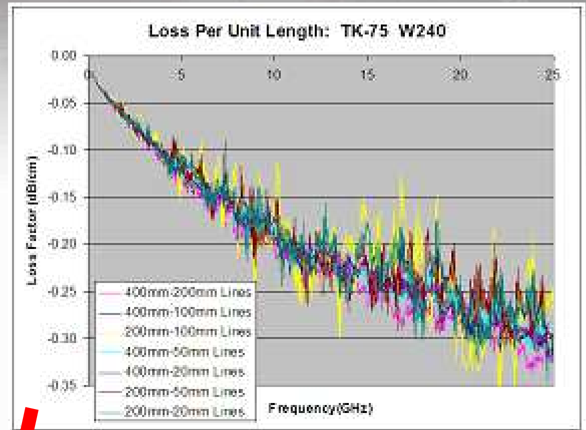
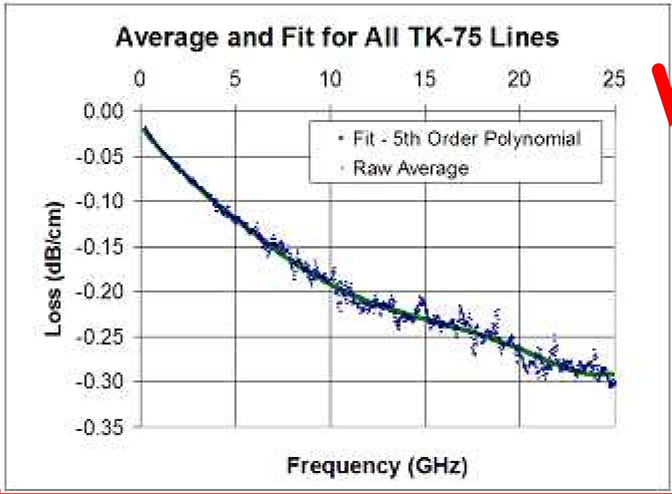
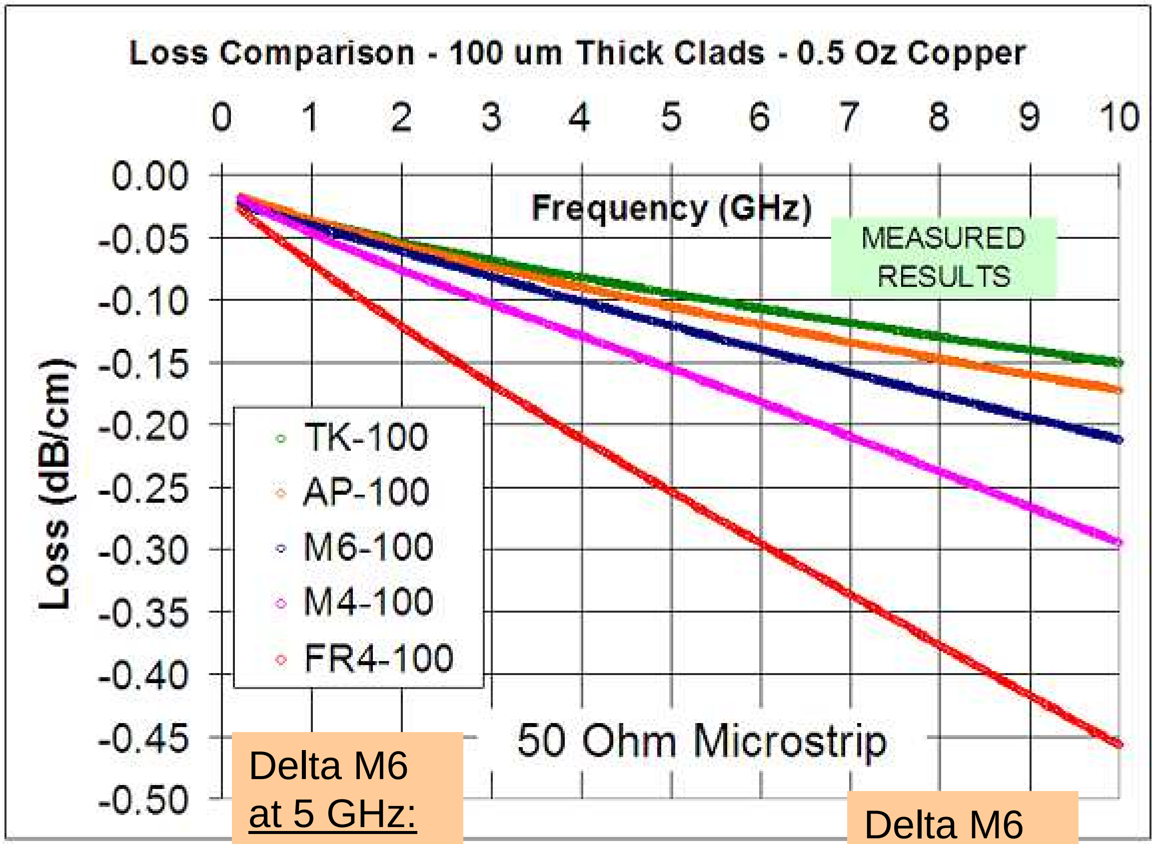


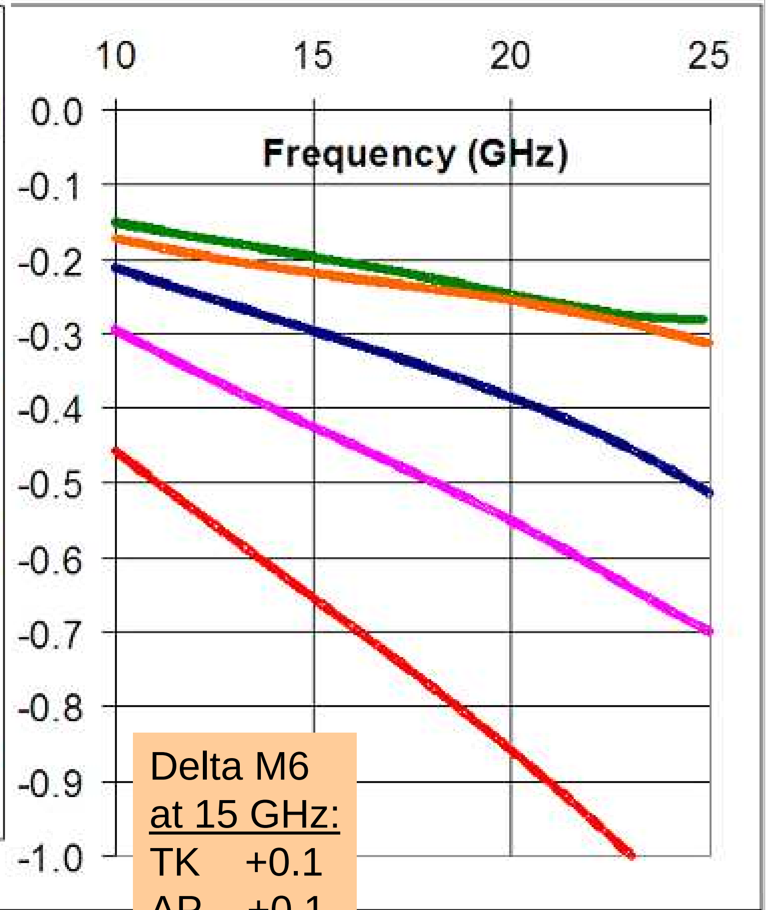
Loss/Length for each case length difference 100 mm or more



Average of 25 lines (five lengths x five widths) from the TK-75 clad

Summary Data – Loss 100 um Clads



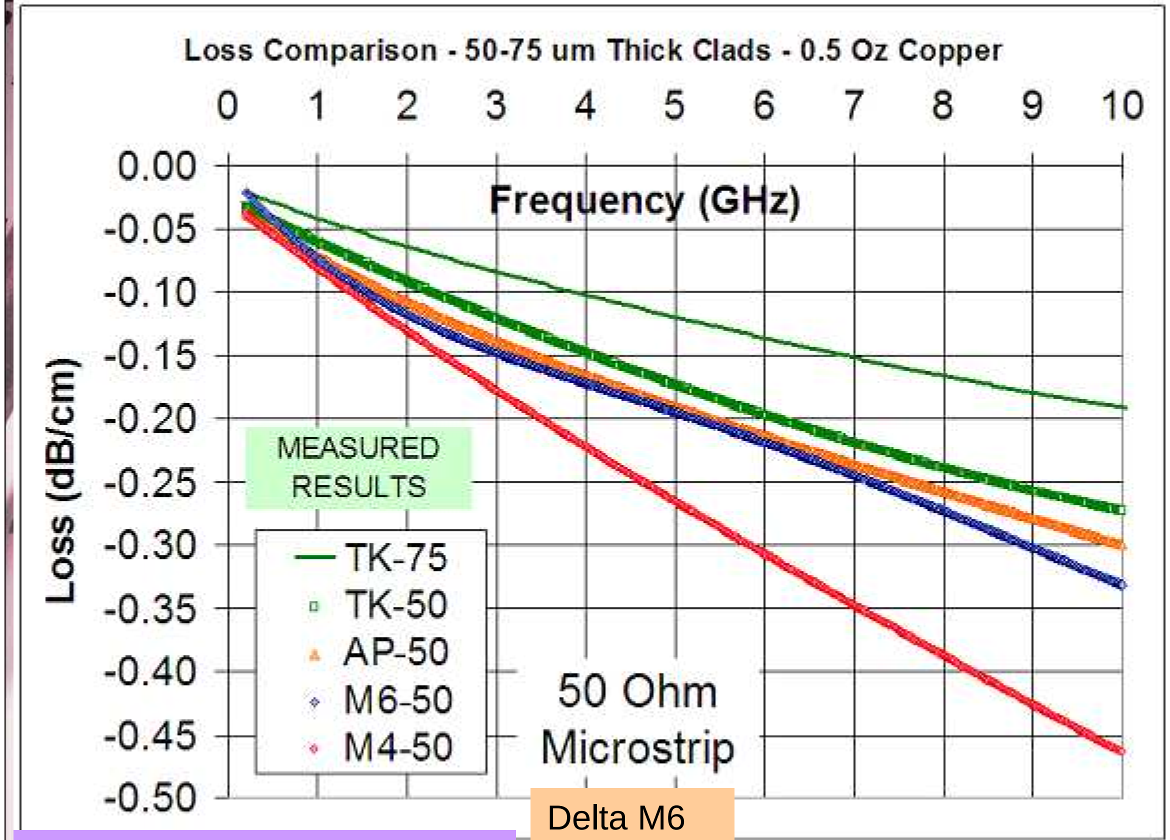


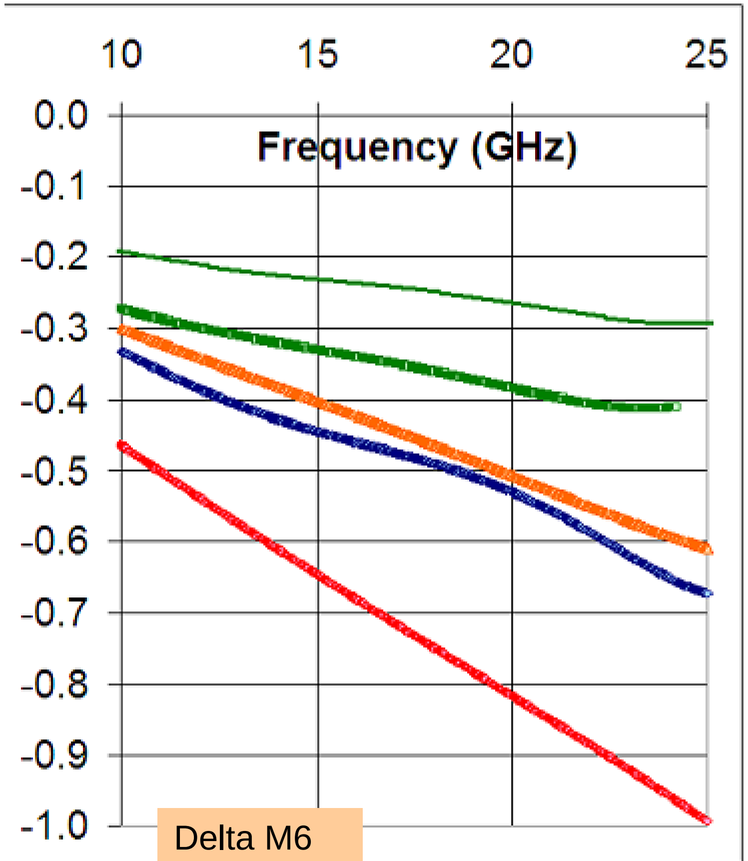
Delta M6
<u>at 5 GHz:</u>
TK +0.03
AP +0.01
M4 -0.04
FR4 -0.14

Delta M6
<u>at 10 GHz:</u>
TK +0.06
AP +0.04
M4 -0.08
FR4 -0.25

Delta M6
<u>at 15 GHz:</u>
TK +0.1
AP +0.1
M4 -0.1
FR4 -0.4

Summary Data – Loss 50-75um Clads





Thickness Effect at 5 GHz:
M6(50)-M6(100) = -0.07
M4(50)-M4(100) = -0.02
AP(50)-AP(100) = -0.08
TK(50)-TK(100) = -0.08

Delta M6 at 5 GHz:
TK +0.02
AP 0
M4 -0.07

Thickness Effect at 10 GHz:
M6(50)-M6(100) = -0.12
M4(50)-M4(100) = -0.01
AP(50)-AP(100) = -0.13
TK(50)-TK(100) = -0.12

Delta M6 at 10 GHz:
TK +0.06
AP +0.02
M4 -0.13

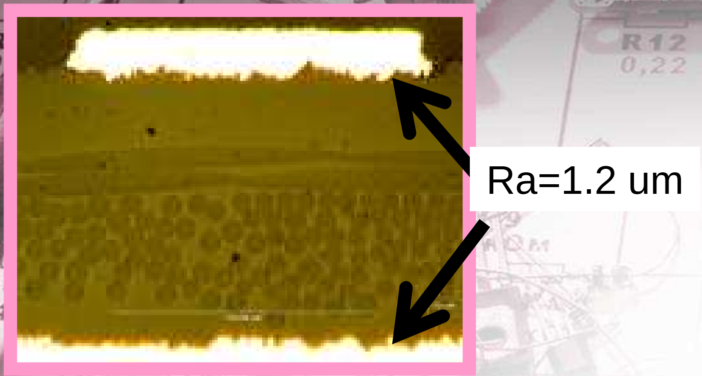
Lessons Learned from Loss Measurements

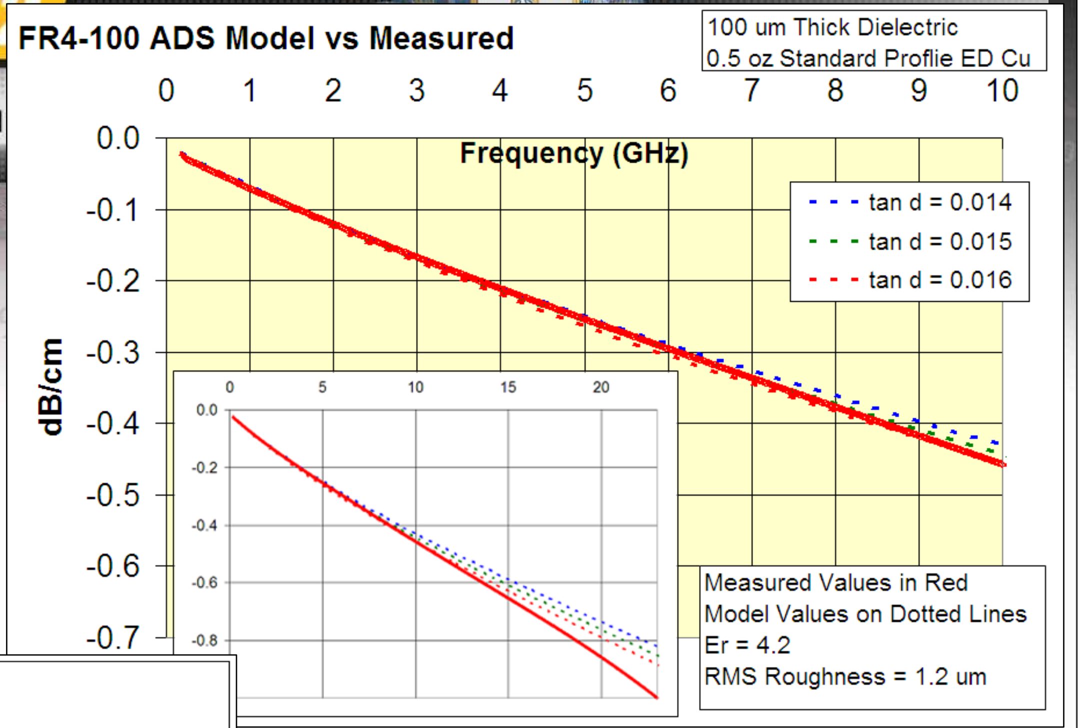
- Thickness of dielectric has a HUGE impact.
- The differences between 100 um thick and 50 um thick versions of the same dielectric are LARGER than any differences between different types of low-loss dielectrics of the same thickness.
- Loss differences get larger as frequency increases
  - Differences about double at 10 GHz versus 5 GHz
- dB per cm versus Frequency is roughly a linear function between 5 GHz and 25 GHz (once skin effect becomes dominant).

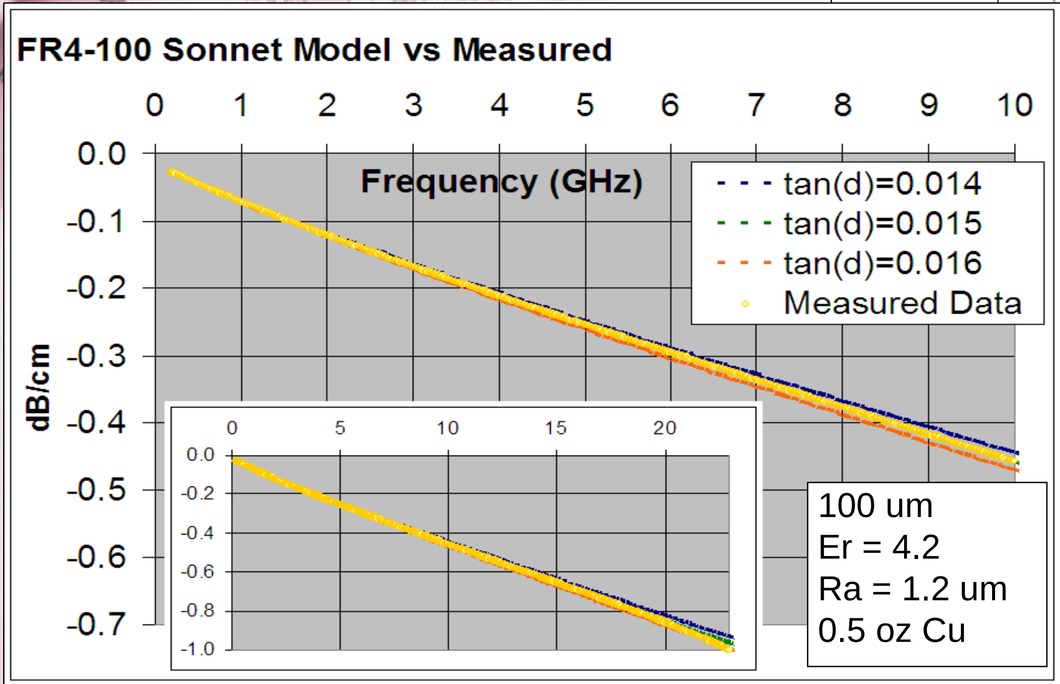
Extraction of Loss Tangent

- Roughness (Ra) estimated from measurements of treated side of Cu (flex samples) and estimated from cross sections (rigid samples).
- Conductivity measured by measuring DC resistance and back-calculating from cross sectional dimensions of lines. Found to be approximately 4 x 10^7 S/m. Same value used for all models.
- Loss Models Developed:
  - Used Agilent ADS and Polar SI9000 to calculate loss/cm up to 25 GHz. Determined to give virtually the same results.
  - Sonnet EM solver with thick metal model with roughness.
    - For composite dielectric, models are generated that assume…
      - Homogeneous (averaged) dielectric properties
      - Composite – individual dielectrics considered separately

FR4-100







Tan d between 0.014 – 0.016 at frequencies <10 GHz and >0.016 at higher frequencies

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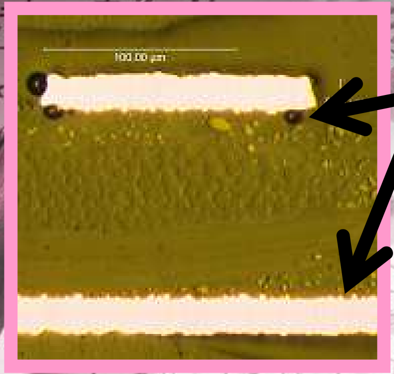
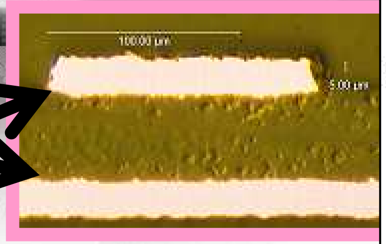
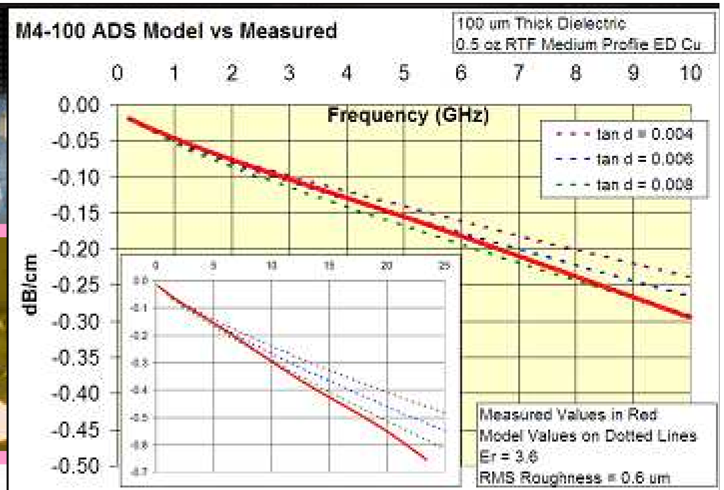
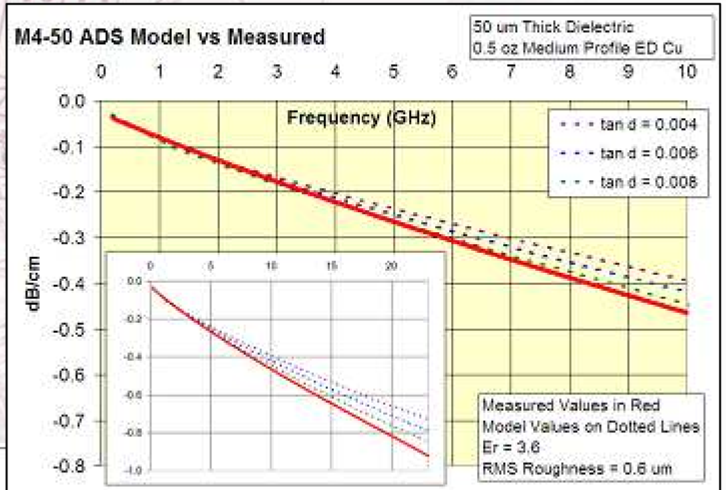
M4-100, M4-50

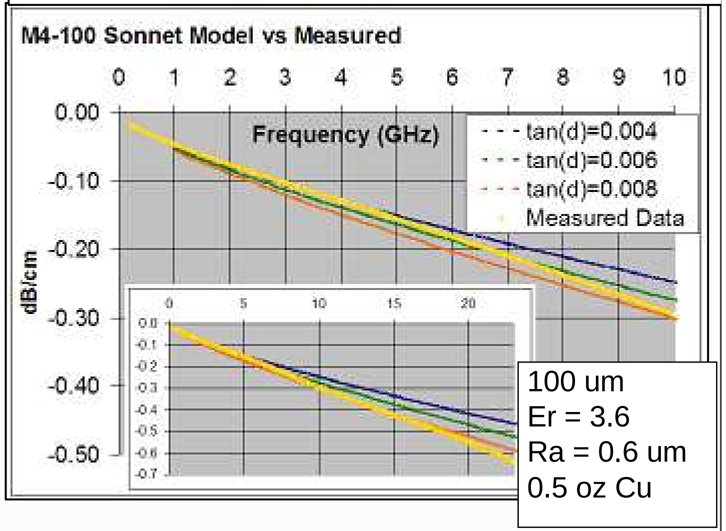


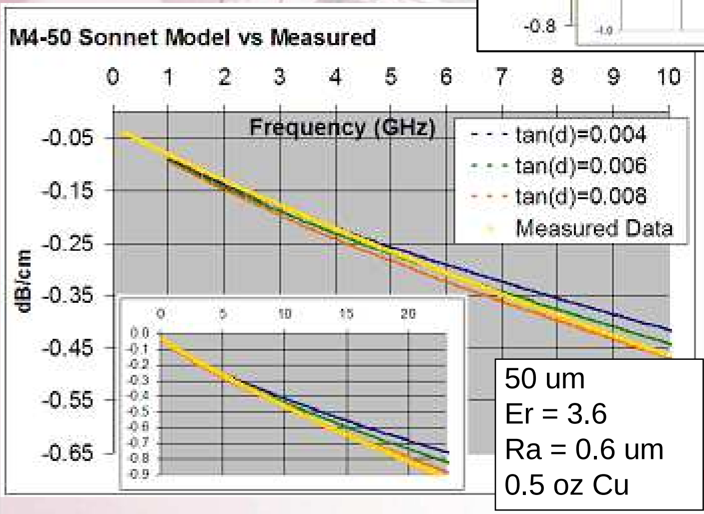
Ra=0.6 um





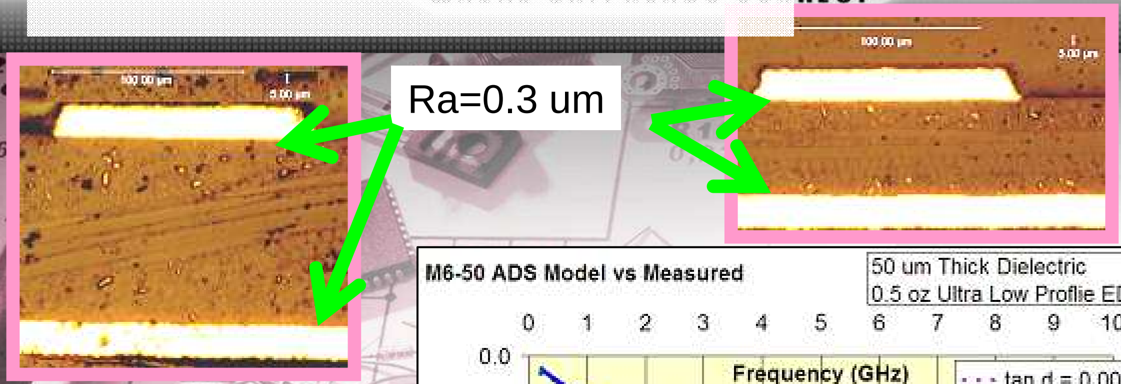


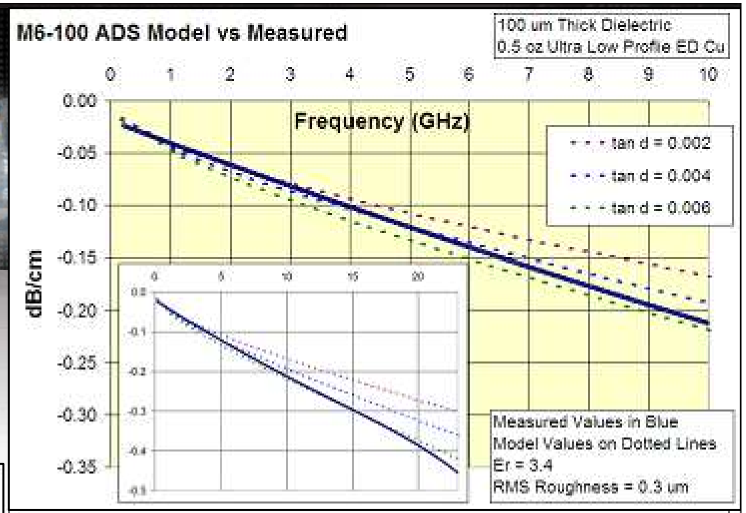


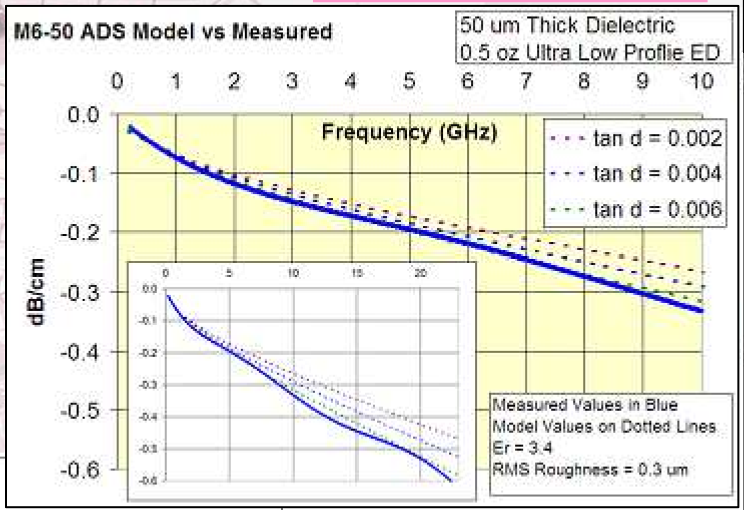


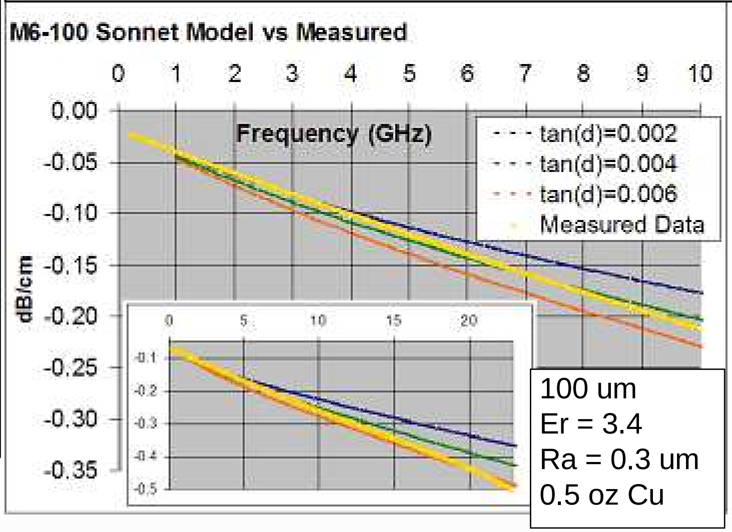
Tan d is between 0.004 – 0.006 at frequencies <5 GHz, 0.006 – 0.008 between 5-10 GHz and >0.008 at higher frequencies

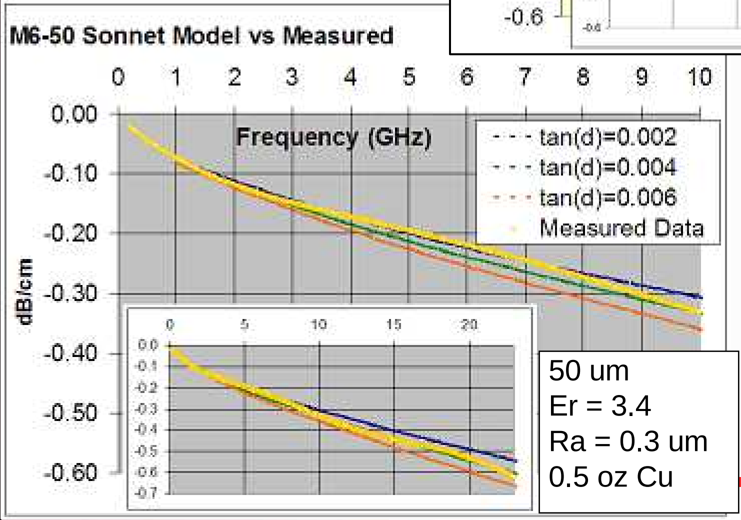
M6-100, M6-50











Tan d is 0.002 at frequencies <5 GHz, 0.002 – 0.004 between 5-10 GHz and >0.004 at higher frequencies

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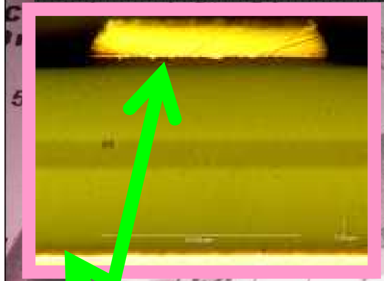
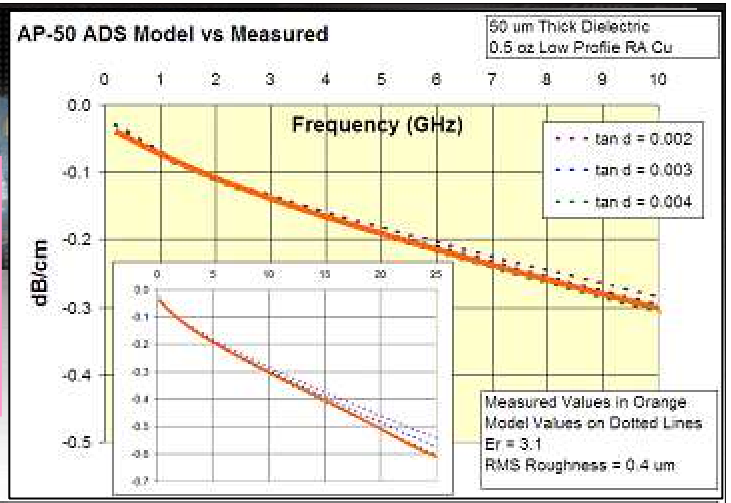
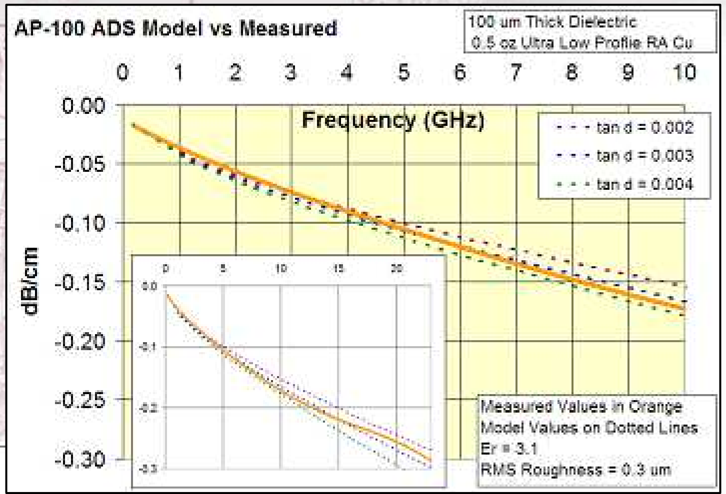
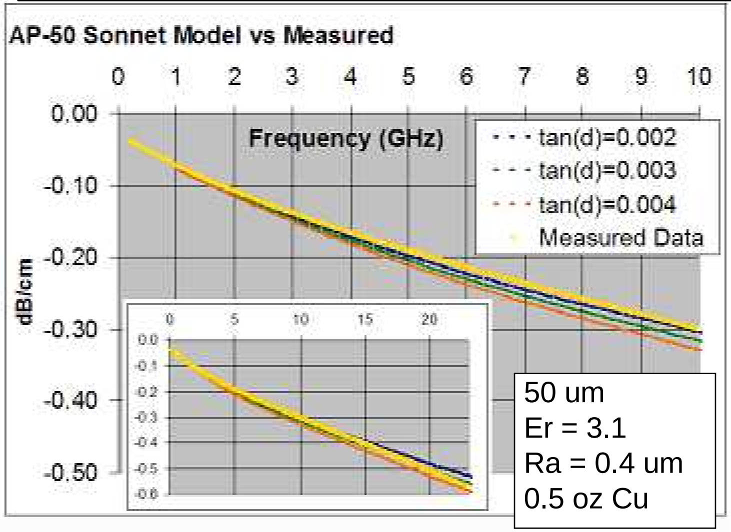
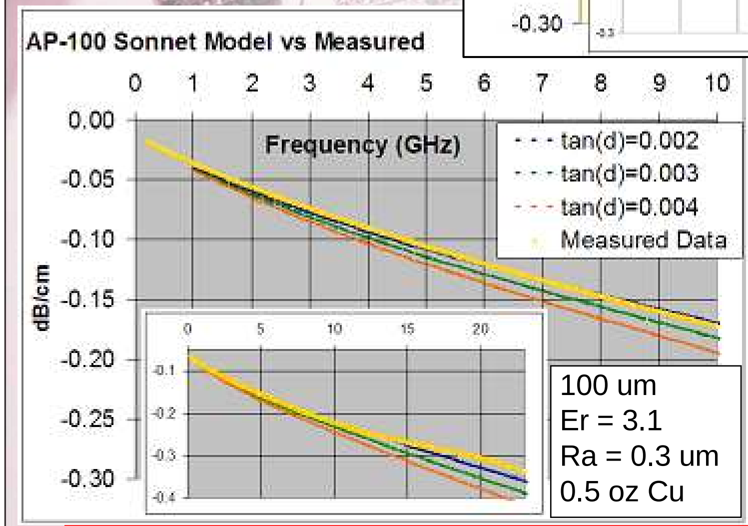
AP-100, AP-50











Tan d is 0.002 at frequencies <5 GHz, 0.002 – 0.003 between 5-10 GHz and 0.003 – 0.004 between 10-20 GHz

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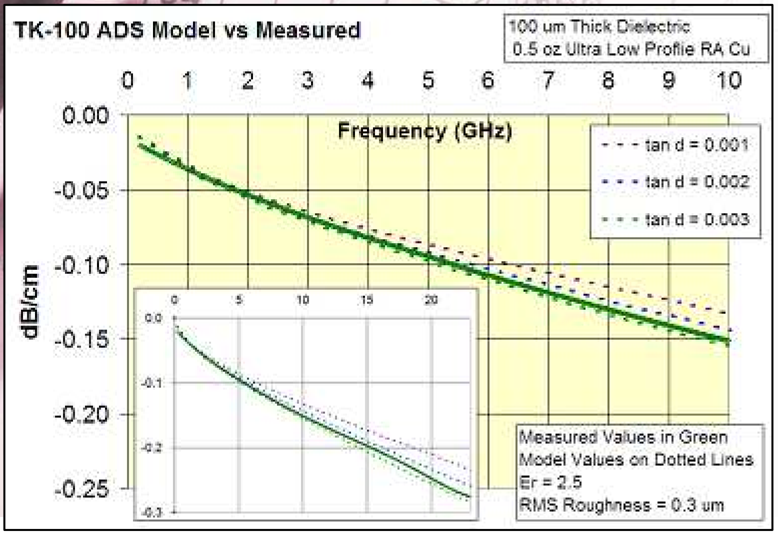
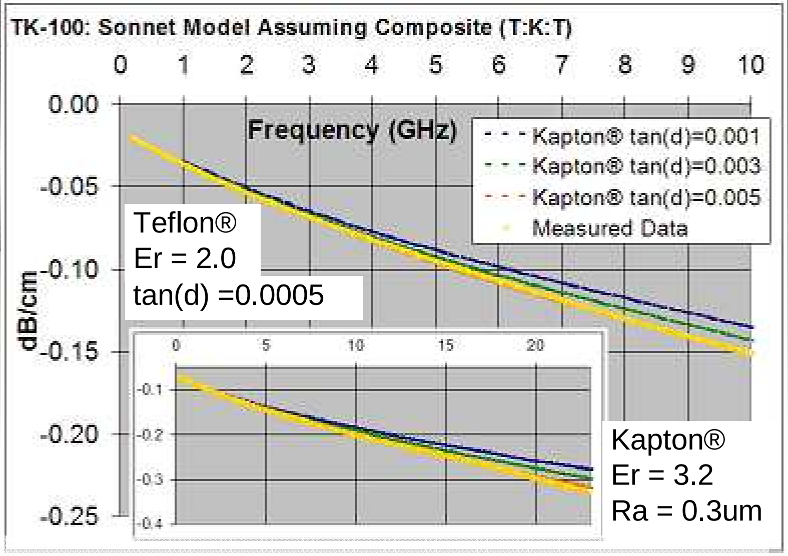
TK-100

Ra=0.3 um





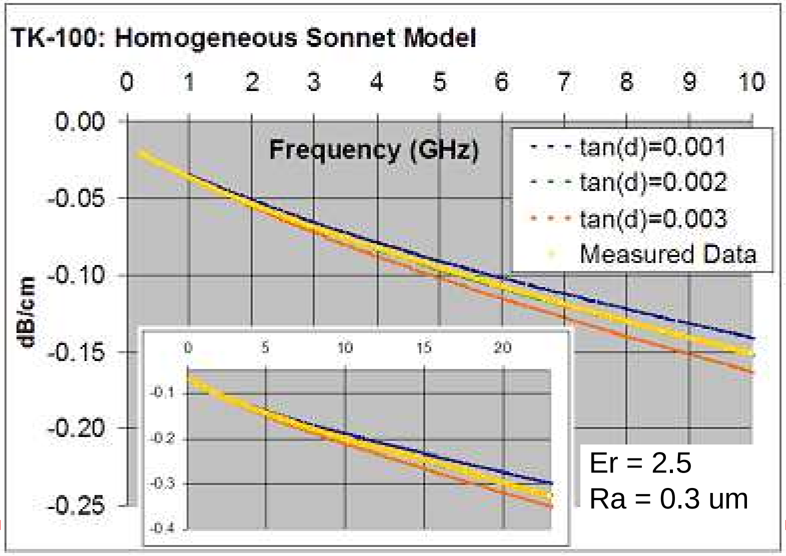
<u>If considered as composite:</u>

Teflon® Tan d = 0.0005

Kapton® Tan d = 0.003-0.005 up to 20 GHz

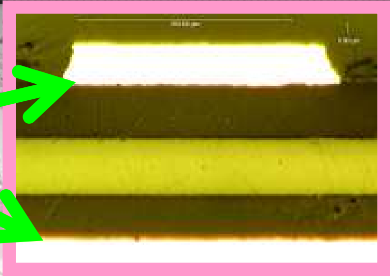
<u>If considered as a homogeneous structure:</u>

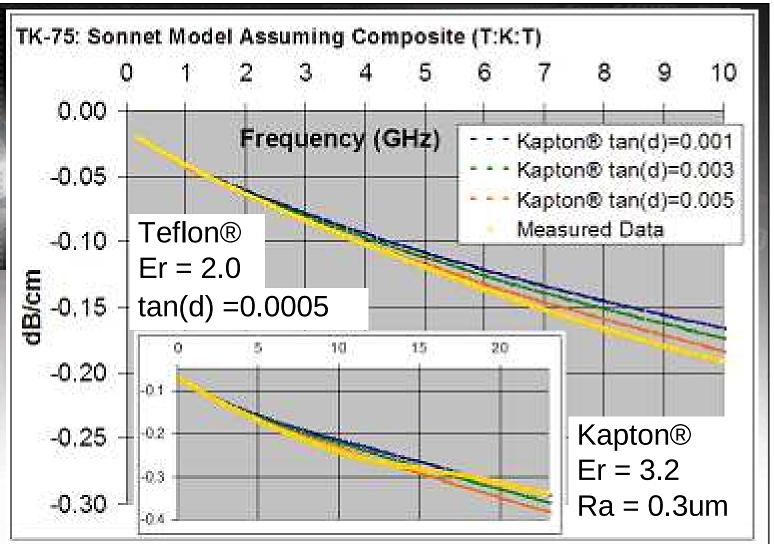
Tan d is 0.002 at frequencies up to 20 GHz

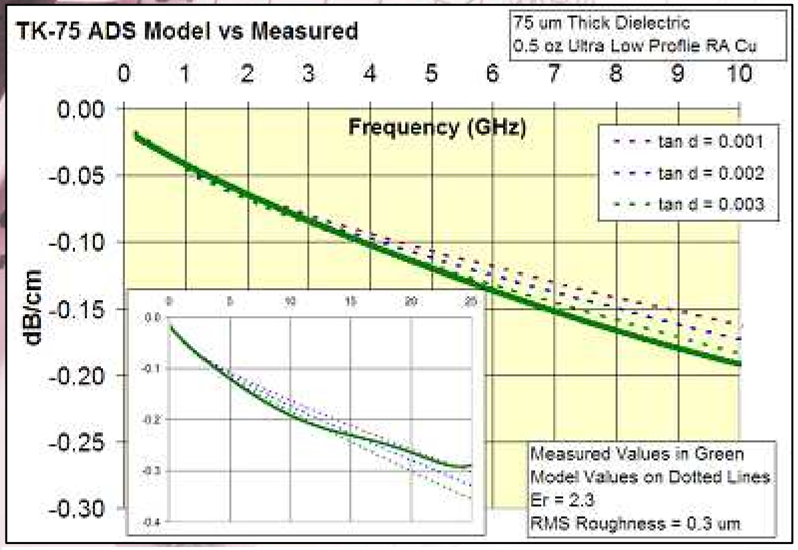


TK-75

Ra=0.3 um

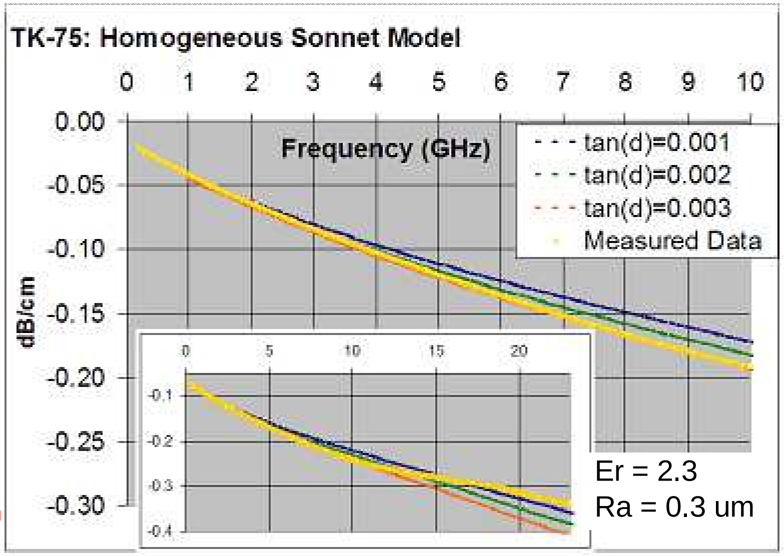






<u>If considered as composite:</u>
A little better agreement between model and measured, but does not explain loss behavior > 15 GHz. Theory: Teflon® is under-represented in the composite model.

<u>If considered as a homogeneous structure:</u>
Tan d is 0.002 – 0.004 up to 10 GHz then goes down to 0.001 at around 15 GHz



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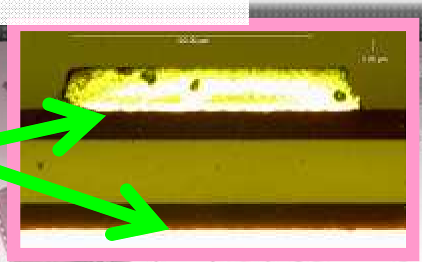
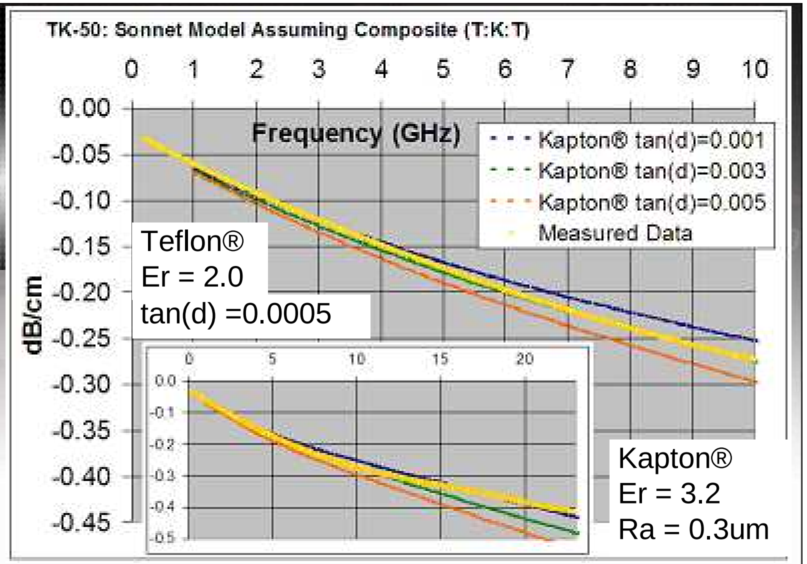
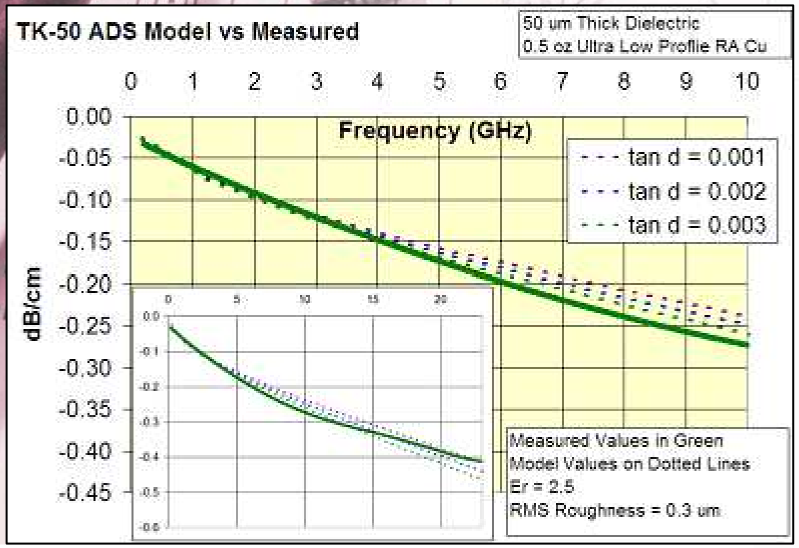
TK-50

Ra=0.3 um





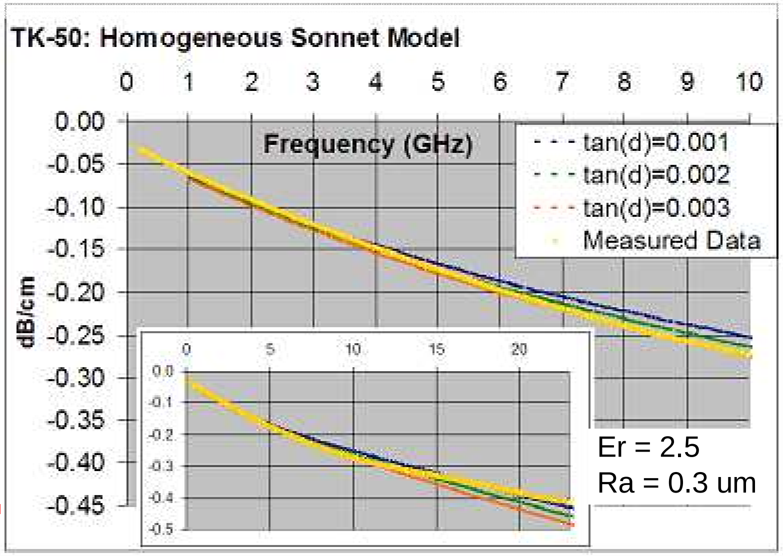


If considered as composite:

A little better agreement between model and measured, but does not explain loss behavior > 15 GHz. Theory: Teflon® is under-represented in the composite model.

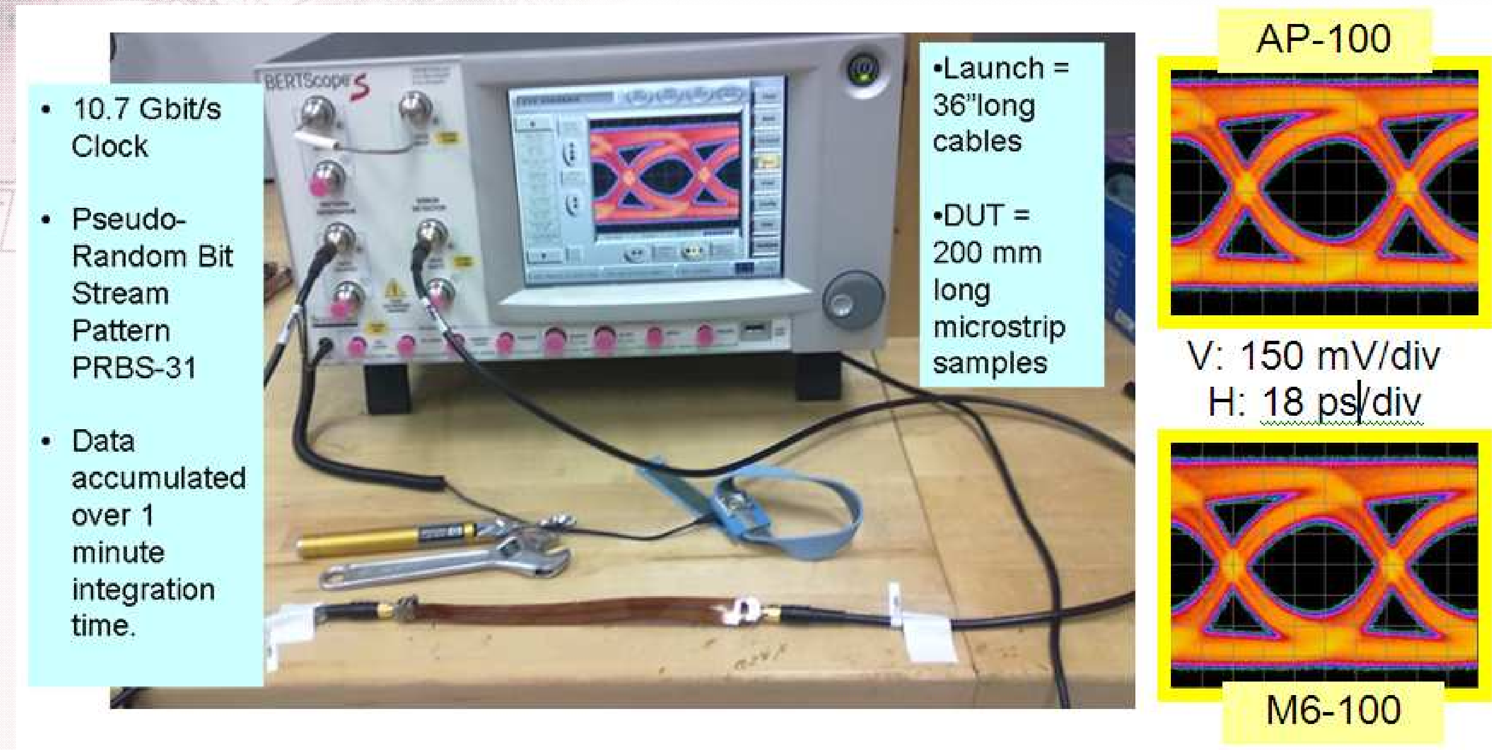
If considered as a homogeneous structure:

Tan d is 0.002 – 0.004 up to 10 GHz then goes down to 0.001 at around 15 GHz



Eye Pattern Testing

- First a disclaimer
  - I am not a digital signaling expert. This is new to me.
- This was done on the "Apples to Apples" principle.



Eye Pattern Measurement / Analysis

200 mm Lengths For All Two 36" cables used for interface to BERTScope	Rise Time (ps) Time (ps)	% difference vs M6	Signal Amplitude (mV)	% difference vs M6	P-P Jitter (ps) (ps)	% difference vs M6	Eye Height (mV) (mV)	% difference vs vs M6	Eye Width (ps) (ps)	% difference vs vs M6	Signal to Noise Ratio (dB)	% difference vs vs M6
2x36"cables+2cm Thru	30.4		882.9		12.5		701.8		81.3		7.5	
100um FR4: 51 ohms	52.9	8%	739.3	-8%	34.4	65%	241.1	-45%	60.4	-17%	3.1	-1.5 dB
100um M4 51 ohms	52.3	7%	785.7	-2%	25.4	22%	362.9	-18%	68.6	-6%	4.0	-0.6 dB
100um M6 50 ohms	49.1		800.0		20.8		440.0		72.8		4.6	
100um AP: 55 ohms	47.4	-3%	817.5	2%	19.8	-5%	463.9	5%	74.9	3%	5.0	+0.4 dB
100um TK: 60 ohms	46.8	-5%	822.9	3%	18.4	-12%	478.9	9%	75.2	3%	5.1	+0.5 dB
75um TK: 50 ohms	49.3		823.9		20.4		447.9		73.7		4.8	
50um M4: 51 ohms	53.7	1%	730.0	-4%	37.7	19%	222.9	-30%	56.0	-11%	2.9	-0.8 dB
50um M6: 52 ohms	53.3		757.2		31.7		320.0		63.3		3.7	
50um AP: 50 ohms	50.9	-5%	754.3	0%	26.8	-16%	334.3	4%	67.4	6%	3.9	+0.2 dB
50um TK: 49 ohms	52.9	-1%	782.2	3%	24.1	-24%	366.4	15%	70.2	11%	4.3	+0.6 dB

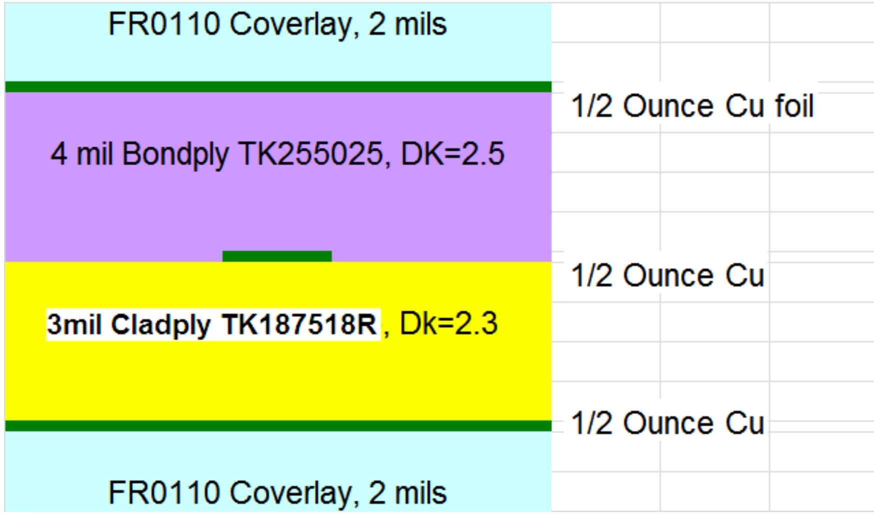
- Attempted to compare 50 ohm examples of each. The TK-100 was the lowest impedance line available.
- Lower Er for flex materials leads to less jitter and improved eye width.
- Lower loss for flex materials leads improved eye height.

Phase II – Simbeor Parameter Extraction

- A second method was used to extract dielectric constant (Dk) and dissipation factor (Df) values
  - Flex assemblies were manufactured by Samtec
  - Custom SMA connectors with optimized footprints were developed
  - VNA measurements were made and Dk and DF values extracted using Simbeor, a commercial tool.

Phase II – Sample Cross Section

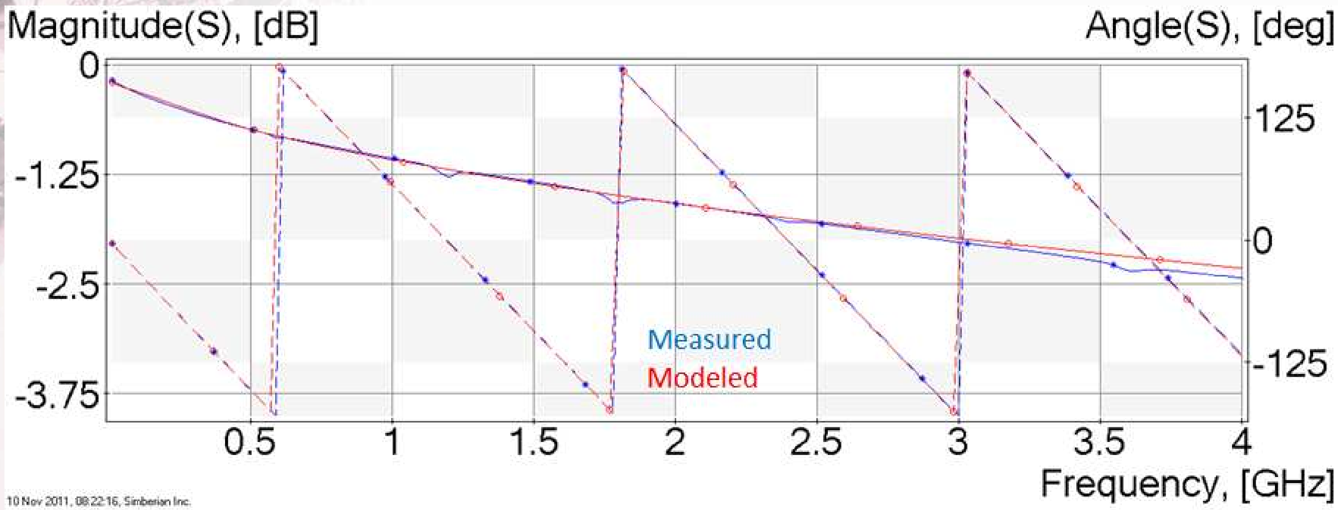
- The samples in Phase II differed from Phase 1
  - An offset stripline topology was evaluated rather than a microstrip
  - Only the TK family of materials was tested
  - Simbeor method requires only two samples of differing lengths to be characterized
    - Launch discontinuities must be "the same" for both test samples



Phase II – Parameter Extraction

- By adjusting the surface roughness, copper conductivity, Dk and Df, a model is developed which approximates the measured insertion loss
  - Copper conductivity = 4.25x 10^7 S/m
  - Roughness = 1.2um (surface roughness)

    Note: Roughness is considered differently in Simbeor than in ADS or Sonnet



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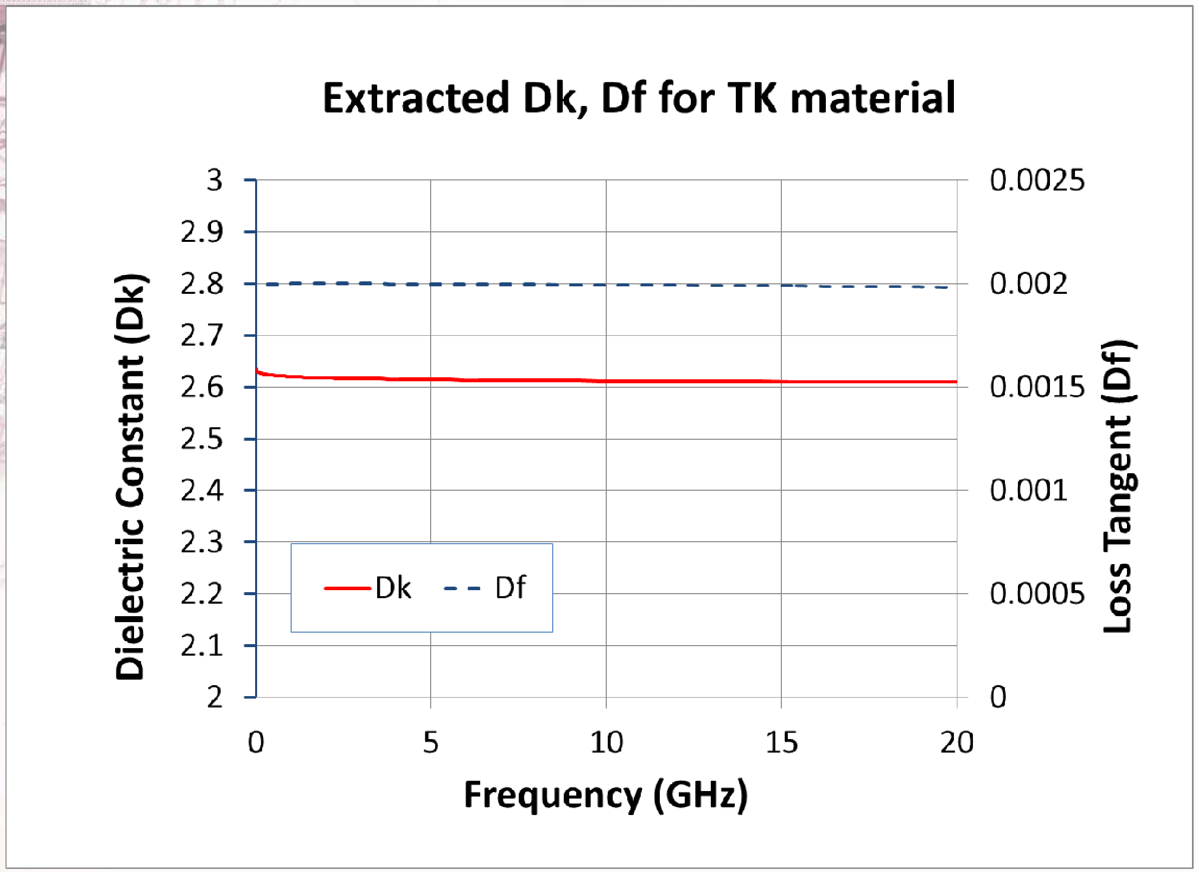
Phase II – Results of Extraction

- The extracted values have minor frequency variation as required for causality condition



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Phase II – Comparison to Phase I Results

- Again, the samples used in the Phase II Simbeor extraction differed slightly from the Phase 1 samples
  - Offset stripline vs microstrip (Phase 1)
  - Overall the correlation is good

	Simbeor Extraction	Phase 1
Dk	2.62	2.5
Df	0.002	0.002

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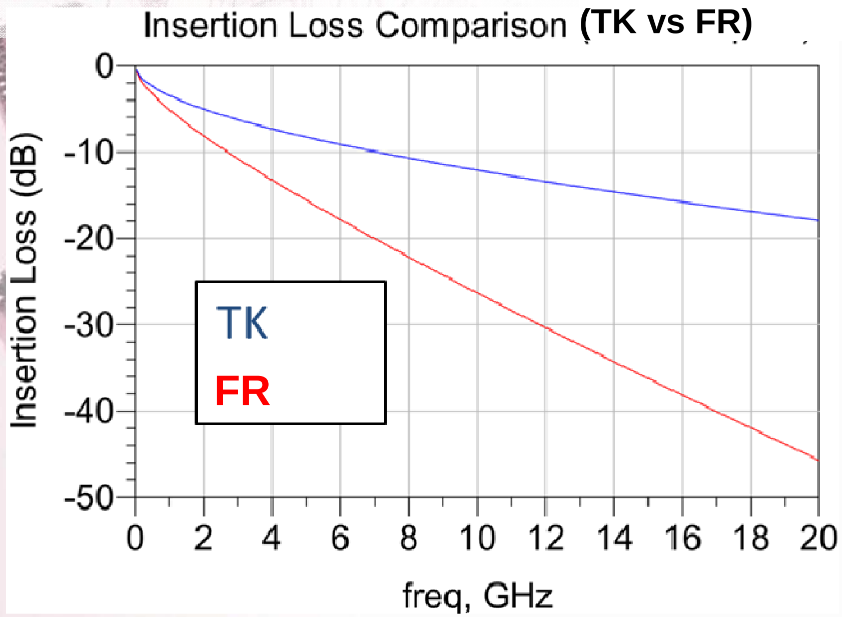
Phase III – Application Example

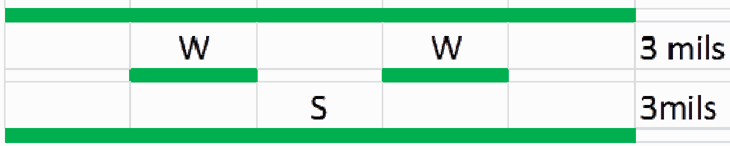
- Consider a flex assembly based channel for PCI Express, Generation III (PCIe G3) applications
  - 8 Gb/s data rate
  - Equalization
    - 3 tap FIR de-emphasis equalization
    - 2 pole CTLE filter
    - 1 tap DFE
  - Tx/Rx package models
- Analyze two different channels
  - Pyralux® FR Bondply (Kapton®)
  - Pyralux® TK (Teflon®/Kapton®)

Phase III – Flex Performance Comparison

- The lower Dk results in wider trace widths for TK materials resulting in better loss performance
- Lower Df for TK results in better insertion loss
- Analysis below is for 18” trace length

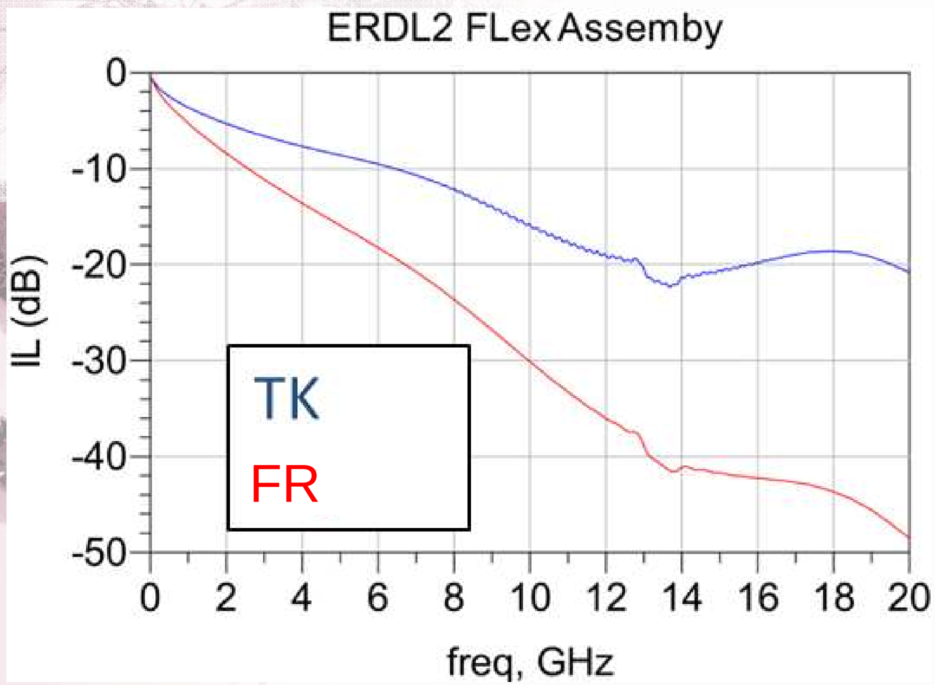


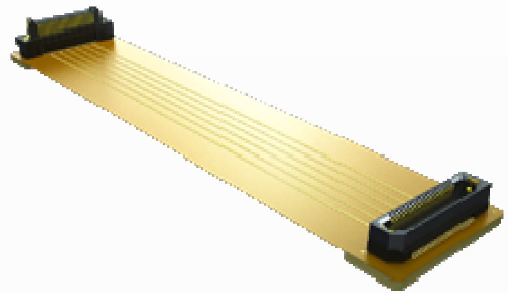
	Df	Dk	W	S
FR	0.02	3.02	3.5 mils	5 mils
TK	0.002	2.6	4 mils	5 mils



Phase III – Flex Assembly Performance Comparison

- Samtec Edge Rate™ ERM8/ERF8 Series connector models are added to the 18” flex model to form an ERDL2 Series Flex Circuit Assembly





ERDL2 Series Flex Assembly

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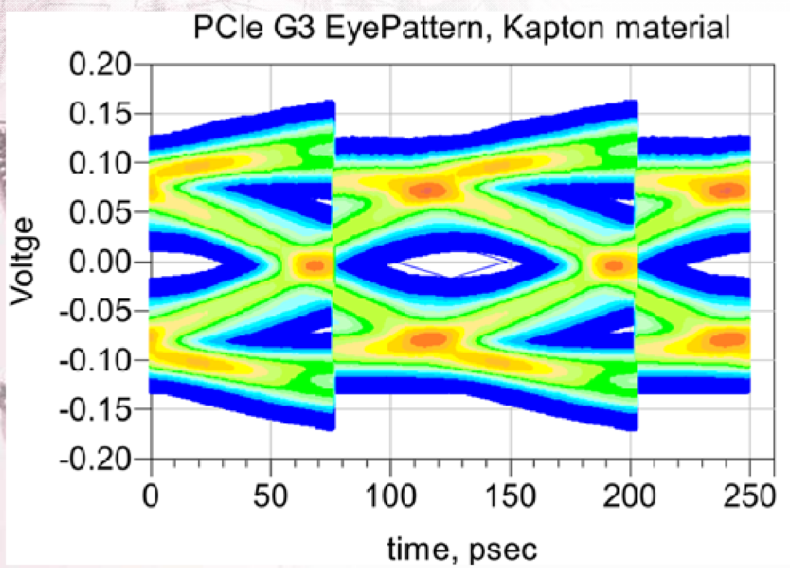
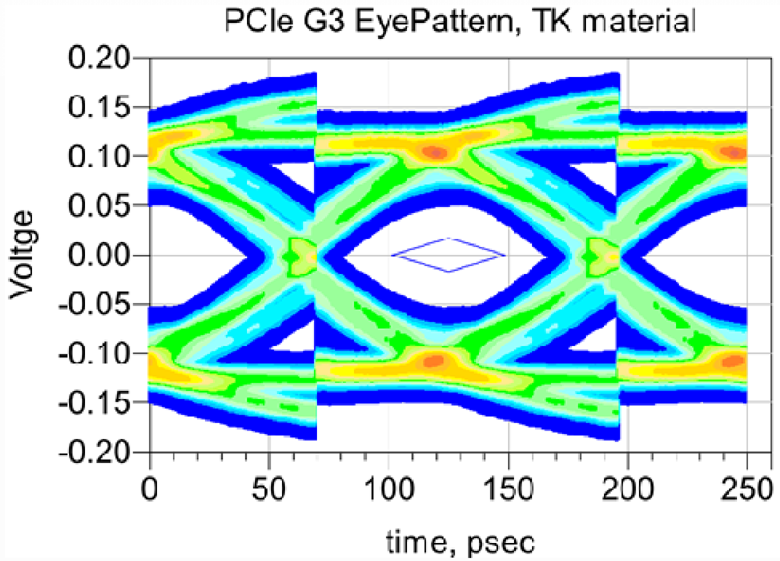
Phase III – ADS Simulation Environment

- A PCIe G3 simulation environment was developed in ADS
  - Batch simulation of different trace lengths
  - Parameter sweeps for the different equalization setting
  - Multi-agressor crosstalk effects included
  - PCIe G3 Tx/Rx package effects
  - Tx jitter modeled
  - Eye mask templates included
  - Results correlated to SEASIM
- The ERDL2 Series Flex Circuit Assembly was modeled in this simulation environment

Phase III – PCIe G3 Results

- The lower loss in the ERDL2 Series Flex Circuit Assembly with TK material easily mets the G3 eye mask





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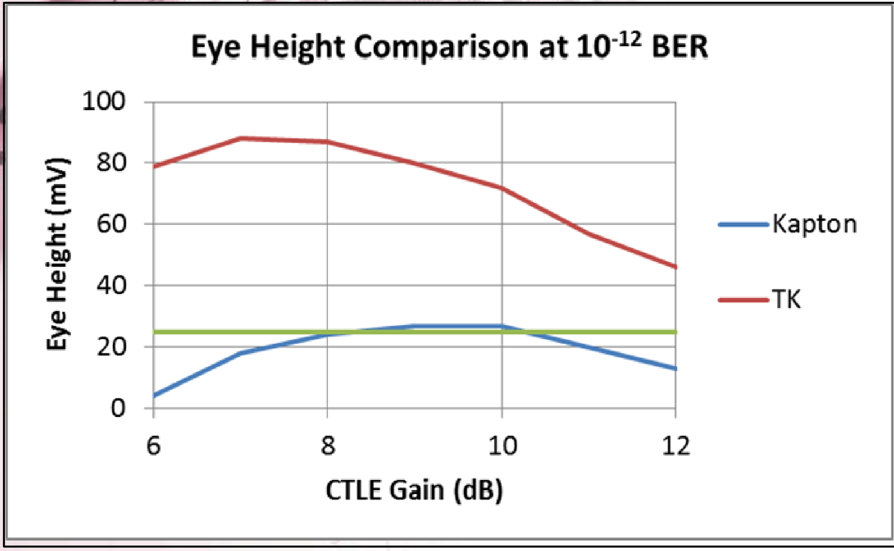
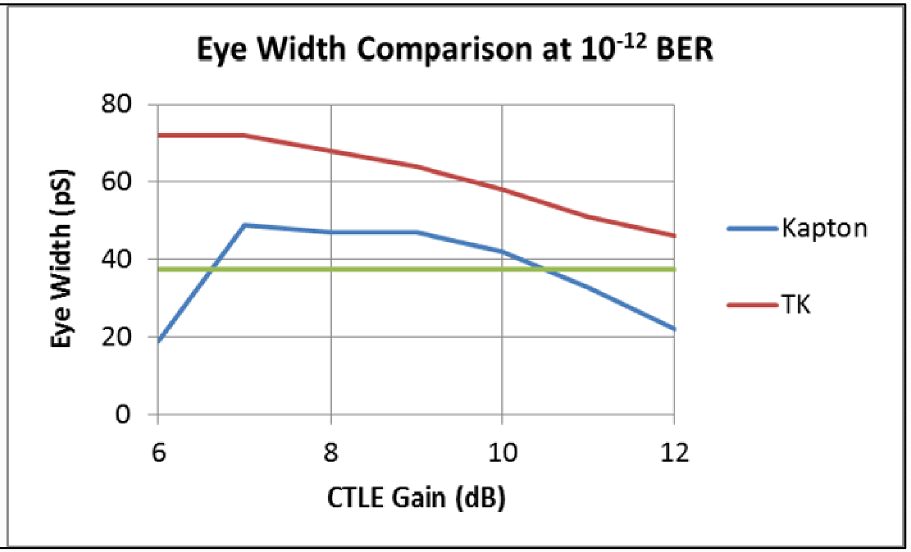
Phase III – PCIe G3 Results

- By sweeping the CTLE gain, we can optimize the PCIe G3 equalization settings for a particular channel



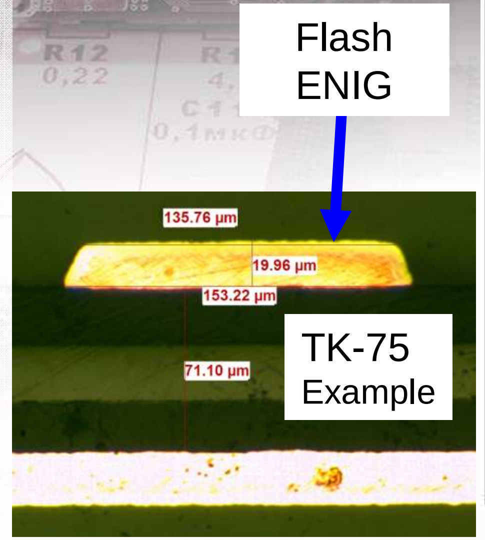


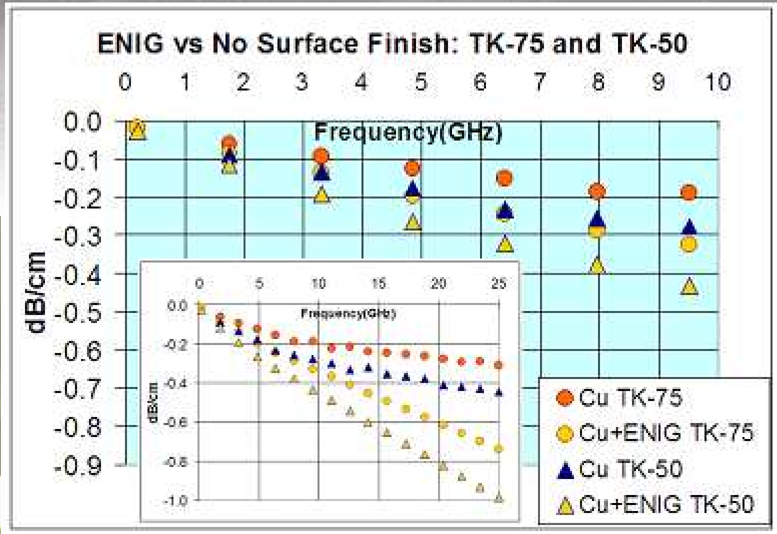
Phase III – Summary

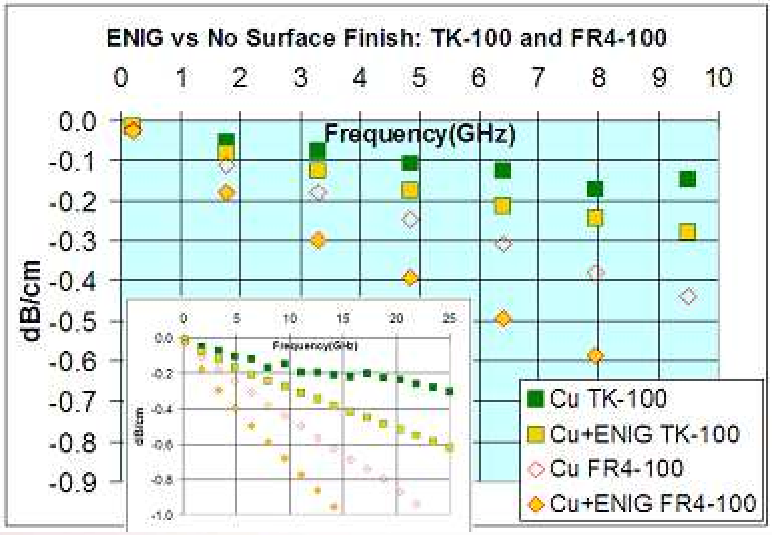
- Material parameters extracted match the DuPont results
  - Different samples/structure
  - Different test lab
  - Different measured data post processing method
- Lower Dk and Df of TK material results in improved performance at the flex assembly level
  - A PCIe G3 example was shown for an 18” flex assembly length

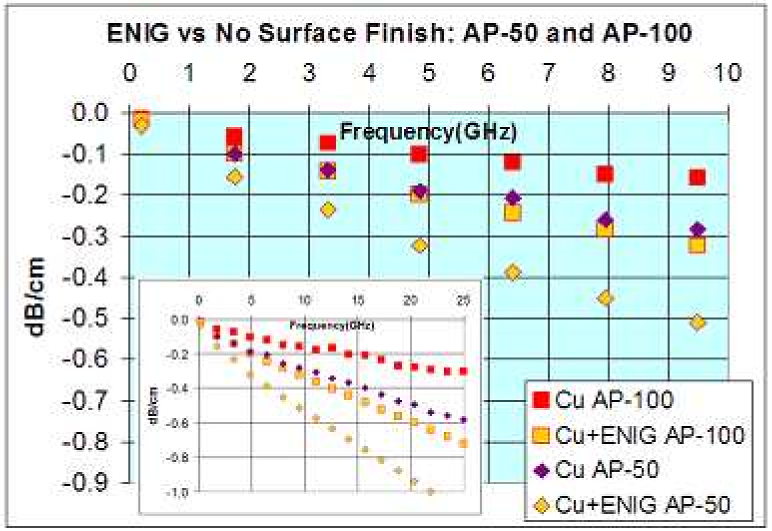
Additional Work – ENIG Finish

- Effect of ENIG is slightly greater than cutting dielectric thickness in half.
- Ferromagnetic properties of ENIG is the principal culprit for this effect.









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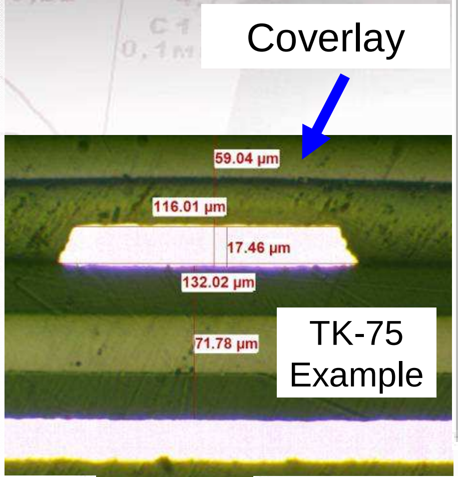
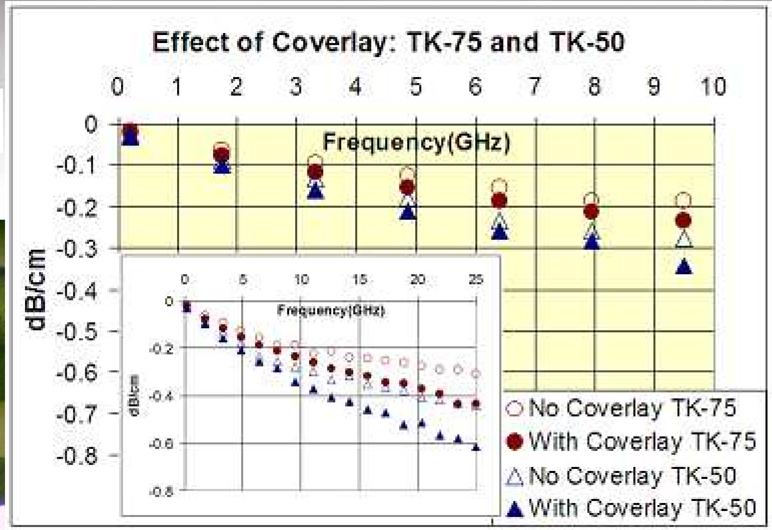
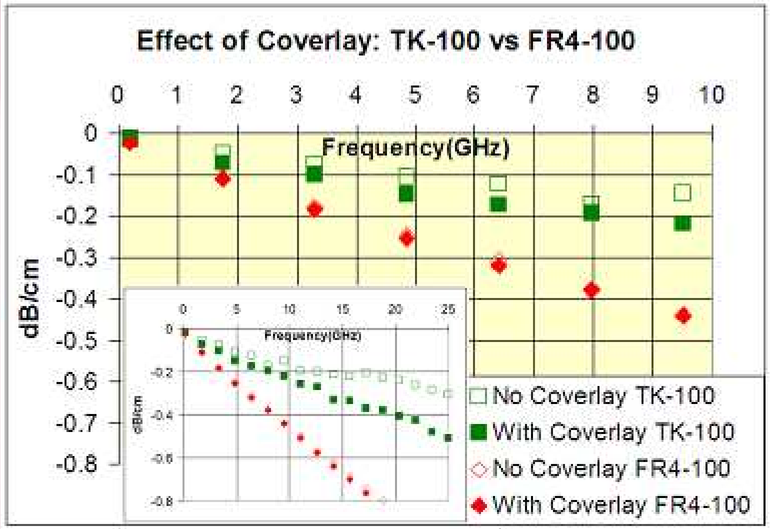
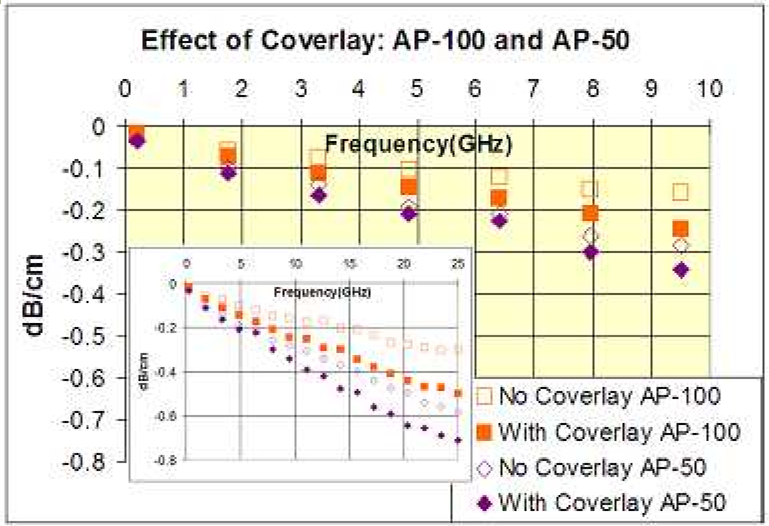
Additional Work – Loss From Coverlay

- Effect of coverlay is significant and has more of an impact for thinner clads.
- Even though relatively thin, the effect must be considered.









Eye Patterns with Coverlay

200 mm Lengths For All Two 36" cables used for interface to BERTScope	Rise Time (ps)		Fall Time (ps)		Amplitude		P-P Jitter (ps)		Eye Height (mV)		Eye Width (ps)		Signal to Noise Ratio	
	Time (ps)	% diff with coverlay	(ps)	% diff with coverlay	(mV)	% diff with coverlay	(ps)	% diff with coverlay	(mV)	% diff with coverlay	(ps)	% diff with coverlay	(dB)	dB diff with coverlay
2x36"cables+2cm Thru	31.0		29.7		884.3		12.5		704.3		80.9		7.5	
100um FR4: 48 ohms	54.8	4%	53.0	2%	727.2	-2%	39.3	14%	218.6	-9%	54.5	-10%	2.8	-0.3 dB
100um AP: 55 ohms	48.9	3%	48.3	3%	788.6	-4%	21.3	7%	425.7	-8%	72.5	-3%	4.6	-0.4 dB
100um TK: 55 ohms	50.6	8%	49.9	9%	830.0	1%	21.4	17%	434.3	-9%	72.8	-3%	4.6	-0.5 dB
75um TK: 52 ohms	52.5	6%	51.6	7%	794.3	-4%	24.4	20%	402.9	-10%	70.3	-5%	4.5	-0.3 dB
50um AP: 48 ohms	51.9	2%	51.6	1%	715.7	-5%	32.7	22%	268.6	-20%	61.0	-9%	3.3	-0.6 dB
50um TK: 50 ohms	53.8	2%	52.7	0%	761.4	-3%	33.1	37%	274.3	-25%	61.4	-13%	3.4	-0.9 dB

- Coverlay had a more negative impact on jitter than expected. This is likely due to the dielectric constant mismatch between the coverlay and the clad dielectric. Mismatch is larger with the composite clads.
- Degradation in eye height consistent with loss degradation shown in previous slide.
- Coverlay effect is more significant as overall stackup thickness decreases.

Summary and Conclusions

- Transmission results reported instead of just bulk dielectric properties.
- Flex copper clad laminates have desirable properties versus thin rigid, especially at frequencies >10 GHz
  - Lower Permittivity
  - Lower Loss
  - Wider Eye
- Dk and Df data is reliable, having been tested using different samples and techniques. Separate labs report the same values
- PCIe G3 channel simulations of flex assemblies show the advantage of improved materials in an 8 Gbps application
- Effects of surface finishes and coverlay also must be considered
  - ENIG has a large impact on loss
  - Coverlay has a significant impact on loss and eye pattern

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