Practical Channel Modeling for High-speed Design

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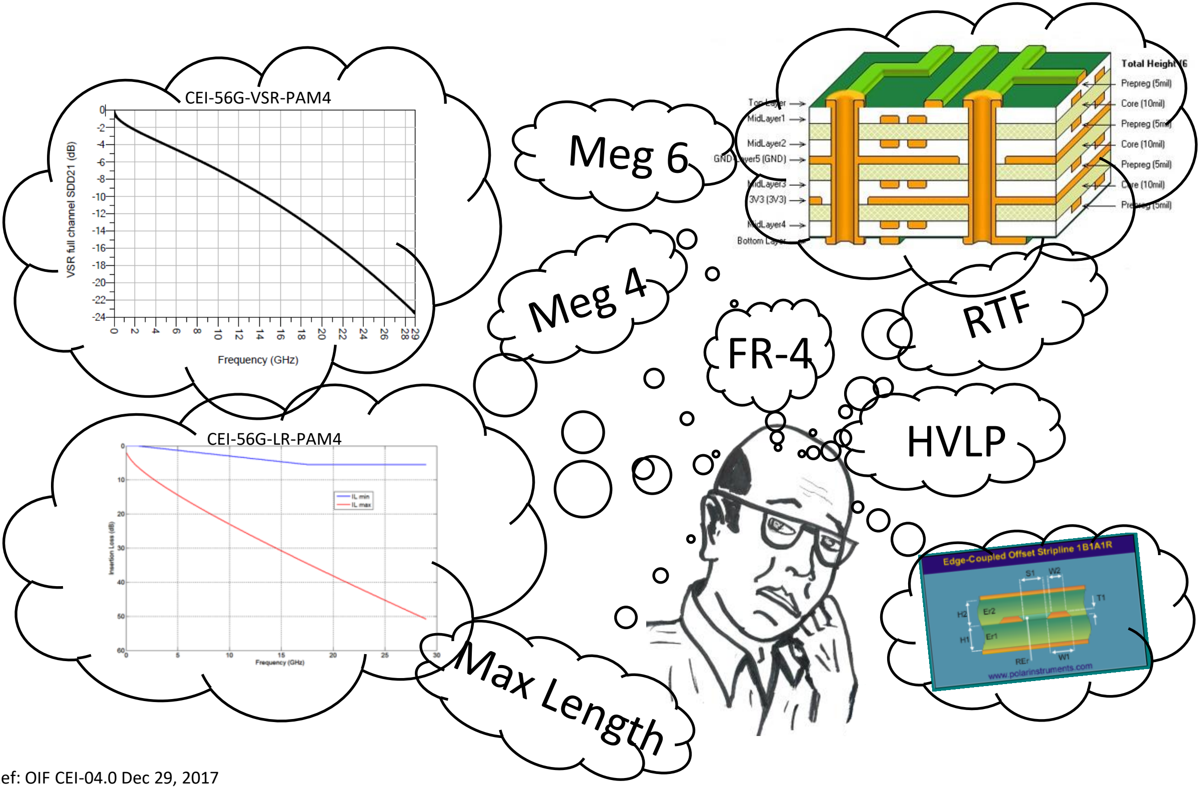
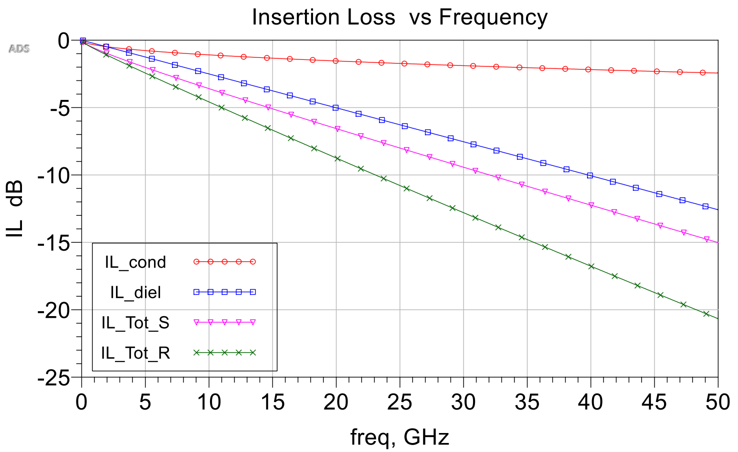
High-level Design Challenges



Choosing appropriate diff pair geometry, board material and stackup to meet insertion loss budgets for industry standards can be overwhelming

Ref: OIF CEI-04.0 Dec 29, 2017

Transmission Line Modeling

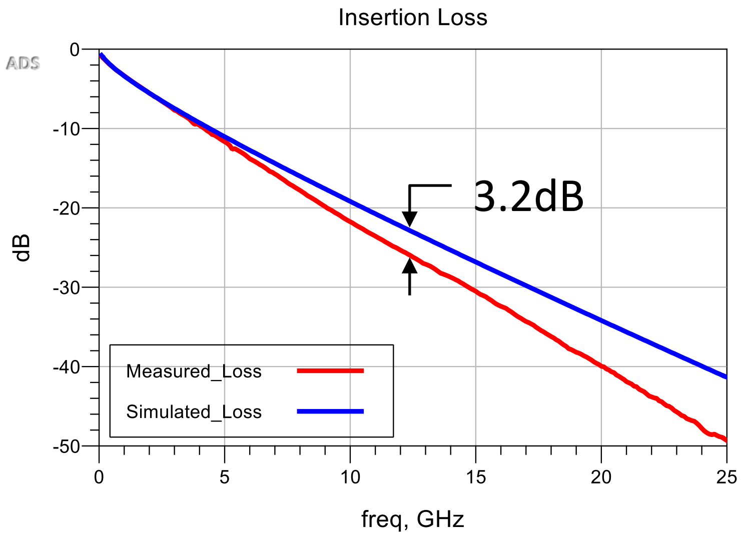


Important to model dielectric and conductor loss accurately

$$IL_{total}(f) = IL_{diel}(f) + K_{SR}(f) \times IL_{conductor}(f)$$

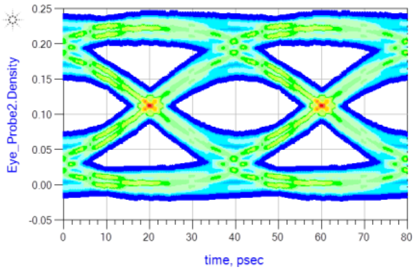
Simulated with Keysight ADS [13]

Failure To Model Roughness Properly Can Ruin You Day!

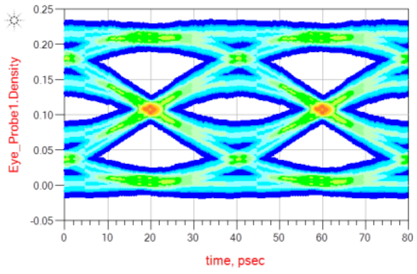


With just 3.2dB delta @12.5 GHz => ½ the eye height with rough copper

Smooth Copper



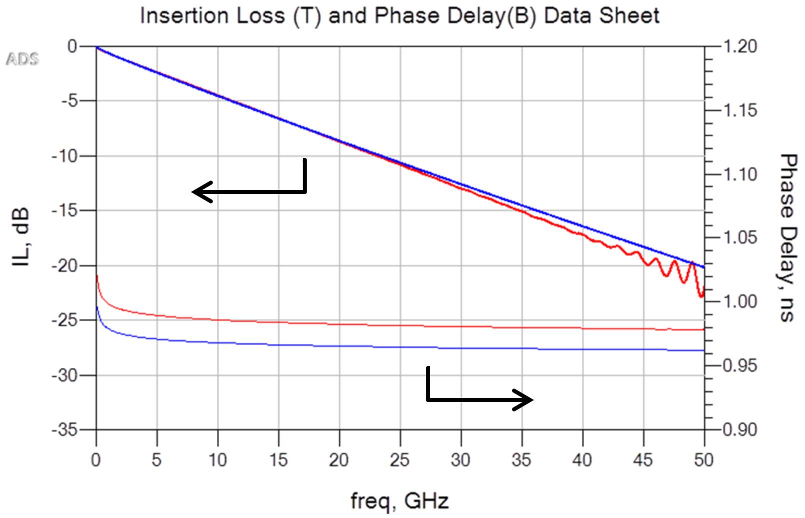
Rough Copper



25Gb/s

Simulated with Keysight ADS [13]

Dielectric Properties



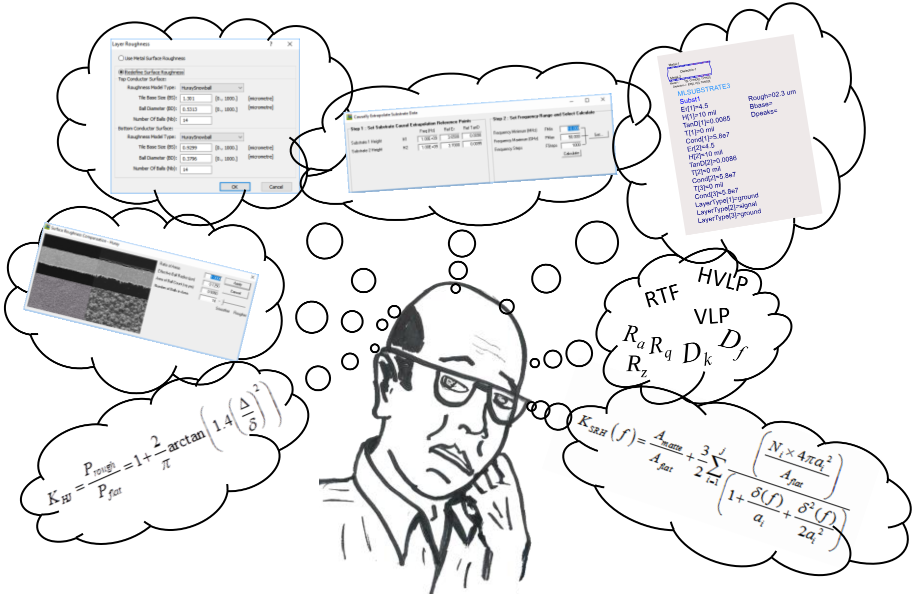
---- Measured ---- Simulated

Failure to correct D_k from data sheet due to conductor roughness => inaccuracy in simulated IL & Phase Delay

Simulated with Keysight ADS [13]

EDA Tool Challenges

✓ **Many EDA tools include latest and greatest models for conductor surface roughness and wideband dielectric properties**

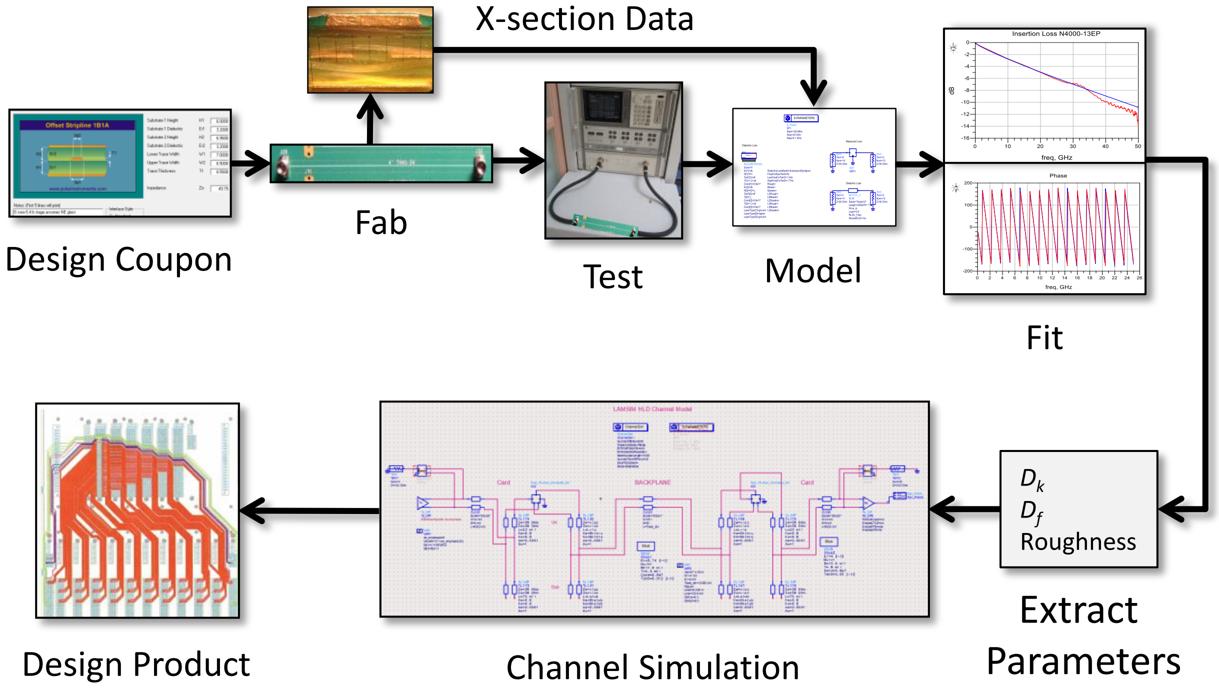


Layer Roughness
○ Use Metal Surface Roughness
● Redefine Surface Roughness
Top Conductor Surface:
Roughness Model Type: HurraySnowball
Tile Base Size (BS): 1.301 [0., 1000.] [micrometre]
Ball Diameter (BD): 0.5313 [0., 1000.] [micrometre]
Number Of Balls (Nb): 14
Bottom Conductor Surface:
Roughness Model Type: HurraySnowball
Tile Base Size (BS): 0.9299 [0., 1000.] [micrometre]
Ball Diameter (BD): 0.3796 [0., 1000.] [micrometre]
Number Of Balls (Nb): 14

MLSUBSTRATE3
Subst1
Er[1]=4.5
H[1]=10 mil
TanD[1]=0.0085
T[1]=0 mil
Cond[1]=5.8e7
Er[2]=4.5
H[2]=10 mil
TanD[2]=0.0086
T[2]=0 mil
Cond[2]=5.8e7
T[3]=0 mil
Cond[3]=5.8e7
LayerType[1]=ground
LayerType[2]=signal
LayerType[3]=ground
Rough=02.3 um
Bbase=
Dpeaks=

But obtaining the right parameters to feed models is always a challenge

Design Feedback Method



Design Coupon

Fab

X-section Data

Test

Model

Fit

D_k
D_f
Roughness

Extract Parameters

Channel Simulation

Design Product

Benefits:

- Practical
- Accurate

Issues:

- Expertise required
- Time
- Money
- Extracted parameters only accurate for sample from which they were extracted

“Sometimes an OK answer NOW! is better than a good answer late….” **– Eric Bogatin**

What You Will Learn

- ✓ How to apply my Cannonball model to determine Huray roughness parameters from data sheet alone
- ✓ How to determine D_{keff} due to roughness from data sheets alone
- ✓ How to apply these parameters in the latest version of Polar Si9000e Field Solver
- ✓ How to pull it all together using Keysight ADS software

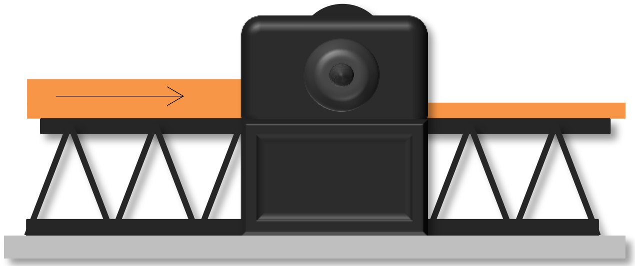
Outline

- Overview
- Modeling Conductor Roughness:
  - Hammerstad Model
  - Huray Model
  - Cannonball-Huray Model
- D_{keff} Due to Roughness Model
- Model Validation
- Practical Channel Modeling for High-speed Design Case Study

Overview

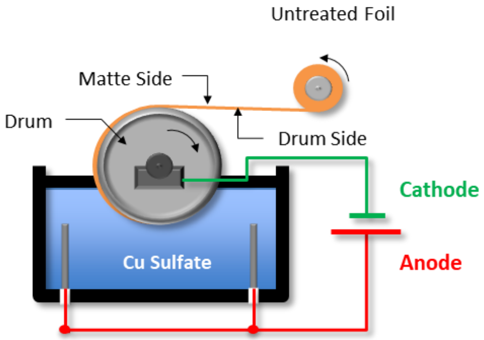
Copper Foil Manufacturing Processes

Rolled



VS

Electro-deposited (ED)

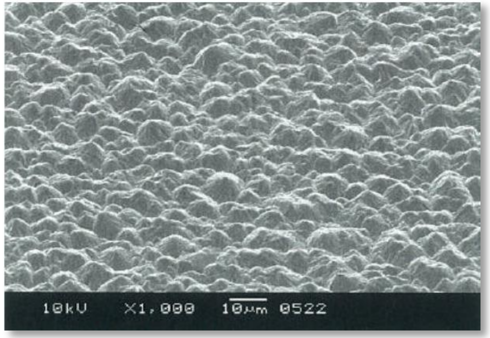


- Smoother
- Higher Cost

- Rougher
- Lower Cost

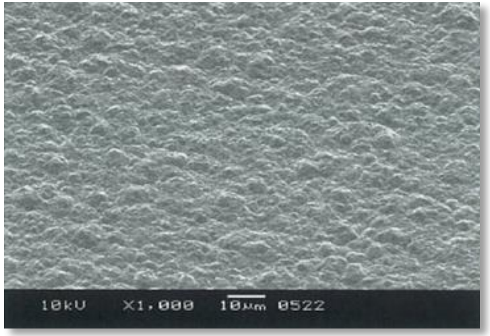
Common ED Roughness Profiles

IPC Standard Profile



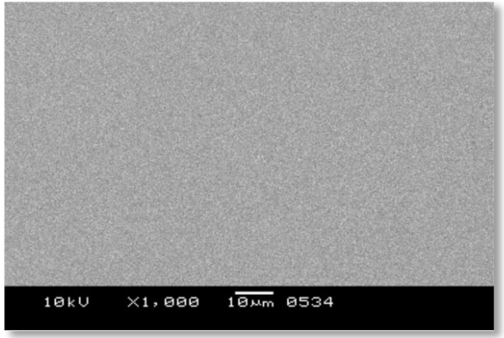
No min/max spec

IPC Very Low Profile(VLP)



< 5.2 μm max

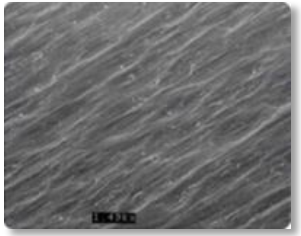
Ultra Low Profile (ULP)Class



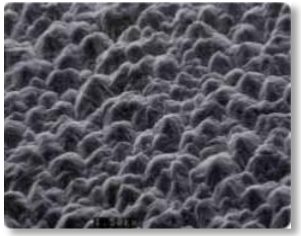
-*Other names: HVLP*, VSP
-No IPC spec
-Typically < 2 μm max

SEM Photos Reference [17]

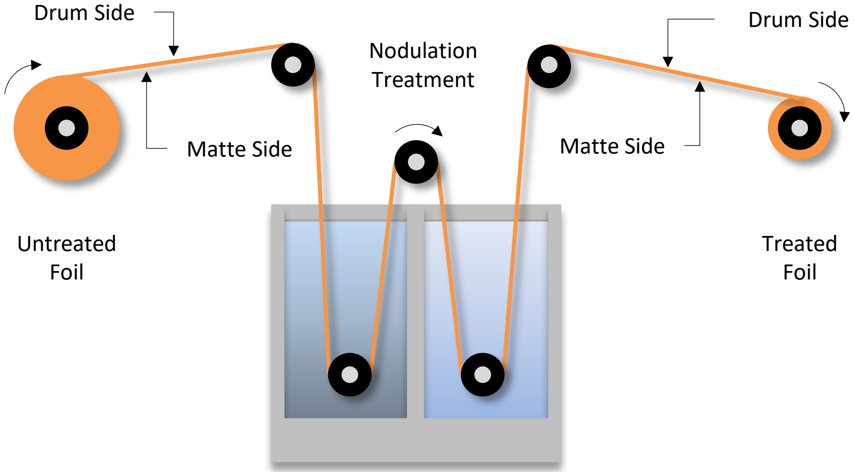
ED Copper Foil Nodulation Treatment

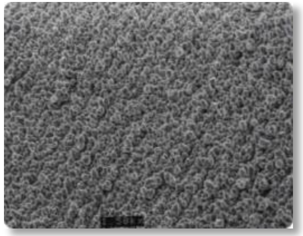


Drum Side Untreated



Matte Side Untreated





Drum Side Treated

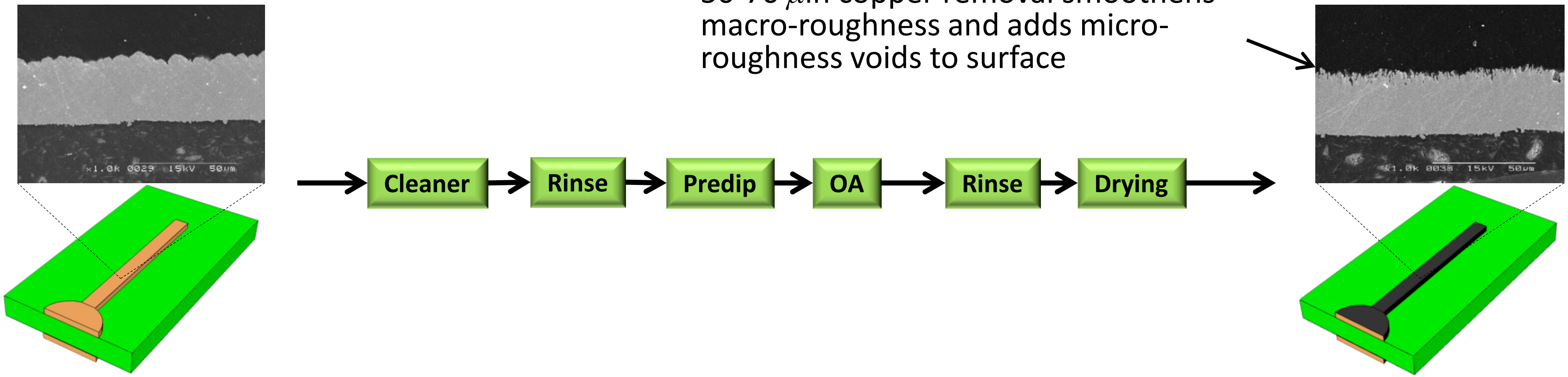
OR

Matte Side Treated

SEM Photos Reference [11]

Oxide/Oxide Alternative Treatment

During PCB fabrication untreated copper on each side of core laminate undergoes a roughening treatment to promote adhesion



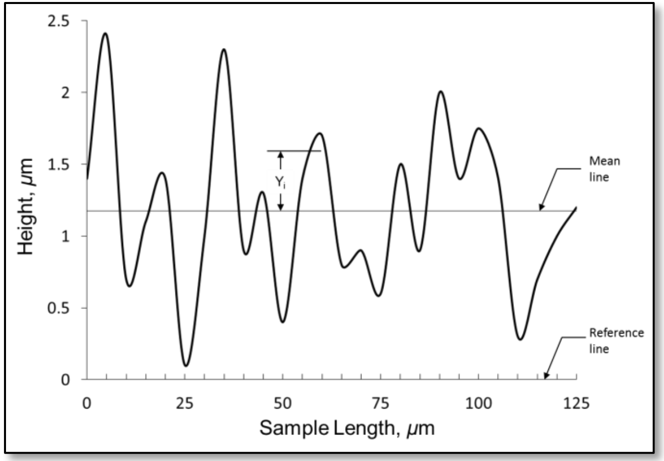
50-70 μin copper removal smoothens macro-roughness and adds micro-roughness voids to surface

Cleaner → Rinse → Predip → OA → Rinse → Drying

Photo Reference [18]

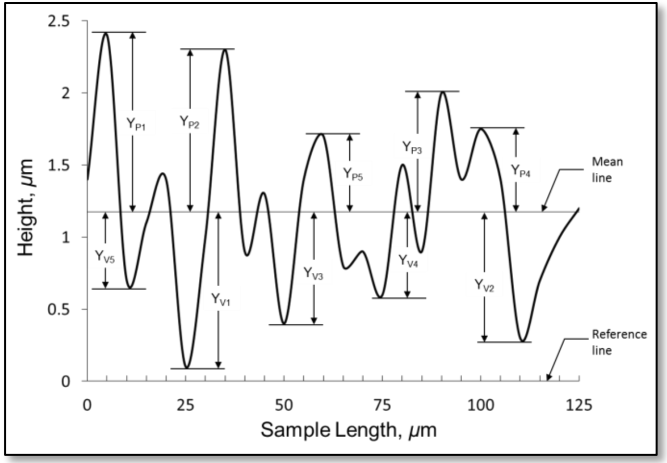
Roughness Parameters

RMS (R_q) / Average (R_a)



$$R_q = \sqrt{\frac{1}{N}\sum_{i=1}^{N} Y_i^2} \qquad R_a = \frac{1}{N}\sum_{i=1}^{N} |Y_i|$$

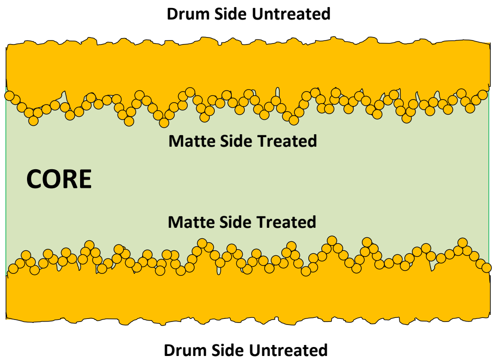
10-point Mean (R_z)



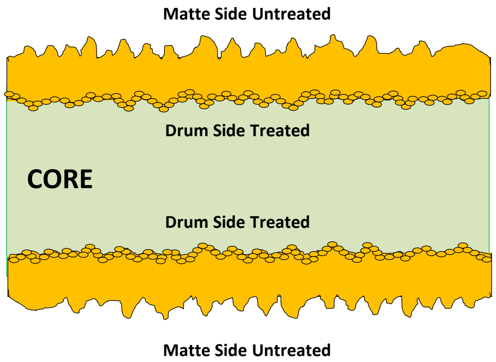
$$R_z = \frac{1}{5}\sum_{i=1}^{5} |Y_{Pi}| + \frac{1}{5}\sum_{i=1}^{5} |Y_{Vi}|$$

Foil Bonding to Core

Standard Treated Foil



Reverse Treated Foil (RTF)



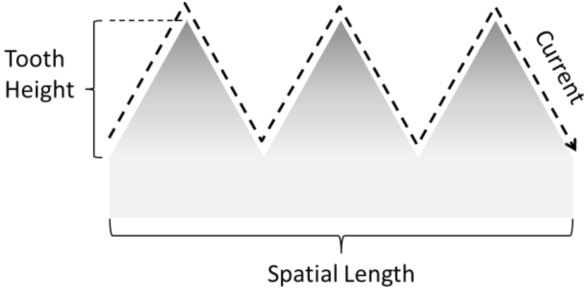
✓ **Treated Side of Raw Foil Always Bonds to Core**

Modeling Conductor Roughness

"All models are wrong but some are useful…"

- George E. P. Box

Hamerstad & Jenson Model

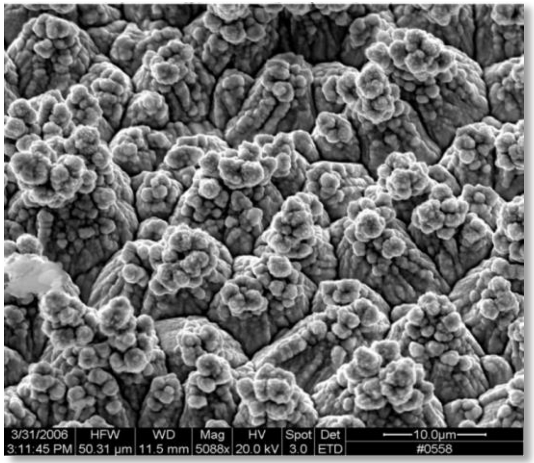


$$K_{HJ} = \frac{P_{rough}}{P_{flat}} = 1 + \frac{2}{\pi}\arctan\left(1.4\left(\frac{\Delta}{\delta}\right)^{2}\right)$$

$\Delta =$ RMS tooth height in meters

Loses accuracy above ~ 3-15GHz depending on roughness of copper

Huray "*snowball*" Model [5]

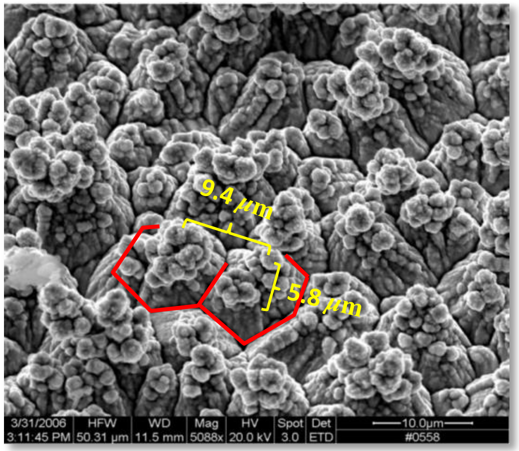


SEM Photo Reference [15]

Based on non-uniform distribution of spheres resembling "snowballs" applied to a matte base

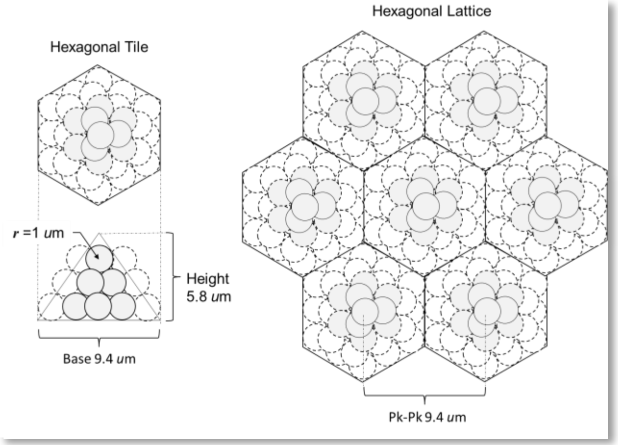
$$K_{SRH}\left(f\right)=\frac{P_{rough}}{P_{flat}}\approx\frac{A_{matte}}{A_{flat}}+\frac{3}{2}\sum_{i=1}^{j}\left(\frac{N_i\times4\pi a_i^{\,2}}{A_{flat}}\right)\left(1+\frac{\delta(f)}{a_i}+\frac{\delta^2(f)}{2a_i^{\,2}}\right)^{-1}$$

Huray Model Prior Art [6]

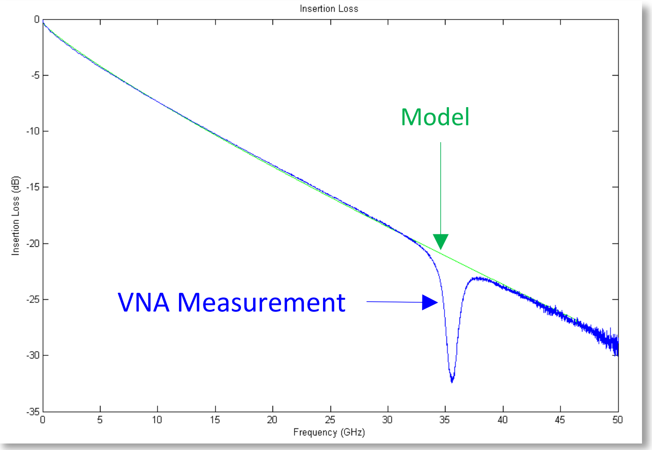


SEM Photo Reference [15]

Assumes stacked "snowballs" arranged in hexagonal lattice



11 spheres min; 38 spheres max of radius 1μm to fit within hex tile area and height of 5.8μm



Plot Reference [15]

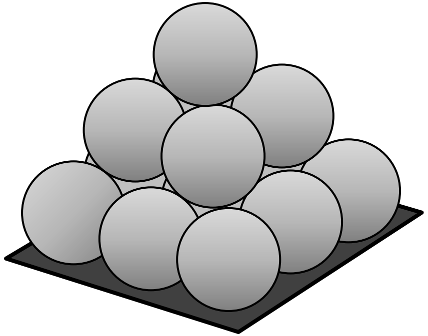
Fit equation parameters to measured data

Cannonball-Huray Model [3]

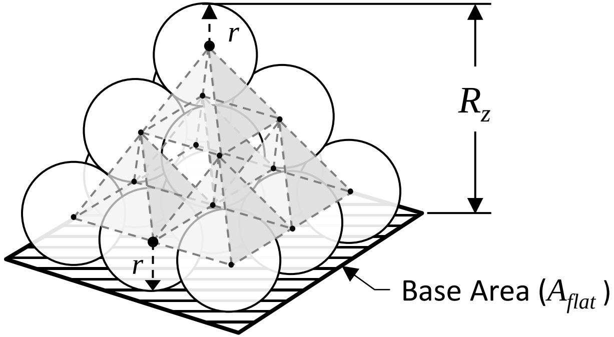
$$K_{SRH}(f)=\frac{A_{matte}}{A_{flat}}+\frac{3}{2}\sum_{i=1}^{j}\frac{\left(\dfrac{N_i\times 4\pi r^2}{A_{flat}}\right)}{\left(1+\dfrac{\delta(f)}{r}+\dfrac{\delta^2(f)}{2r^2}\right)}$$

$$K_{CH}(f)\approx 1+\frac{3}{2}\frac{\left(\dfrac{14\times 4\pi r^2}{36r^2}\right)}{\left(1+\dfrac{\delta(f)}{r}+\dfrac{\delta^2(f)}{2r^2}\right)}$$

$$\boxed{K_{CH}(f)\approx 1+\left[\frac{2.33\pi}{\left(1+\dfrac{\delta(f)}{r}+\dfrac{\delta^2(f)}{2r^2}\right)}\right]}$$



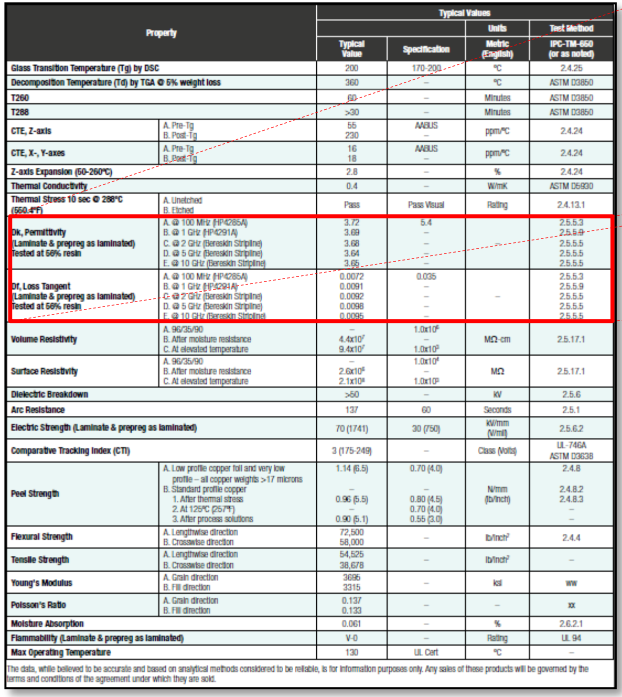
N_i=14 Spheres



$$\boxed{r\approx 0.06(R_z);\ A_{flat}\approx 36(r)^2}$$

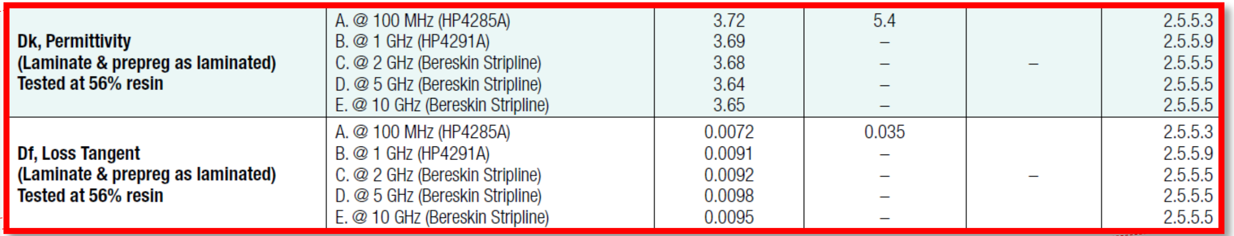
Modeling D_{keff} Due to Surface Roughness

Marketing Data Sheet Issues



Property		Typical Values			
				Units	Test Method
		Typical Value	Specification	Metric (English)	IPC-TM-650 (or as noted)
Glass Transition Temperature (Tg) by DSC		200	170-200	°C	2.4.25
Decomposition Temperature (Td) by TGA @ 5% weight loss		360	–	°C	ASTM D3850
T260		60	–	Minutes	ASTM D3850
T288		>30	–	Minutes	ASTM D3850
CTE, Z-axis	A. Pre-Tg B. Post-Tg	55 230	AABUS –	ppm/°C	2.4.24
CTE, X-, Y-axes	A. Pre-Tg B. Post-Tg	16 18	AABUS –	ppm/°C	2.4.24
Z-axis Expansion (50-260°C)		2.8	–	%	2.4.24
Thermal Conductivity		0.4	–	W/mK	ASTM D5930
Thermal Stress 10 sec @ 288°C (550.4°F)	A. Unetched B. Etched	Pass	Pass Visual	Rating	2.4.13.1
Dk, Permittivity (Laminate & prepreg as laminated) Tested at 56% resin	A. @ 100 MHz (HP4285A) B. @ 1 GHz (HP4291A) C. @ 2 GHz (Bereskin Stripline) D. @ 5 GHz (Bereskin Stripline) E. @ 10 GHz (Bereskin Stripline)	3.72 3.69 3.68 3.64 3.65	5.4 – – – –	–	2.5.5.3 2.5.5.9 2.5.5.5 2.5.5.5 2.5.5.5
Df, Loss Tangent (Laminate & prepreg as laminated) Tested at 56% resin	A. @ 100 MHz (HP4285A) B. @ 1 GHz (HP4291A) C. @ 2 GHz (Bereskin Stripline) D. @ 5 GHz (Bereskin Stripline) E. @ 10 GHz (Bereskin Stripline)	0.0072 0.0091 0.0092 0.0098 0.0095	0.035 – – – –	–	2.5.5.3 2.5.5.9 2.5.5.5 2.5.5.5 2.5.5.5
Volume Resistivity	A. 96/35/90 B. After moisture resistance C. At elevated temperature	– $4.4x10^7$ $9.4x10^7$	$1.0x10^6$ – $1.0x10^3$	MΩ-cm	2.5.17.1
Surface Resistivity	A. 96/35/90 B. After moisture resistance C. At elevated temperature	– $2.6x10^6$ $2.1x10^8$	$1.0x10^4$ – $1.0x10^3$	MΩ	2.5.17.1
Dielectric Breakdown		>50	–	kV	2.5.6
Arc Resistance		137	60	Seconds	2.5.1
Electric Strength (Laminate & prepreg as laminated)		70 (1741)	30 (750)	kV/mm (V/mil)	2.5.6.2
Comparative Tracking Index (CTI)		3 (175-249)	–	Class (Volts)	UL-746A ASTM D3638
Peel Strength	A. Low profile copper foil and very low profile – all copper weights >17 microns B. Standard profile copper 1. After thermal stress 2. At 125°C (257°F) 3. After process solutions	1.14 (6.5) – 0.96 (5.5) – 0.90 (5.1)	0.70 (4.0) – 0.80 (4.5) 0.70 (4.0) 0.55 (3.0)	N/mm (lb/inch)	2.4.8 2.4.8.2 2.4.8.3 – –
Flexural Strength	A. Lengthwise direction B. Crosswise direction	72,500 58,000	–	lb/inch²	2.4.4
Tensile Strength	A. Lengthwise direction B. Crosswise direction	54,525 38,678	–	lb/inch²	–
Young's Modulus	A. Grain direction B. Fill direction	3695 3315	–	ksi	ww
Poisson's Ratio	A. Grain direction B. Fill direction	0.137 0.133	–	–	xx
Moisture Absorption		0.061	–	%	2.6.2.1
Flammability (Laminate & prepreg as laminated)		V-0	–	Rating	UL 94
Max Operating Temperature		130	UL Cert	°C	–

The data, while believed to be accurate and based on analytical methods considered to be reliable, is for information purposes only. Any sales of these products will be governed by the terms and conditions of the agreement under which they are sold.

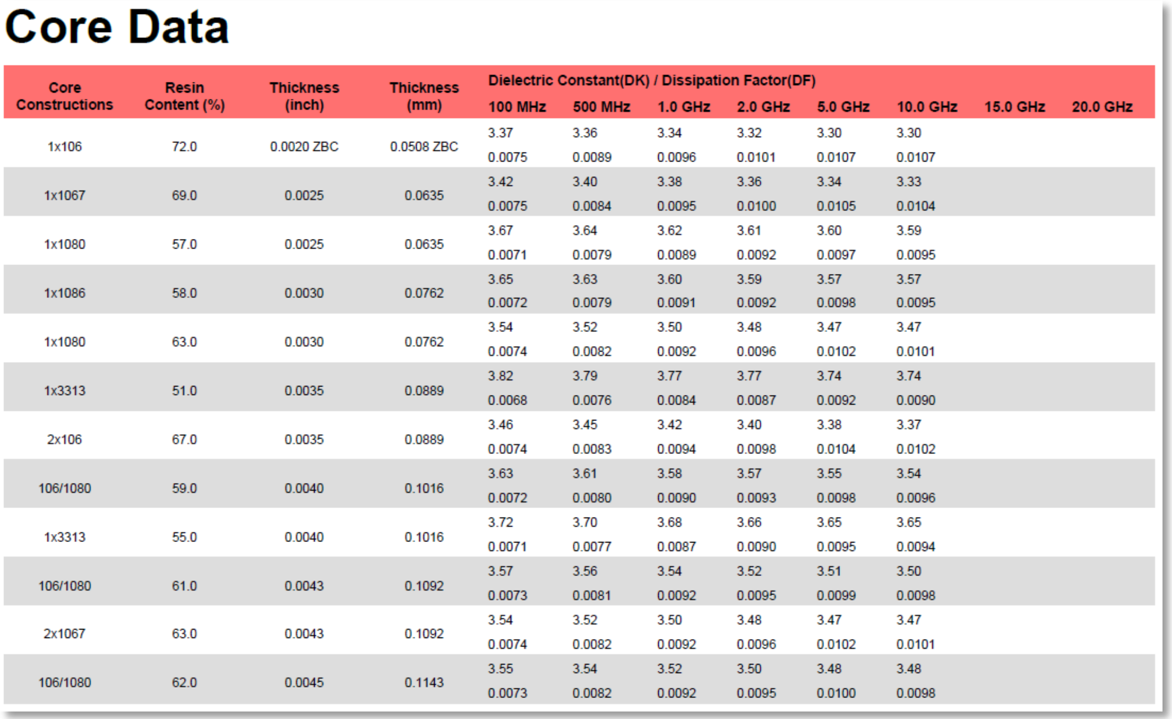


Dk, Permittivity (Laminate & prepreg as laminated) Tested at 56% resin	A. @ 100 MHz (HP4285A) B. @ 1 GHz (HP4291A) C. @ 2 GHz (Bereskin Stripline) D. @ 5 GHz (Bereskin Stripline) E. @ 10 GHz (Bereskin Stripline)	3.72 3.69 3.68 3.64 3.65	5.4 – – – –	–	2.5.5.3 2.5.5.9 2.5.5.5 2.5.5.5 2.5.5.5
Df, Loss Tangent (Laminate & prepreg as laminated) Tested at 56% resin	A. @ 100 MHz (HP4285A) B. @ 1 GHz (HP4291A) C. @ 2 GHz (Bereskin Stripline) D. @ 5 GHz (Bereskin Stripline) E. @ 10 GHz (Bereskin Stripline)	0.0072 0.0091 0.0092 0.0098 0.0095	0.035 – – – –	–	2.5.5.3 2.5.5.9 2.5.5.5 2.5.5.5 2.5.5.5

Using Dk/Df numbers from marketing data sheets for stackup and channel modeling will give inaccurate results

Reference: Isola [9]

Engineering Data Sheets



Core Data

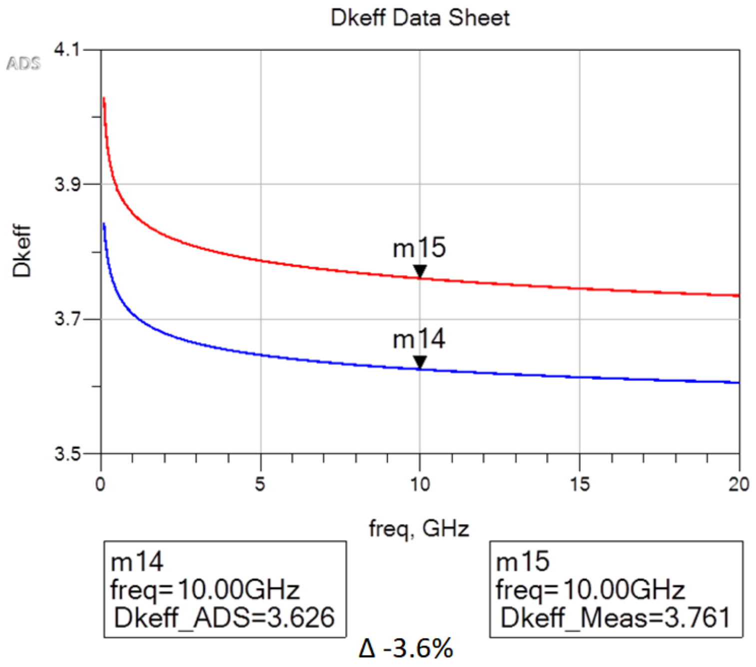
Core Constructions	Resin Content (%)	Thickness (inch)	Thickness (mm)	Dielectric Constant(DK) / Dissipation Factor(DF)							
				100 MHz	500 MHz	1.0 GHz	2.0 GHz	5.0 GHz	10.0 GHz	15.0 GHz	20.0 GHz
1x106	72.0	0.0020 ZBC	0.0508 ZBC	3.37 0.0075	3.36 0.0089	3.34 0.0096	3.32 0.0101	3.30 0.0107	3.30 0.0107		
1x1067	69.0	0.0025	0.0635	3.42 0.0075	3.40 0.0084	3.38 0.0095	3.36 0.0100	3.34 0.0105	3.33 0.0104		
1x1080	57.0	0.0025	0.0635	3.67 0.0071	3.64 0.0079	3.62 0.0089	3.61 0.0092	3.60 0.0097	3.59 0.0095		
1x1086	58.0	0.0030	0.0762	3.65 0.0072	3.63 0.0079	3.60 0.0091	3.59 0.0092	3.57 0.0098	3.57 0.0095		
1x1080	63.0	0.0030	0.0762	3.54 0.0074	3.52 0.0082	3.50 0.0092	3.48 0.0096	3.47 0.0102	3.47 0.0101		
1x3313	51.0	0.0035	0.0889	3.82 0.0068	3.79 0.0076	3.77 0.0084	3.77 0.0087	3.74 0.0092	3.74 0.0090		
2x106	67.0	0.0035	0.0889	3.46 0.0074	3.45 0.0083	3.42 0.0094	3.40 0.0098	3.38 0.0104	3.37 0.0102		
106/1080	59.0	0.0040	0.1016	3.63 0.0072	3.61 0.0080	3.58 0.0090	3.57 0.0093	3.55 0.0098	3.54 0.0096		
1x3313	55.0	0.0040	0.1016	3.72 0.0071	3.70 0.0077	3.68 0.0087	3.66 0.0090	3.65 0.0095	3.65 0.0094		
106/1080	61.0	0.0043	0.1092	3.57 0.0073	3.56 0.0081	3.54 0.0092	3.52 0.0095	3.51 0.0099	3.50 0.0098		
2x1067	63.0	0.0043	0.1092	3.54 0.0074	3.52 0.0082	3.50 0.0092	3.48 0.0096	3.47 0.0102	3.47 0.0101		
106/1080	62.0	0.0045	0.1143	3.55 0.0073	3.54 0.0082	3.52 0.0092	3.50 0.0095	3.48 0.0100	3.48 0.0098		

Provides:

- ✓ Actual core/prepreg thicknesses
- ✓ Resin content
- ✓ Dk(*f*) /Df(*f*) for different glass styles

Reference: Isola [9]

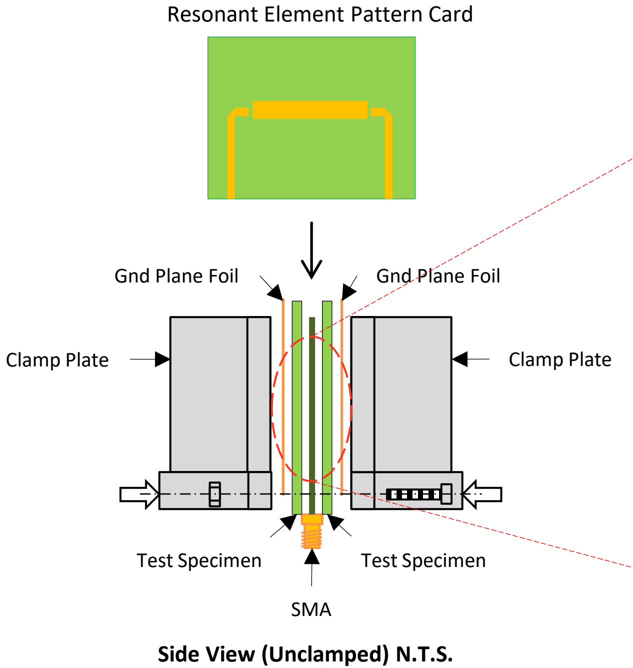
Dielectric Modeling Issue



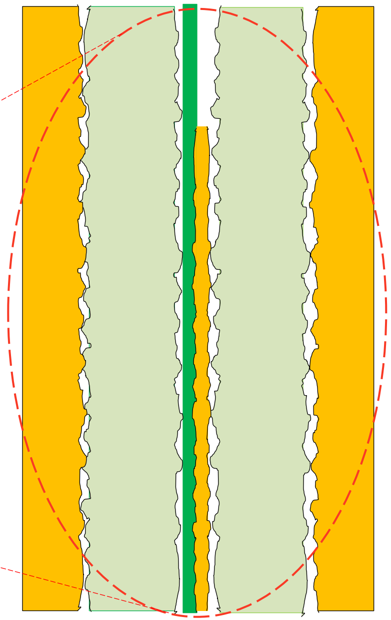
When Data Sheet D_k is not the same as Effective D_k

Simulated with Keysight ADS [13]

IPC-TM-650 Clamped Stripline Resonator Test Method [14]



Side View (Unclamped) N.T.S.



Side View (Clamped) N.T.S.

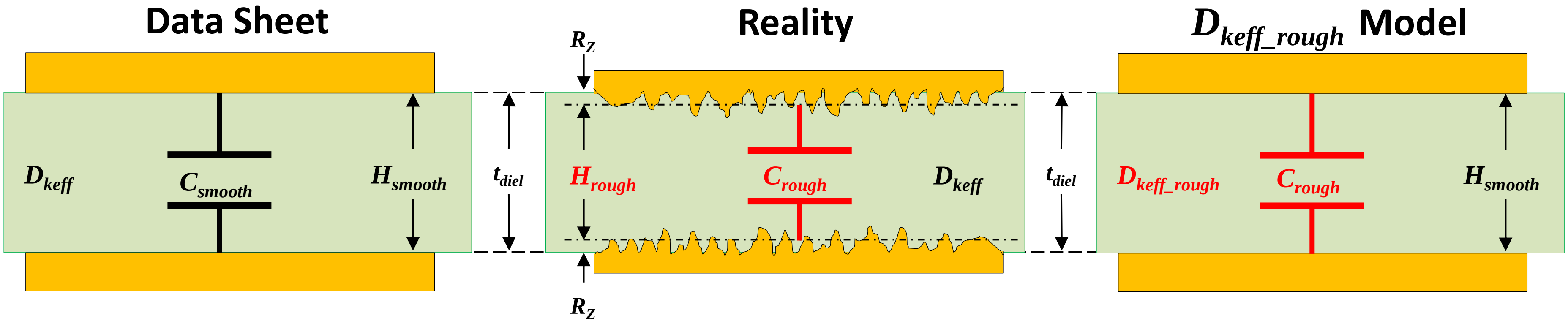
Issue:

Since resonant element pattern card & material U.T. not physically bonded together => small air gaps between various layers & conductor roughness affects published results

Published D_k not same as D_{keff} due to roughness

IPC-TM-650 - Section 2.5.5.5 - Rev C - Test Fixture [14]

D_{keff} Due to Roughness Model [1]



$$C_{smooth} = D_{keff}\left(\frac{\varepsilon_0 A}{H_{smooth}}\right)$$

$$C_{rough} = D_{keff}\left(\frac{\varepsilon_0 A}{H_{rough}}\right) = D_{keff}\left(\frac{\varepsilon_0 A}{(H_{smooth} - 2R_z)}\right)$$

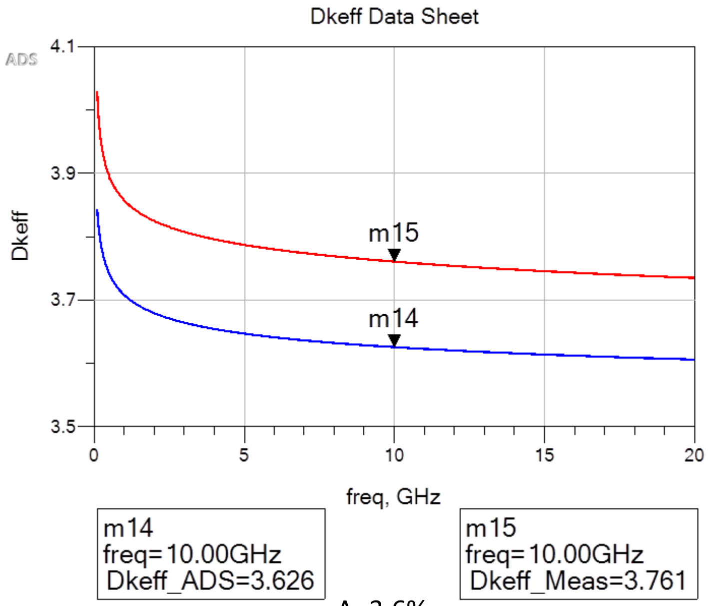
$$C_{rough} = D_{keff\_rough}\left(\frac{\varepsilon_0 A}{H_{smooth}}\right)$$

$$\frac{H_{smooth}}{H_{rough}} = \frac{C_{rough}}{C_{smooth}} = \frac{D_{keff\_rough}\left(\frac{\varepsilon_0 A}{H_{smooth}}\right)}{D_{keff}\left(\frac{\varepsilon_0 A}{H_{smooth}}\right)} = \frac{D_{keff\_rough}}{D_{keff}}$$

⇒

$$\boxed{D_{keff\_rough} = \frac{H_{smooth}}{(H_{smooth} - 2R_z)} \times D_{keff}}$$

FR408HR/RTF Simulation Results for D_{keff}

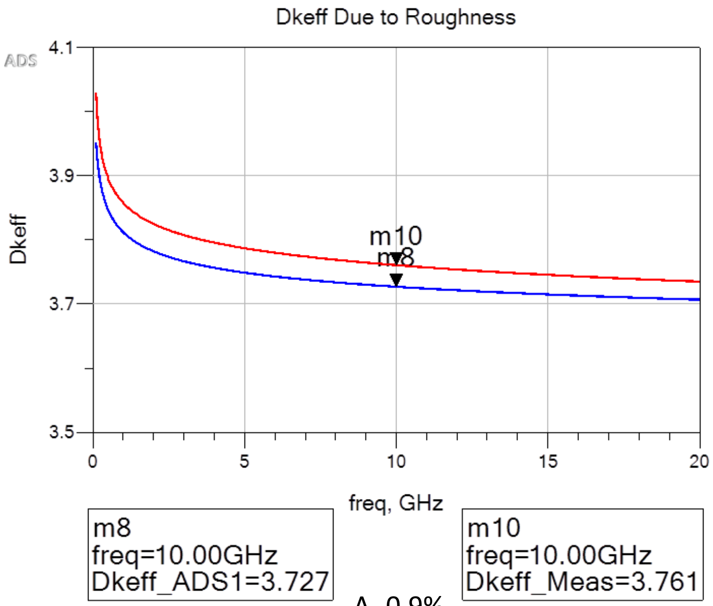


m14
freq=10.00GHz
Dkeff_ADS=3.626

m15
freq=10.00GHz
Dkeff_Meas=3.761

Δ -3.6%

Data Sheet Values



m8
freq=10.00GHz
Dkeff_ADS1=3.727

m10
freq=10.00GHz
Dkeff_Meas=3.761

Δ -0.9%

D_{keff} Roughness Model

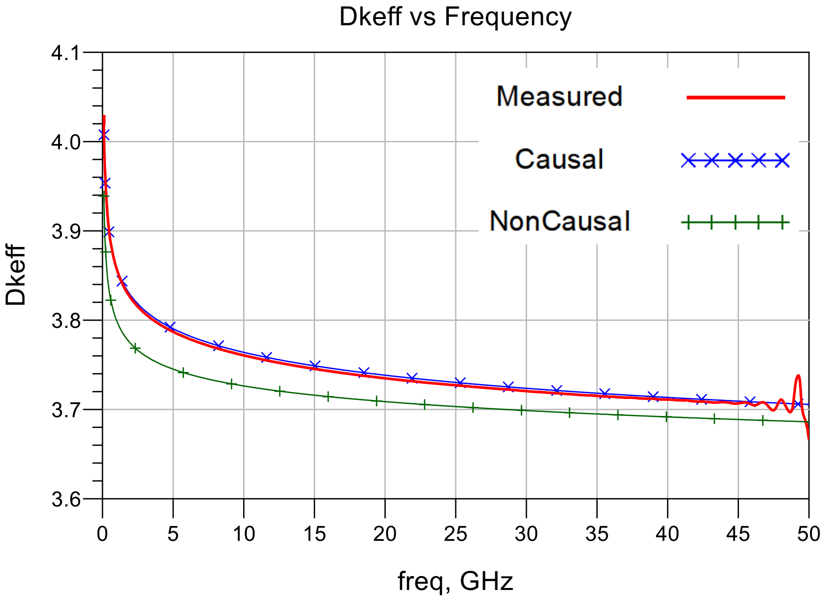
Simulated with Keysight ADS [13]

Causal Roughness Correction Factors [4]

$$Z_{rough}(if) = \overbrace{\underbrace{K(if)}_{\text{Complex roughness correction factor}}(1+i)\sqrt{\pi f}\,R_s}^{\text{Complex impedance of rough metal}} = \overbrace{\underbrace{[K_{re}(f) - K_{im}(f)]}_{\text{Loss correction factor}}\sqrt{\pi f}\,R_s}^{\text{Real part of internal impedance of rough metal}} + \overbrace{i\underbrace{[K_{re}(f) + K_{im}(f)]}_{\text{Inductance correction factor}}\sqrt{\pi f}\,R_s}^{\text{Imaginary part of internal impedance of rough metal}}$$

This is what we used to call “roughness correction” factor

A Causal Conductor Roughness Model and its Effect on Transmission Line Characteristics [4]



D_{keff} corrected due to roughness and complex roughness correction factor applied

✓Excellent Results!

Modeled with Hyperlynx [20] and Simulated with Keysight ADS[13]

Model Validations

CMP-28 Test Platform [7]

Features:

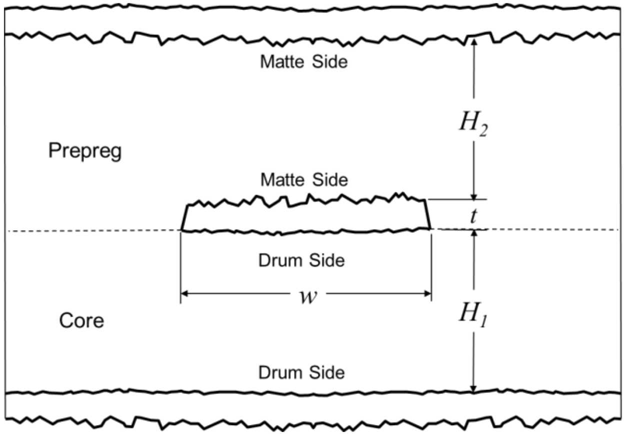
- FR408HR material with reverse-treated foil (RTF)
- Assembled with 2.92mm (CMP-28) or 2.4mm (CMP-32) connectors
- 3D EM benchmark structures
  - Loss structures for material extraction
  - Resonators for measurement correspondence
  - Multi-impedance structures for VNA time transform analysis

Applications:

- 3D-EM and measurement assistance for the SI practitioner
  - Vias
  - Multimode Analysis
  - Meshing Analysis Structure
  - Advanced Material Extraction and Loss Modeling
- THRU Calibration, T-matrix de- embedding
- Advanced Crosstalk analysis
- TRL/LRM Calibration Verification/Benchmark

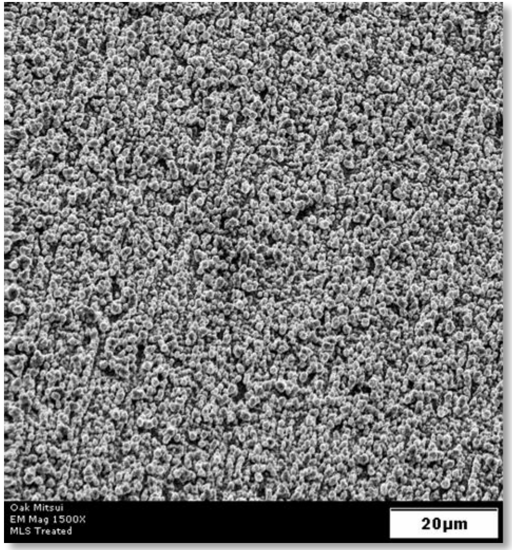
Photo courtesy Wild River Technology [7]

FR408HR/RTF Data Sheet & Test Board Design Parameters [7],[9],[11]



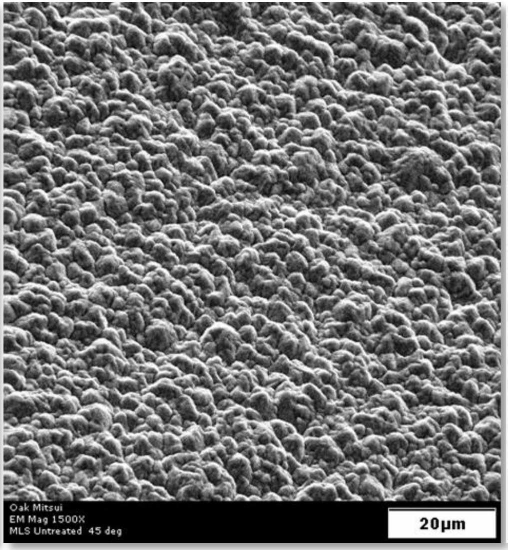
Parameter	FR408HR/RTF
D_k Core/Prepreg	3.65/3.59 @10GHz
D_f Core/Prepreg	0.0094/0.0095 @ 10GHz
R_z Drum side	3.048 μm
R_z Before Micro-etch-Matte side	5.715 μm
R_z After 50 μin (1.27 μm) Micro-etch treatment -Matte side	4.445 μm
Trace Thickness, t	1.25 mils (31.73 μm)
Trace Etch Factor	60 deg taper
Trace Width, w	11 mils (279.20 μm)
Core thickness, H1	12 mils (304.60 μm)
Prepreg thickness, H2	10.6 mils (269.00 μm)
De-embedded trace length	6.00 in (15.24 cm)

MLS RT foil



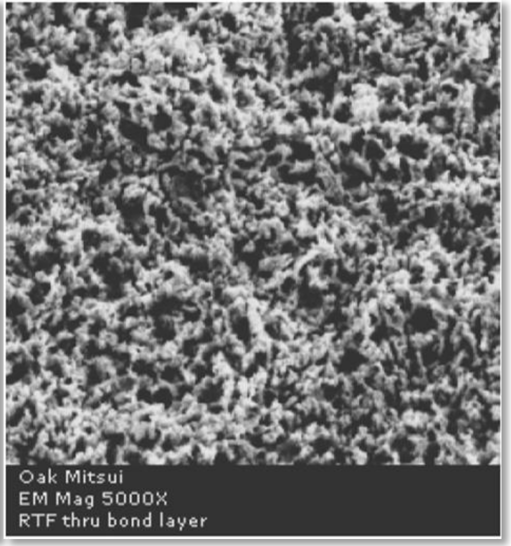
Treated drum side

Rz = 3.175 μm



Untreated matte side

Rz = 5.715 μm

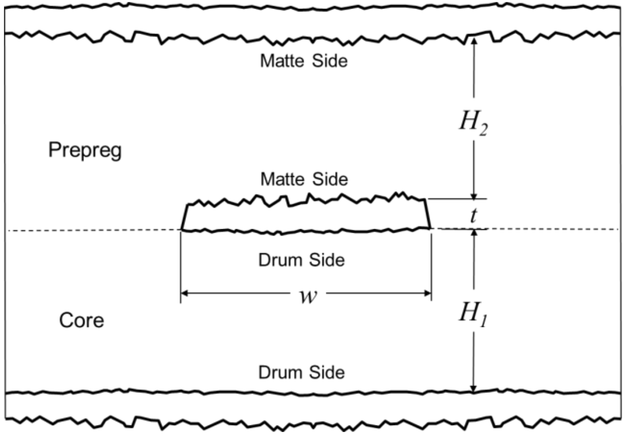


Matte side after etch treatment

Rz = 4.443 μm

Photos courtesy of Oak-mitsui [11]

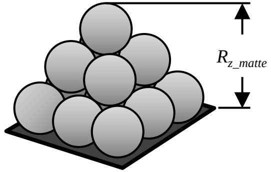
Determine D_{keff} Due to Roughness Core/Prepreg



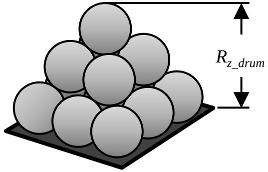
$$D_{keff\_prepreg} = \frac{H_{2\_smooth}}{\left(H_{2\_smooth} - 2R_{z\_matte}\right)} \times D_{k\_prepreg} = \frac{269\mu m}{\left(269\mu m - 2\times 4.445\mu m\right)} \times 3.59 = 3.713$$

$$D_{keff\_core} = \frac{H_{1\_smooth}}{\left(H_{1\_smooth} - 2R_{z\_drum}\right)} \times D_{k\_core} = \frac{304.6\mu m}{\left(304.6\mu m - 2\times 3.048\mu m\right)} \times 3.65 = 3.725$$

Determine Sphere Radius (r) & Base Area (A_{flat})



Matte-side



Drum-side

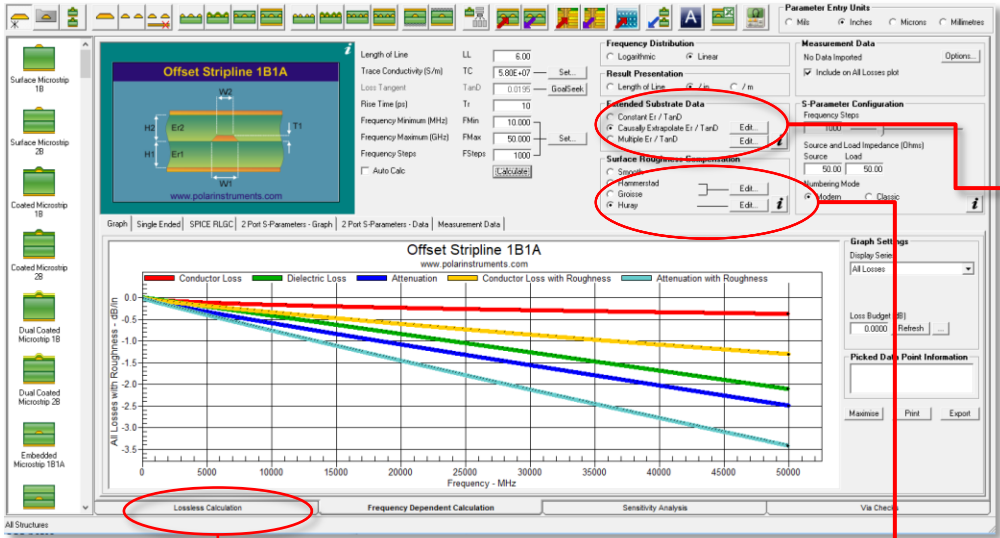
$$\begin{aligned} r_{matte} &\approx 0.06 R_{z\_matte} \\ &\approx 0.06 \times 4.443 \mu m \\ &\approx 0.266 \mu m \end{aligned}$$

$$\begin{aligned} r_{drum} &\approx 0.06 R_{z\_drum} \\ &\approx 0.06 \times 3.048 \mu m \\ &\approx 0.182 \mu m \end{aligned}$$

$$\begin{aligned} r_{eff} &\approx \frac{r_{matte} + r_{drum}}{2} \\ &\approx \frac{0.266 \mu m + 0.182 \mu m}{2} \\ &\approx 0.224 \mu m \end{aligned}$$

$$\begin{aligned} A_{flat} &= 36 \left(r_{eff} \right)^2 \\ &= 36 (0.224 \mu m)^2 \\ &= 1.806 \mu m^2 \end{aligned}$$

Input Design Parameters Polar Si9000e [12]



Parameter Entry Units: ○ Mils ● Inches ○ Microns ○ Millimetres

Length of Line LL 6.00
Trace Conductivity (S/m) TC 5.80E+07 — Set...
Loss Tangent TanD 0.0195 — GoalSeek
Rise Time (ps) Tr 10
Frequency Minimum (MHz) FMin 10.000
Frequency Maximum (GHz) FMax 50.000 — Set...
Frequency Steps FSteps 1000
☐ Auto Calc
Calculate

Frequency Distribution: ○ Logarithmic ● Linear

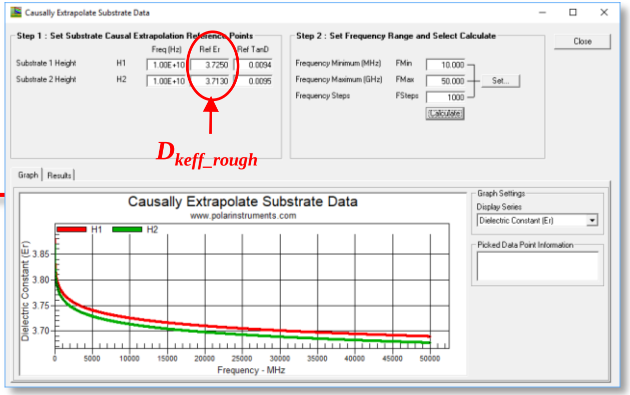
Result Presentation: ○ Length of Line ● / in ○ / m

Extended Substrate Data: ○ Constant Er / TanD ● Causally Extrapolate Er / TanD Edit... ○ Multiple Er / TanD Edit...

Surface Roughness Compensation: ○ Smooth ○ Hammerstad ○ Groisse Edit... ● Huray Edit...

Measurement Data: No Data Imported Options... ☑ Include on All Losses plot

S-Parameter Configuration: Frequency Steps 1000; Source and Load Impedance (Ohms) Source 50.00 Load 50.00; Numbering Mode ● Modern ○ Classic



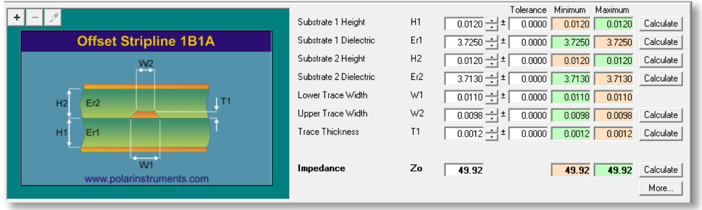
Step 1 : Set Substrate Causal Extrapolation Reference Points

		Freq (Hz)	Ref Er	Ref TanD
Substrate 1 Height	H1	1.00E+10	3.7250	0.0094
Substrate 2 Height	H2	1.00E+10	3.7130	0.0095

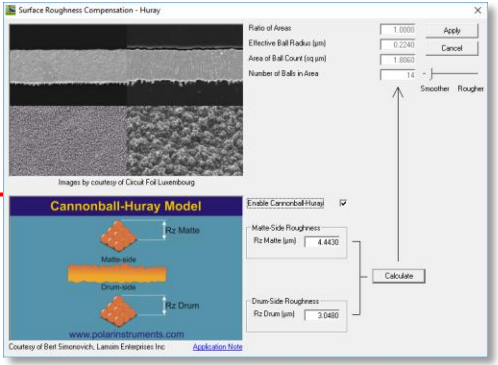
D_{keff_rough}

Step 2 : Set Frequency Range and Select Calculate

Frequency Minimum (MHz) FMin 10.000
Frequency Maximum (GHz) FMax 50.000 — Set...
Frequency Steps FSteps 1000
Calculate



			Tolerance	Minimum	Maximum	
Substrate 1 Height	H1	0.0120	± 0.0000	0.0120	0.0120	Calculate
Substrate 1 Dielectric	Er1	3.7250	± 0.0000	3.7250	3.7250	Calculate
Substrate 2 Height	H2	0.0120	± 0.0000	0.0120	0.0120	Calculate
Substrate 2 Dielectric	Er2	3.7130	± 0.0000	3.7130	3.7130	Calculate
Lower Trace Width	W1	0.0110	± 0.0000	0.0110	0.0110	
Upper Trace Width	W2	0.0098	± 0.0000	0.0098	0.0098	Calculate
Trace Thickness	T1	0.0012	± 0.0000	0.0012	0.0012	Calculate
Impedance	**Zo**	**49.92**		**49.92**	**49.92**	Calculate
						More...



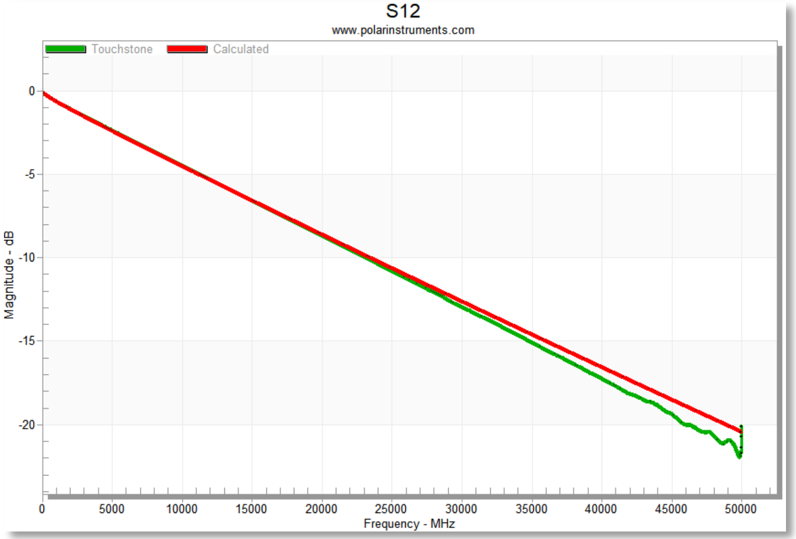
Ratio of Areas 1.0000
Effective Ball Radius (μm) 0.2240
Area of Ball Count (sq μm) 1.8060
Number of Balls in Area 14

Enable Cannonball-Huray ☑

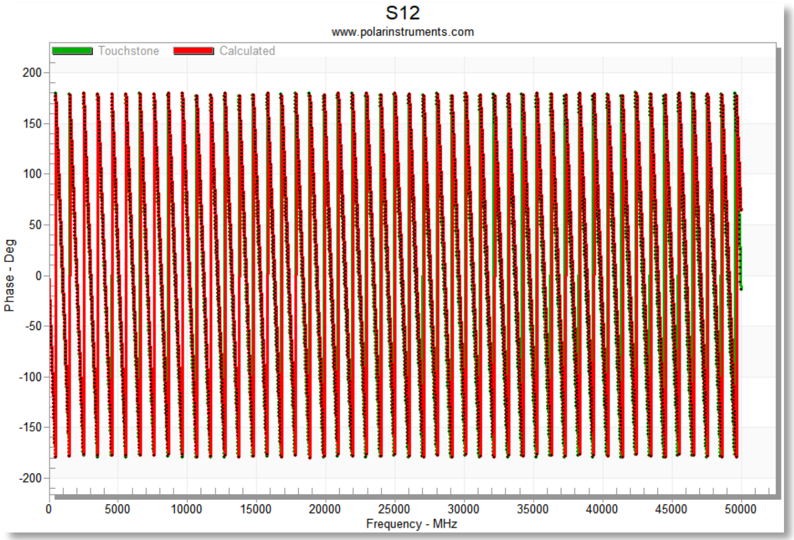
Matte-Side Roughness: Rz Matte (μm) 4.4430

Drum-Side Roughness: Rz Drum (μm) 3.0480

Simulated vs Measured



Insertion Loss

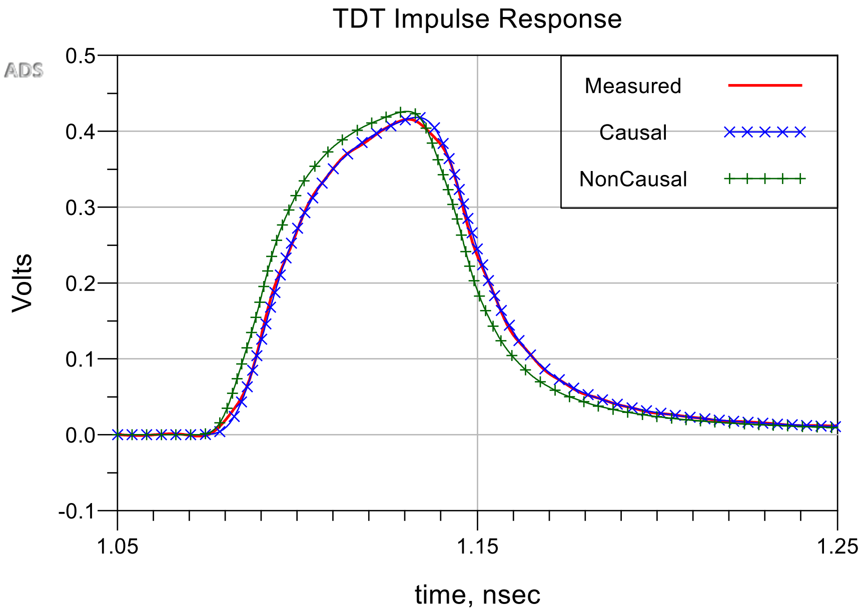


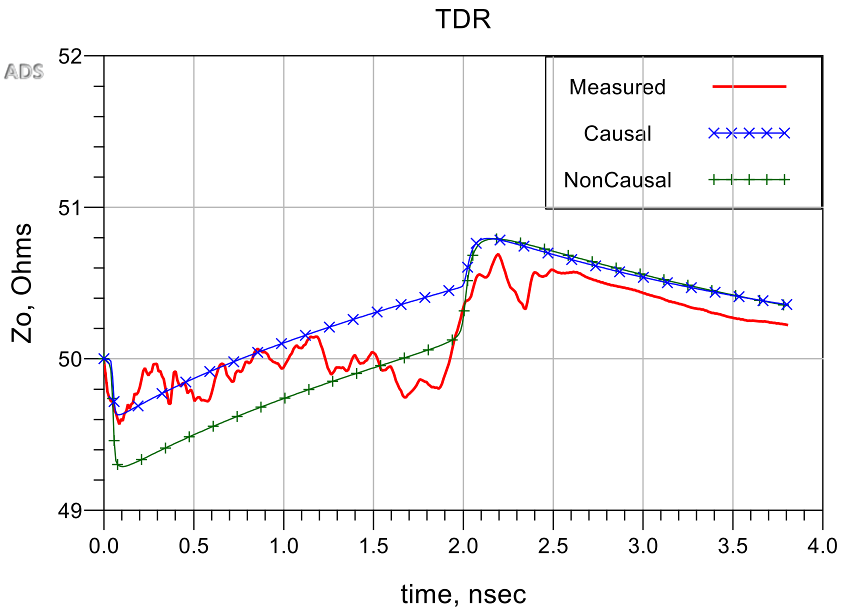
Phase

✓ Excellent Correlation!

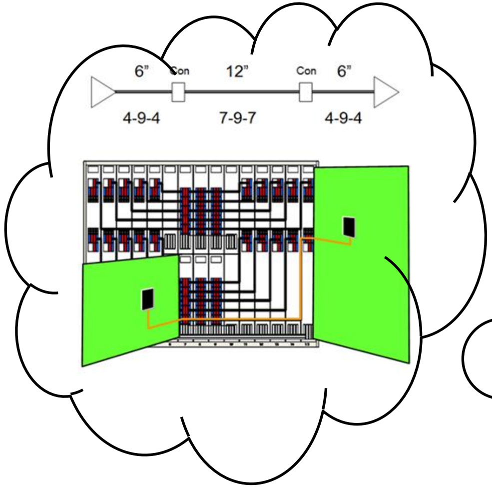
Modeled and Simulated with Polar Si9000e [12]

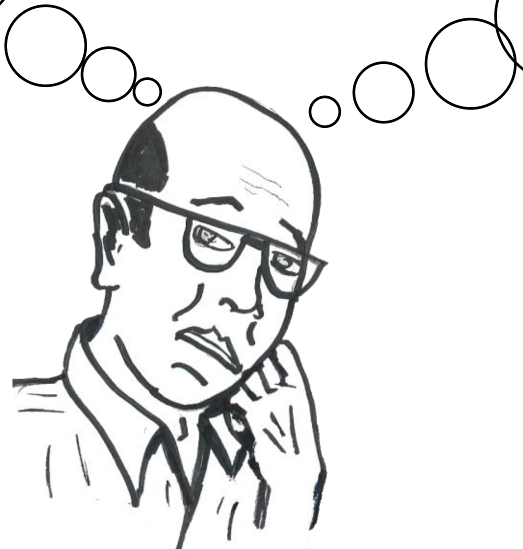
FR408HR Simulation Results for Impulse and TDR





Modeled with Hyperlynx [20] and Simulated with Keysight ADS[13]



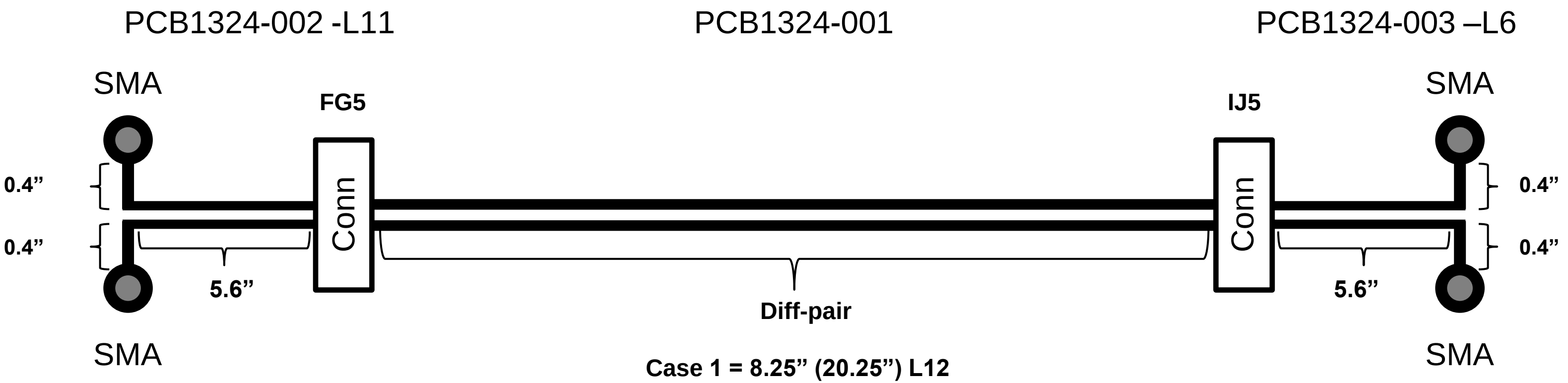


Well…single-ended looks great……BUT how well does this method work to model a practical backplane channel with diff pairs?

ExaMax Demonstrator Platform

- Design Intent - 28 GB/s NRZ
- Meg 6 or N4000-13EPSI Options
  - Nelco N4000-13EPSI Version Used
- MW-G-VSP ½ oz. foil (VLP)
- 2.9 mm coax connectors
- Case 1 = 8.25” (20.25”) L12
- Case 2 = 14.80” (26.8”) L10
- Case 3 = 20.22” (32.22”) L10
- Case 4 = 26.70” (38.70”) L12

Loss Topology Model N4000-13EPSI Summary



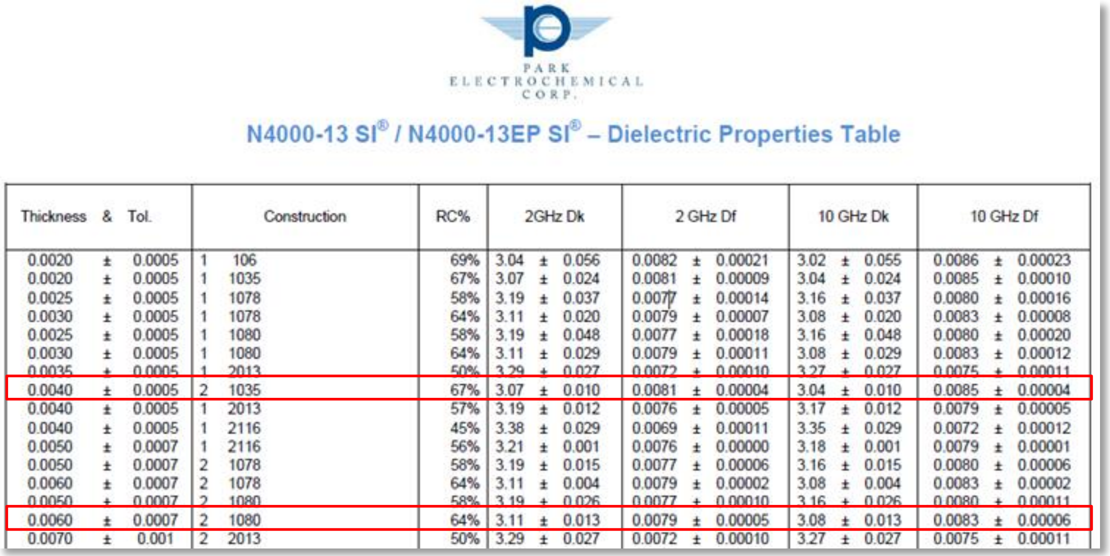
Case 1 = 8.25” (20.25”) L12
Case 2 = 14.80” (26.8”) L10
Case 3 = 20.22” (32.22”) L10
Case 4 = 26.70” (38.70”) L12

W = 4.9mils
S = 6.1mils
t = 0.6 mils

W = 6.3mils()
S = 5.7 mils()
t = 0.6 mils()

W = 4.9mils
S = 6.1mils
t = 0.6 mils

Data Sheet Parameters [10], [11]



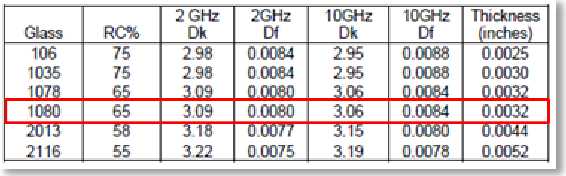
PARK ELECTROCHEMICAL CORP.

N4000-13 SI® / N4000-13EP SI® – Dielectric Properties Table

Thickness & Tol.	Construction	RC%	2GHz Dk	2 GHz Df	10 GHz Dk	10 GHz Df
0.0020 ± 0.0005	1 106	69%	3.04 ± 0.056	0.0082 ± 0.00021	3.02 ± 0.055	0.0086 ± 0.00023
0.0020 ± 0.0005	1 1035	67%	3.07 ± 0.024	0.0081 ± 0.00009	3.04 ± 0.024	0.0085 ± 0.00010
0.0025 ± 0.0005	1 1078	58%	3.19 ± 0.037	0.0077 ± 0.00014	3.16 ± 0.037	0.0080 ± 0.00016
0.0030 ± 0.0005	1 1078	64%	3.11 ± 0.020	0.0079 ± 0.00007	3.08 ± 0.020	0.0083 ± 0.00008
0.0025 ± 0.0005	1 1080	58%	3.19 ± 0.048	0.0077 ± 0.00018	3.16 ± 0.048	0.0080 ± 0.00020
0.0030 ± 0.0005	1 1080	64%	3.11 ± 0.029	0.0079 ± 0.00011	3.08 ± 0.029	0.0083 ± 0.00012
0.0035 ± 0.0005	1 2013	50%	3.29 ± 0.027	0.0072 ± 0.00010	3.27 ± 0.027	0.0075 ± 0.00011
0.0040 ± 0.0005	2 1035	67%	3.07 ± 0.010	0.0081 ± 0.00004	3.04 ± 0.010	0.0085 ± 0.00004
0.0040 ± 0.0005	1 2013	57%	3.19 ± 0.012	0.0076 ± 0.00005	3.17 ± 0.012	0.0079 ± 0.00005
0.0040 ± 0.0005	1 2116	45%	3.38 ± 0.029	0.0069 ± 0.00011	3.35 ± 0.029	0.0072 ± 0.00012
0.0050 ± 0.0007	1 2116	56%	3.21 ± 0.001	0.0076 ± 0.00000	3.18 ± 0.001	0.0079 ± 0.00001
0.0050 ± 0.0007	2 1078	58%	3.19 ± 0.015	0.0077 ± 0.00006	3.16 ± 0.015	0.0080 ± 0.00006
0.0060 ± 0.0007	2 1078	64%	3.11 ± 0.004	0.0079 ± 0.00002	3.08 ± 0.004	0.0083 ± 0.00002
0.0050 ± 0.0007	2 1080	58%	3.19 ± 0.026	0.0077 ± 0.00010	3.16 ± 0.026	0.0080 ± 0.00011
0.0060 ± 0.0007	2 1080	64%	3.11 ± 0.013	0.0079 ± 0.00005	3.08 ± 0.013	0.0083 ± 0.00006
0.0070 ± 0.001	2 2013	50%	3.29 ± 0.027	0.0072 ± 0.00010	3.27 ± 0.027	0.0075 ± 0.00011

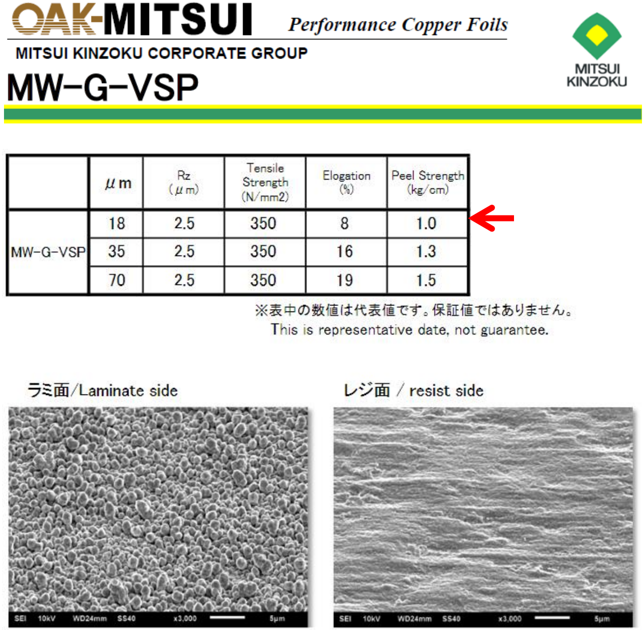
DC Core

BP Core



Glass	RC%	2 GHz Dk	2GHz Df	10GHz Dk	10GHz Df	Thickness (inches)
106	75	2.98	0.0084	2.95	0.0088	0.0025
1035	75	2.98	0.0084	2.95	0.0088	0.0030
1078	65	3.09	0.0080	3.06	0.0084	0.0032
1080	65	3.09	0.0080	3.06	0.0084	0.0032
2013	58	3.18	0.0077	3.15	0.0080	0.0044
2116	55	3.22	0.0075	3.19	0.0078	0.0052

BP/DC Prepreg



OAK-MITSUI *Performance Copper Foils*

MITSUI KINZOKU CORPORATE GROUP

MITSUI KINZOKU

MW–G–VSP

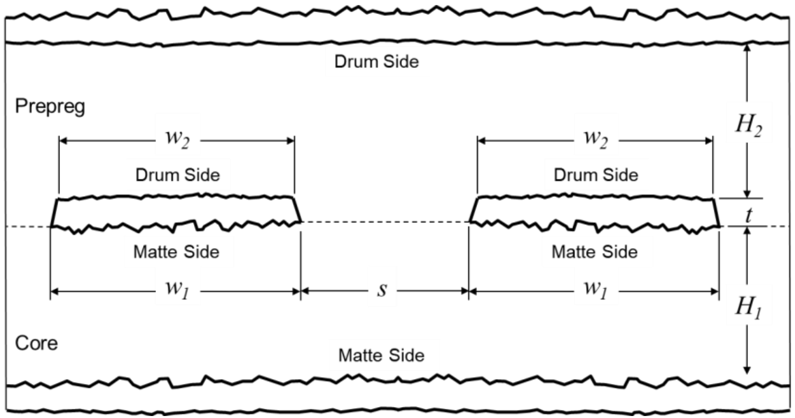
	μm	Rz (μm)	Tensile Strength (N/mm2)	Elogation (%)	Peel Strength (kg/cm)
MW–G–VSP	18	2.5	350	8	1.0
	35	2.5	350	16	1.3
	70	2.5	350	19	1.5

※表中の数値は代表値です。保証値ではありません。
This is representative date, not guarantee.

ラミ面/Laminate side

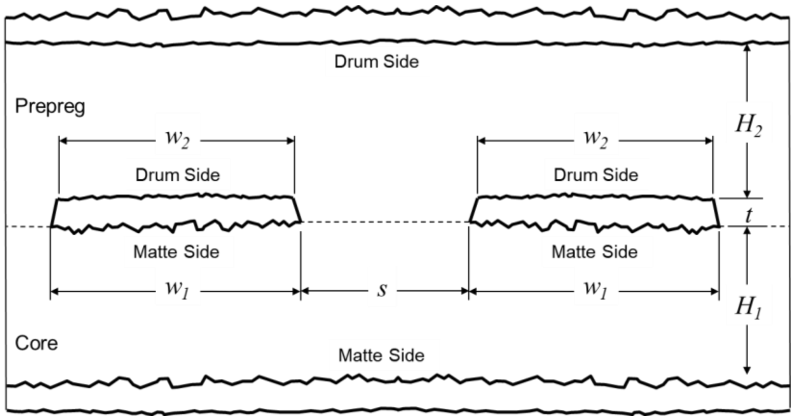
レジ面 / resist side

ExaMax Demonstrator Platform
Data Sheet Design Parameters Summary



Parameter	N4000-13EPSI Backplane	N4000-13EPSI Daughter Card
D_k Core/Prepreg @ $10GHz$	3.08/3.06	3.04/3.06
D_f Core/Prepreg @ $10GHz$	0.0083/0.0084	0.0085/0.0084
R_z Matte side	2.5 μm	2.5μm
R_z Drum side w/OA	1.5 μm	1.5 μm
Trace Thickness, t	0.6 mils	0.6 mils
Trace Width, w_1	6.3 mils	4.9 mils (Diff) 5.4 mils (SE)
Trace Width, w_2	5.7 mils	4.3 mils (Diff) 4.8 mils (SE)
Trace Separation, s	5.7 mils	6.1 mils
Core thickness, H1	6 mils	4 mils
Prepreg thickness, H2	5.8 mils	5.8 mils

Determine D_{keff} Due to Roughness Core/Prepreg



Daughter Card

$$D_{keff\_prepreg} = \frac{H_{smooth}}{\left(H_{smooth} - 2R_{z\_drum}\right)} \times D_{k\_prepreg}$$
$$= \frac{6.2mils \times 25.4}{\left(6.2mils \times 25.4 - 2 \times 1.5\mu m\right)} \times 3.06$$
$$= 3.12$$

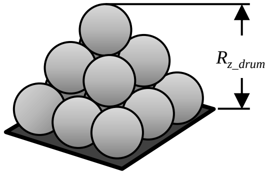
$$D_{keff\_core} = \frac{H_{smooth}}{\left(H_{smooth} - 2R_{z\_matte}\right)} \times D_{k\_core}$$
$$= \frac{4.0mils \times 25.4}{\left(4.0mils \times 25.4 - 2 \times 2.5\mu m\right)} \times 3.04$$
$$= 3.20$$

Backplane

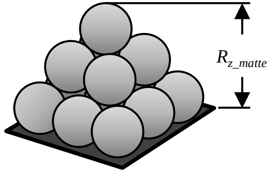
$$D_{keff\_prepreg} = \frac{H_{smooth}}{\left(H_{smooth} - 2R_{z\_drum}\right)} \times D_{k\_prepreg}$$
$$= \frac{6.2mils \times 25.4}{\left(6.2mils \times 25.4 - 2 \times 1.5\mu m\right)} \times 3.06$$
$$= 3.12$$

$$D_{keff\_core} = \frac{H_{smooth}}{\left(H_{smooth} - 2R_{z\_matte}\right)} \times D_{k\_core}$$
$$= \frac{6.0mils \times 25.4}{\left(6.0mils \times 25.4 - 2 \times 2.5\mu m\right)} \times 3.08$$
$$= 3.18$$

Determine Sphere Radius (r) & Base Area (A_{flat})



Drum-side



Matte-side

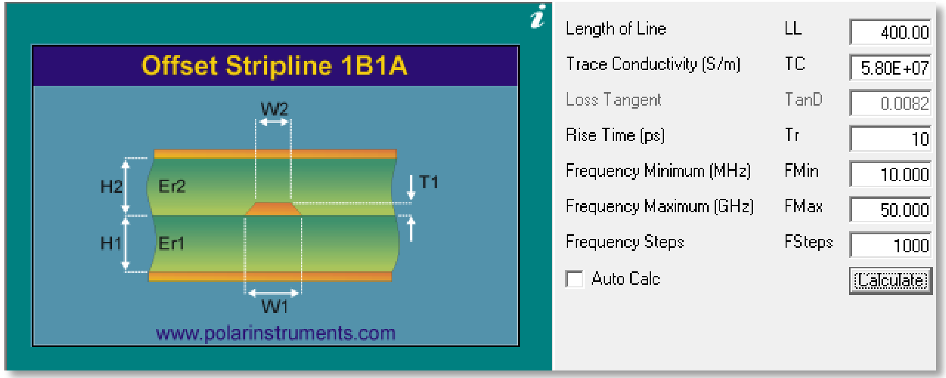
$$r_{drum} \approx 0.06 R_{z\_drum} \approx 0.090\,\mu m$$

$$r_{matte} \approx 0.06 R_{z\_matte} \approx 0.149\,\mu m$$

$$r_{eff} \approx \frac{r_{matte} + r_{drum}}{2} \approx 0.120\,\mu m$$

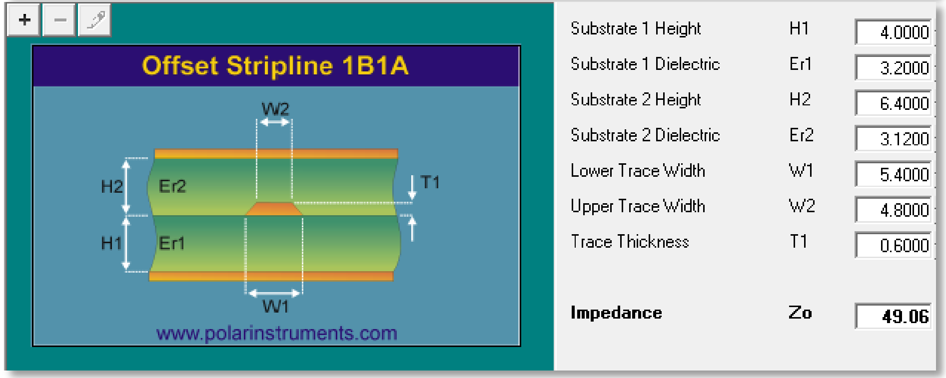
$$A_{flat} \approx 36\left(r_{eff}\right)^2 \approx 0.514\,\mu m^2$$

Polar ExaMax Daughter Card SE Trace Parameters

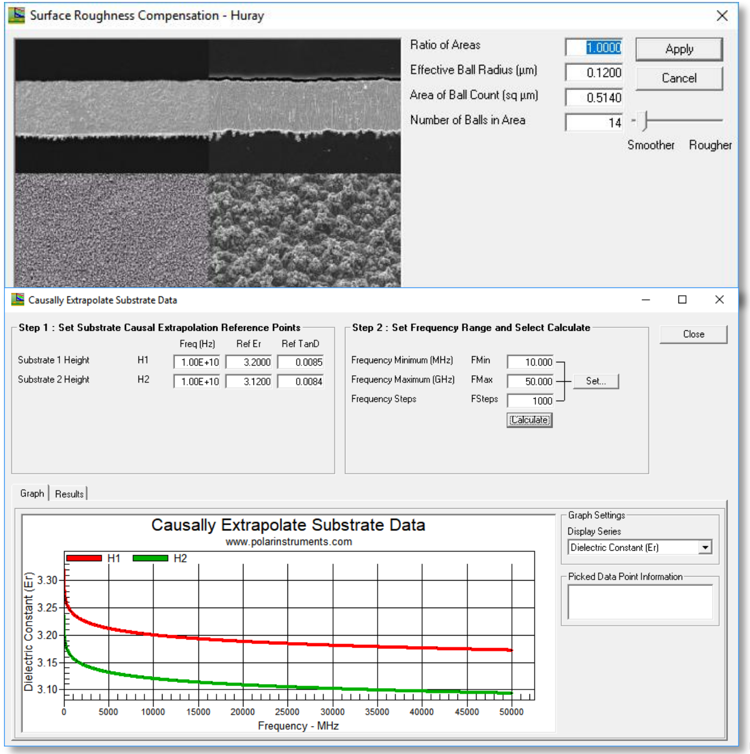


Length of Line	LL	400.00
Trace Conductivity (S/m)	TC	5.80E+07
Loss Tangent	TanD	0.0082
Rise Time (ps)	Tr	10
Frequency Minimum (MHz)	FMin	10.000
Frequency Maximum (GHz)	FMax	50.000
Frequency Steps	FSteps	1000

☐ Auto Calc



Substrate 1 Height	H1	4.0000
Substrate 1 Dielectric	Er1	3.2000
Substrate 2 Height	H2	6.4000
Substrate 2 Dielectric	Er2	3.1200
Lower Trace Width	W1	5.4000
Upper Trace Width	W2	4.8000
Trace Thickness	T1	0.6000
Impedance	**Zo**	**49.06**



Ratio of Areas	1.0000
Effective Ball Radius (µm)	0.1200
Area of Ball Count (sq µm)	0.5140
Number of Balls in Area	14

Step 1 : Set Substrate Causal Extrapolation Reference Points

		Freq (Hz)	Ref Er	Ref TanD
Substrate 1 Height	H1	1.00E+10	3.2000	0.0085
Substrate 2 Height	H2	1.00E+10	3.1200	0.0084

Step 2 : Set Frequency Range and Select Calculate

Frequency Minimum (MHz)	FMin	10.000
Frequency Maximum (GHz)	FMax	50.000
Frequency Steps	FSteps	1000

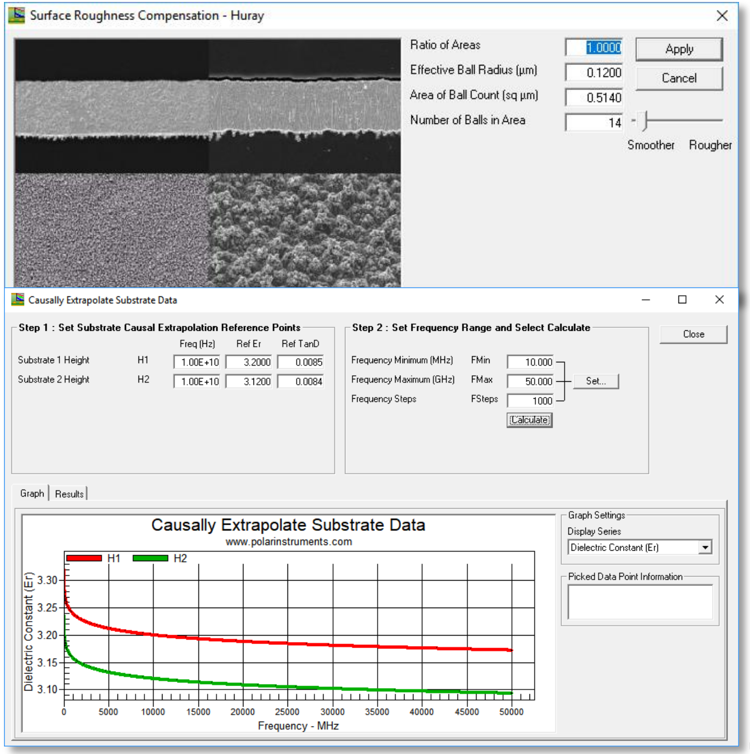
Display Series: Dielectric Constant (Er)

Polar ExaMax Daughter Card Diff Trace Parameters

Length of Line	LL	5600.00
Trace Conductivity (S/m)	TC	5.80E+07
Loss Tangent	TanD	0.0195
Rise Time (ps)	Tr	10
Frequency Minimum (MHz)	FMin	10.000
Frequency Maximum (GHz)	FMax	50.000
Frequency Steps	FSteps	1000

☐ Auto Calc

Substrate 1 Height	H1	4.0000
Substrate 1 Dielectric	Er1	3.2000
Substrate 2 Height	H2	6.4000
Substrate 2 Dielectric	Er2	3.1200
Lower Trace Width	W1	4.9000
Upper Trace Width	W2	4.3000
Trace Separation	S1	6.1000
Trace Thickness	T1	0.6000
Differential Impedance	**Zdiff**	**97.25**



Ratio of Areas	1.0000
Effective Ball Radius (µm)	0.1200
Area of Ball Count (sq µm)	0.5140
Number of Balls in Area	14

Step 1 : Set Substrate Causal Extrapolation Reference Points

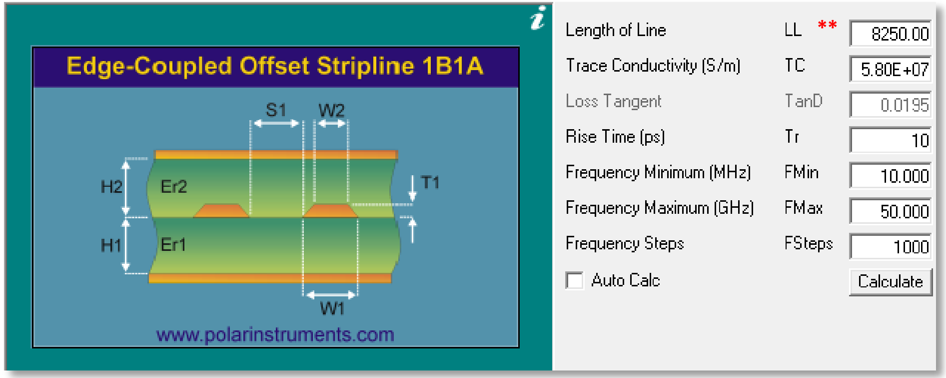
		Freq (Hz)	Ref Er	Ref TanD
Substrate 1 Height	H1	1.00E+10	3.2000	0.0085
Substrate 2 Height	H2	1.00E+10	3.1200	0.0084

Step 2 : Set Frequency Range and Select Calculate

Frequency Minimum (MHz)	FMin	10.000
Frequency Maximum (GHz)	FMax	50.000
Frequency Steps	FSteps	1000

Display Series: Dielectric Constant (Er)

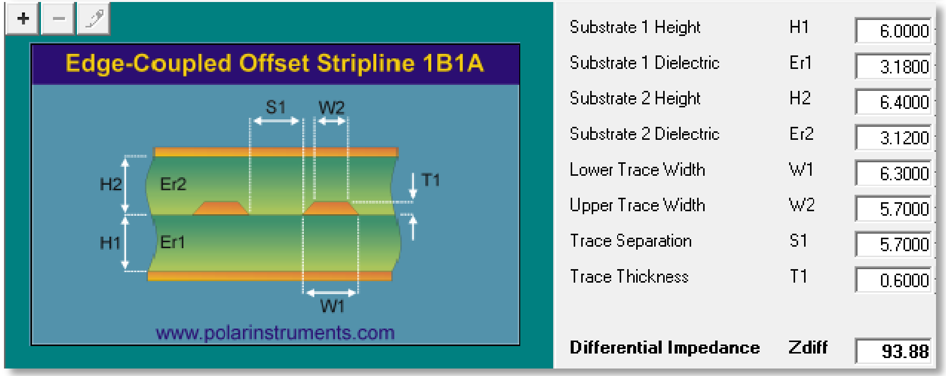
Polar ExaMax Backplane Diff Trace Parameters



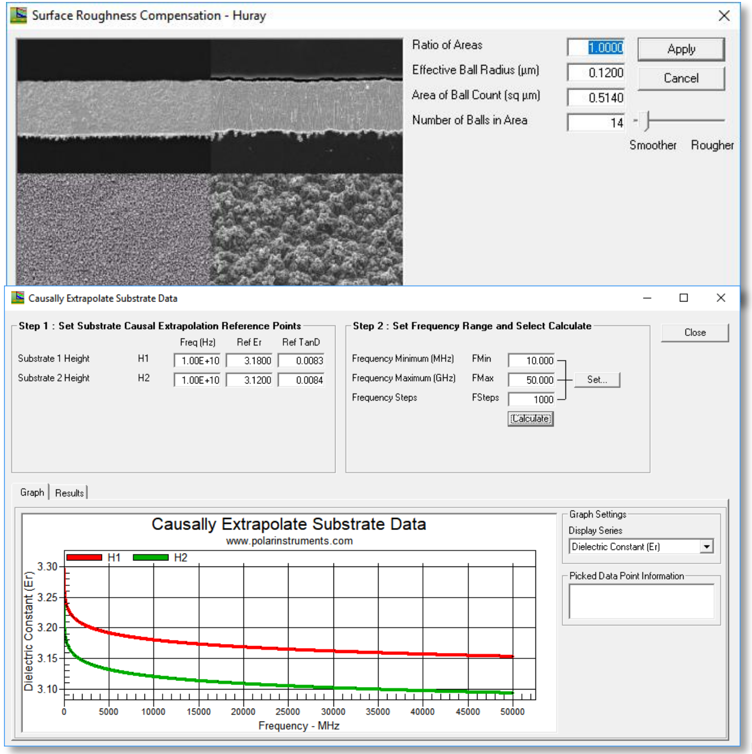
Length of Line	LL **	8250.00
Trace Conductivity (S/m)	TC	5.80E+07
Loss Tangent	TanD	0.0195
Rise Time (ps)	Tr	10
Frequency Minimum (MHz)	FMin	10.000
Frequency Maximum (GHz)	FMax	50.000
Frequency Steps	FSteps	1000

☐ Auto Calc

Calculate



Substrate 1 Height	H1	6.0000
Substrate 1 Dielectric	Er1	3.1800
Substrate 2 Height	H2	6.4000
Substrate 2 Dielectric	Er2	3.1200
Lower Trace Width	W1	6.3000
Upper Trace Width	W2	5.7000
Trace Separation	S1	5.7000
Trace Thickness	T1	0.6000
Differential Impedance	**Zdiff**	**93.88**


Surface Roughness Compensation - Huray

Ratio of Areas	1.0000
Effective Ball Radius (µm)	0.1200
Area of Ball Count (sq µm)	0.5140
Number of Balls in Area	14

Causally Extrapolate Substrate Data

Step 1 : Set Substrate Causal Extrapolation Reference Points

		Freq (Hz)	Ref Er	Ref TanD
Substrate 1 Height	H1	1.00E+10	3.1800	0.0083
Substrate 2 Height	H2	1.00E+10	3.1200	0.0084

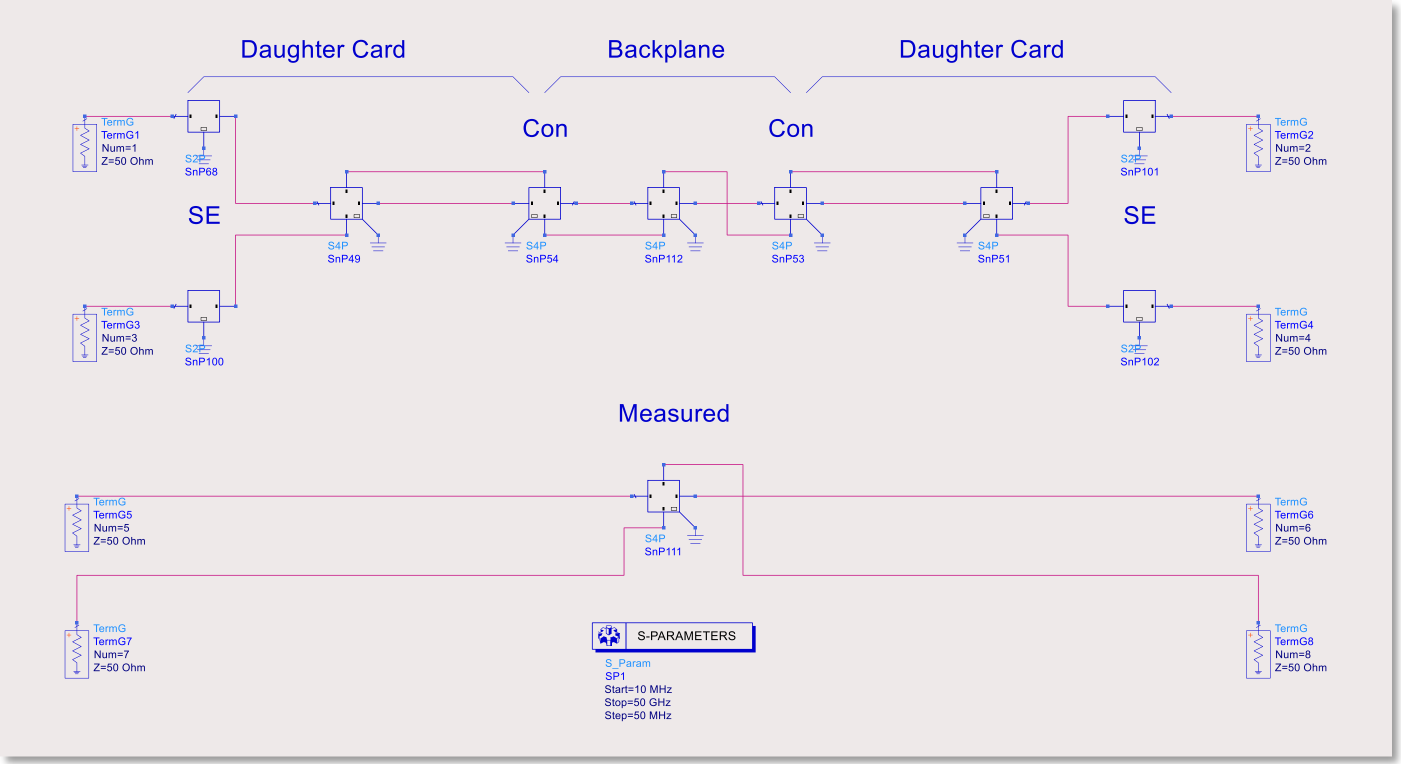
Step 2 : Set Frequency Range and Select Calculate

Frequency Minimum (MHz)	FMin	10.000
Frequency Maximum (GHz)	FMax	50.000
Frequency Steps	FSteps	1000

Graph Settings
Display Series: Dielectric Constant (Er)

**Length of Line (LL) Adjusted for 8.25”; 14.80”; 20.22”; 26.70”

Generic Topology Model



TermG
TermG1
Num=1
Z=50 Ohm

TermG
TermG3
Num=3
Z=50 Ohm

TermG
TermG2
Num=2
Z=50 Ohm

TermG
TermG4
Num=4
Z=50 Ohm

TermG
TermG5
Num=5
Z=50 Ohm

TermG
TermG6
Num=6
Z=50 Ohm

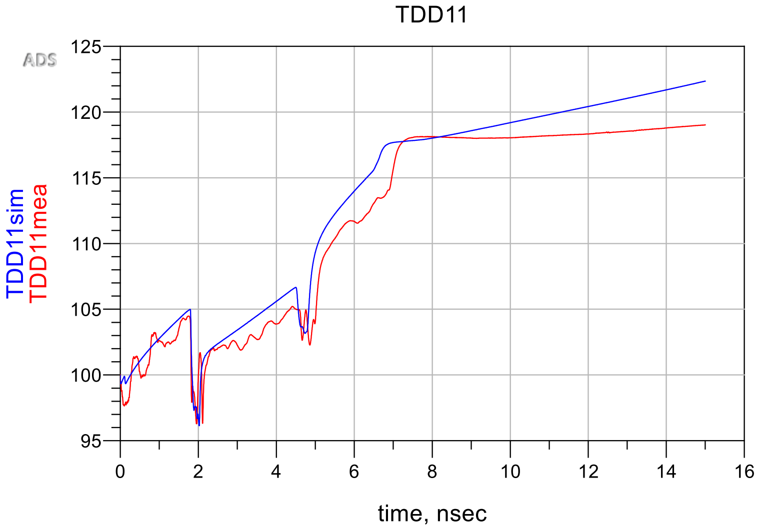
TermG
TermG7
Num=7
Z=50 Ohm

TermG
TermG8
Num=8
Z=50 Ohm

S_Param
SP1
Start=10 MHz
Stop=50 GHz
Step=50 MHz

Modeled with Keysight ADS [13]

ExaMax Backplane Case 1 Total Length = 20.25”

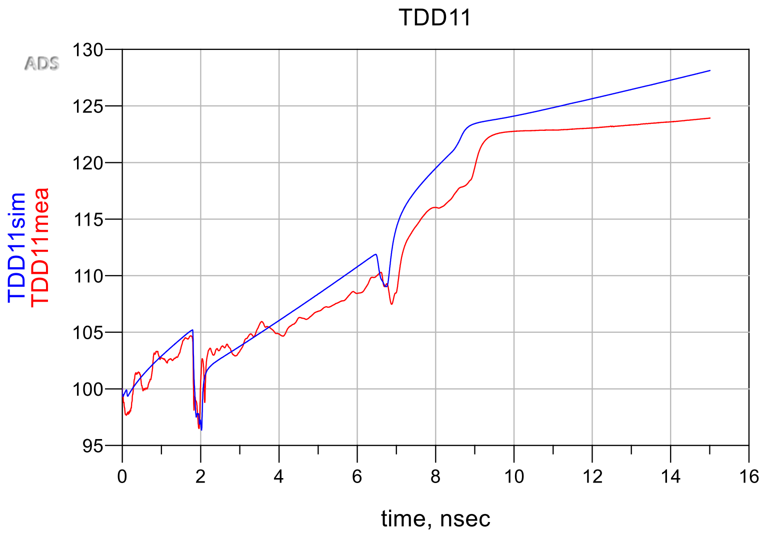


---- Measured
---- Simulated

Simulated with Keysight ADS [13]

ExaMax Backplane Case 2 Total Length = 26.80”

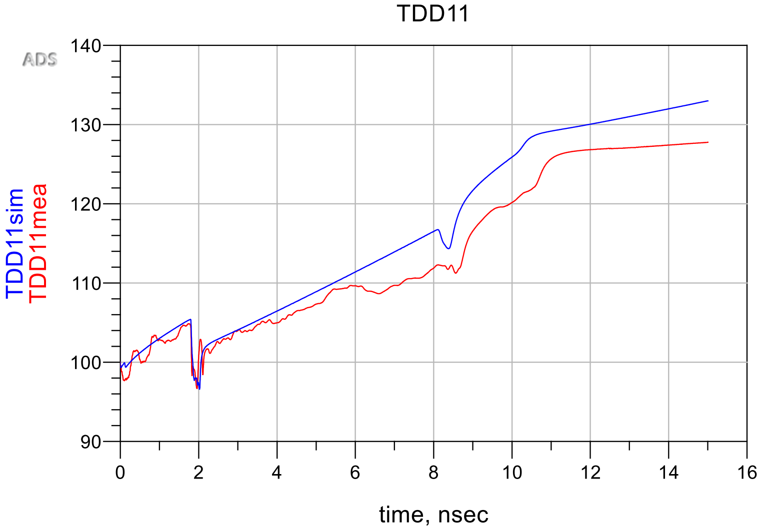

SDD21 Insertion Loss


TDD11

---- Measured
---- Simulated

Simulated with Keysight ADS [13]

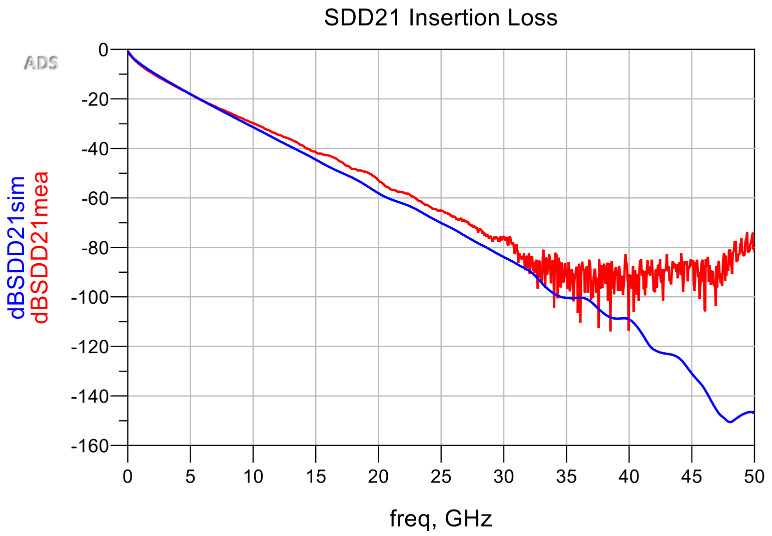
ExaMax Backplane Case 3 Total Length = 32.22”

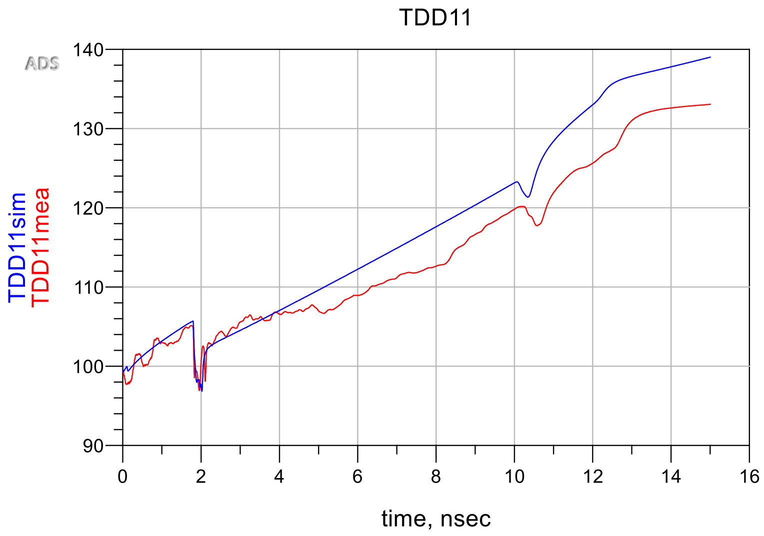


---- Measured
---- Simulated

Simulated with Keysight ADS [13]

ExaMax Backplane Case 4 Total Length = 38.70”

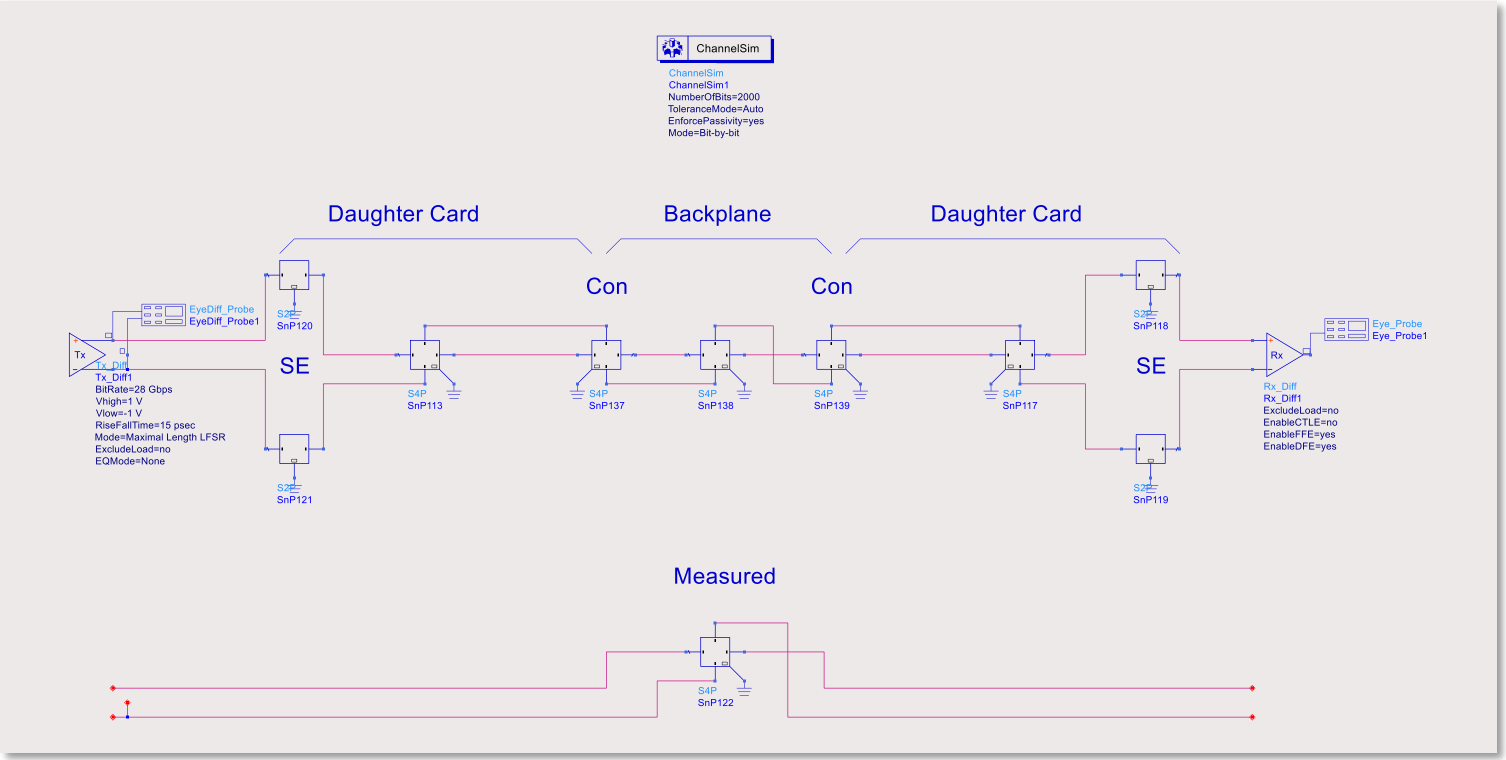




---- **Measured**
---- **Simulated**

Simulated with Keysight ADS [13]

Generic Channel Model



ChannelSim
ChannelSim1
NumberOfBits=2000
ToleranceMode=Auto
EnforcePassivity=yes
Mode=Bit-by-bit

Tx_Diff
Tx_Diff1
BitRate=28 Gbps
Vhigh=1 V
Vlow=-1 V
RiseFallTime=15 psec
Mode=Maximal Length LFSR
ExcludeLoad=no
EQMode=None

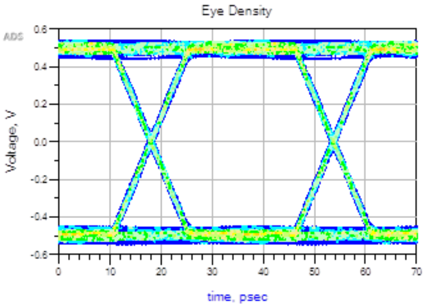
Rx_Diff
Rx_Diff1
ExcludeLoad=no
EnableCTLE=no
EnableFFE=yes
EnableDFE=yes

Modeled with Keysight ADS [13]

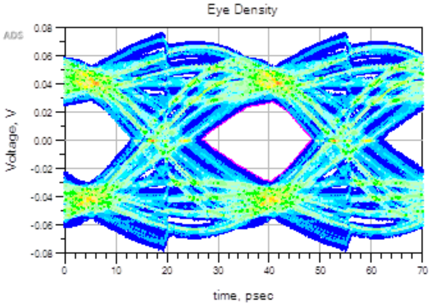
Channel Simulation 28 GB/s Case 1 Total Length = 20.25”

Simulated

Height @ BER
0.909V

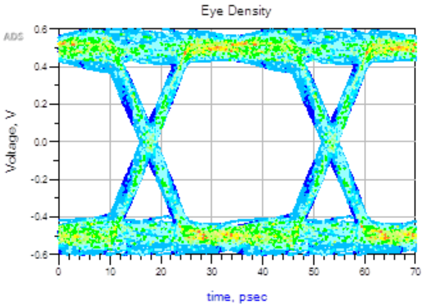


Height @ BER
57mV
Width @ BER
22.32 ps

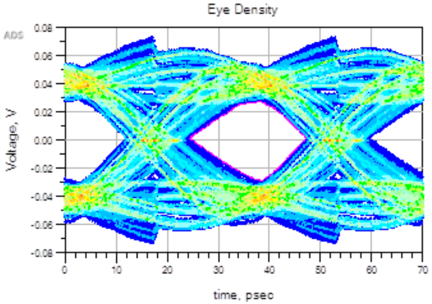


Measured

Height @ BER
0.871V



Height @ BER
57mV
Width @ BER
23.75 ps

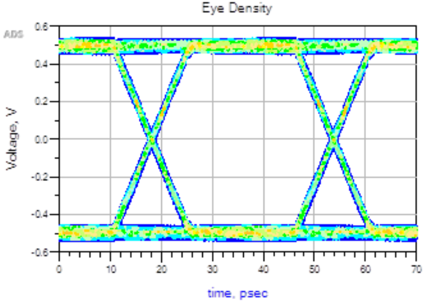


Simulated with Keysight ADS [13]

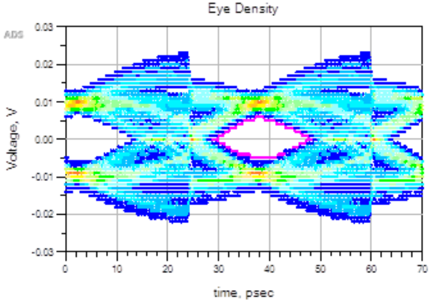
Channel Simulation 28 GB/s Case 4 Total Length = 38.7”

Simulated

Height @ BER
0.923V

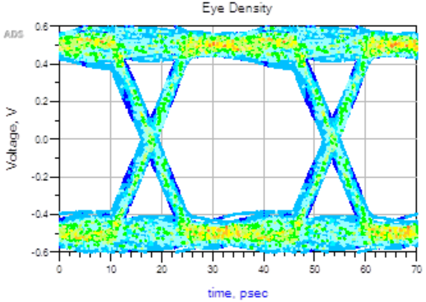


Height @ BER
11mV
Width @ BER
20.00 ps

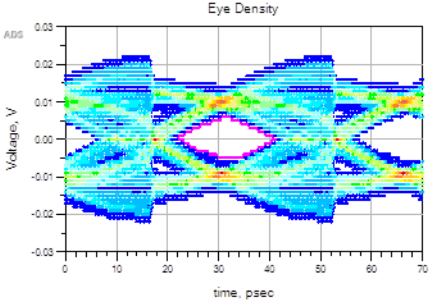


Measured

Height @ BER
0.874V



Height @ BER
11mV
Width @ BER
19.82ps



Simulated with Keysight ADS [13]

Summary

By using Cannonball-Huray model, with copper foil roughness and dielectric material properties obtained solely from manufacturers’ data sheets, a practical method of modeling high-speed differential channels is now achievable using commercial field-solving software employing Huray model.

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