DESIGNCON® 2019
WHERE THE CHIP MEETS THE BOARD

PCB Interconnect Modeling Demystified

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DESIGNCON® 2019
WHERE THE CHIP MEETS THE BOARD
JAN 29 - 31, 2019
UBM

PCB Interconnect Modeling Demystified

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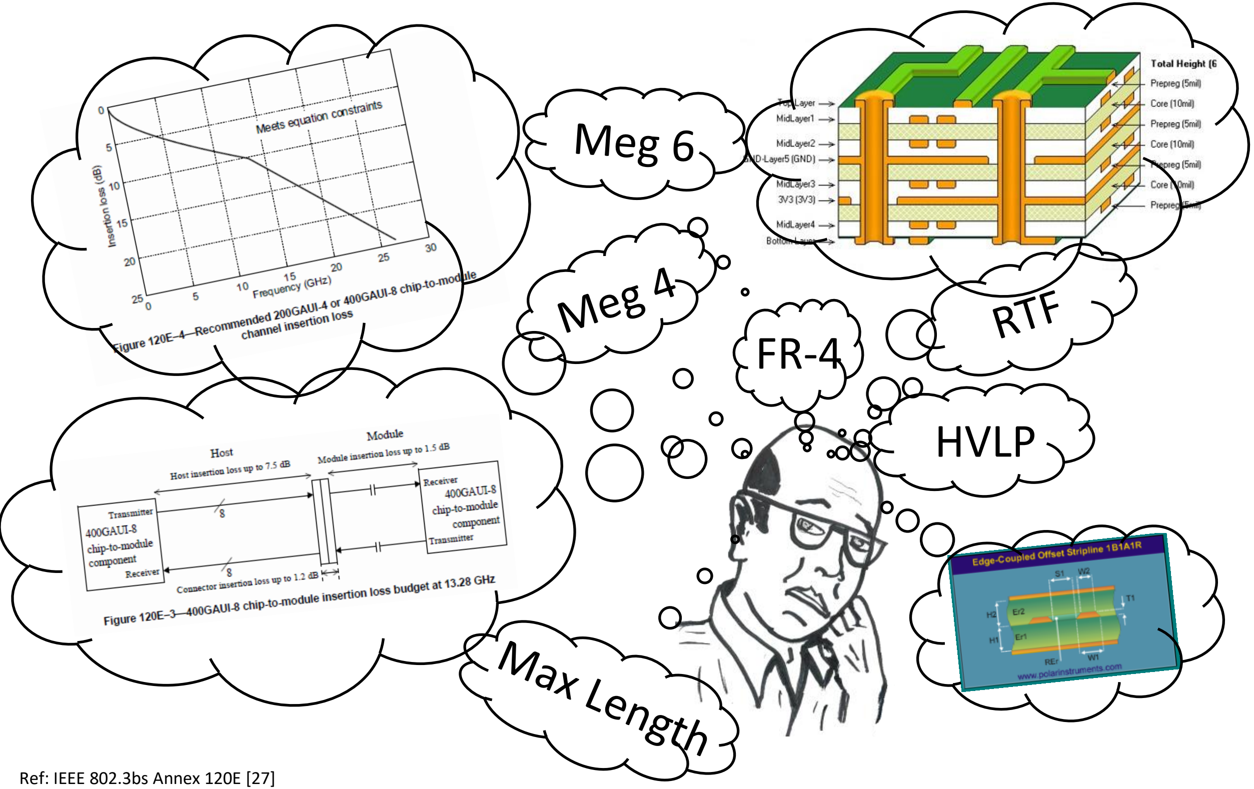
Lamsim Enterprises inc.
Innovative Signal Integrity & Backplane Solutions

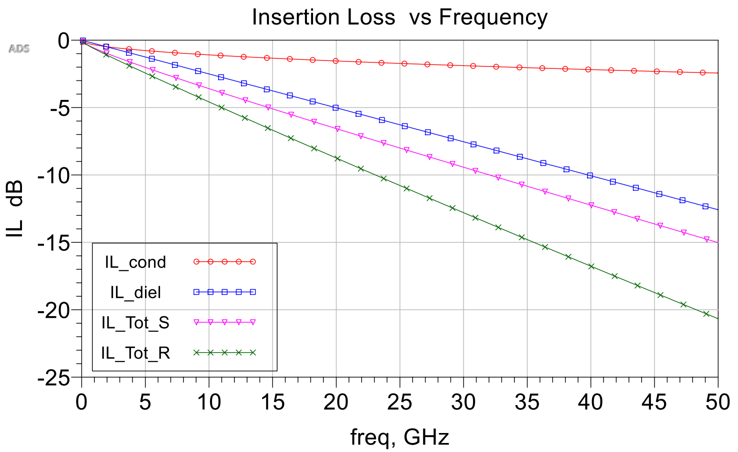
High-level Design Challenges



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

Ref: IEEE 802.3bs Annex 120E [27]

Transmission Line Modeling

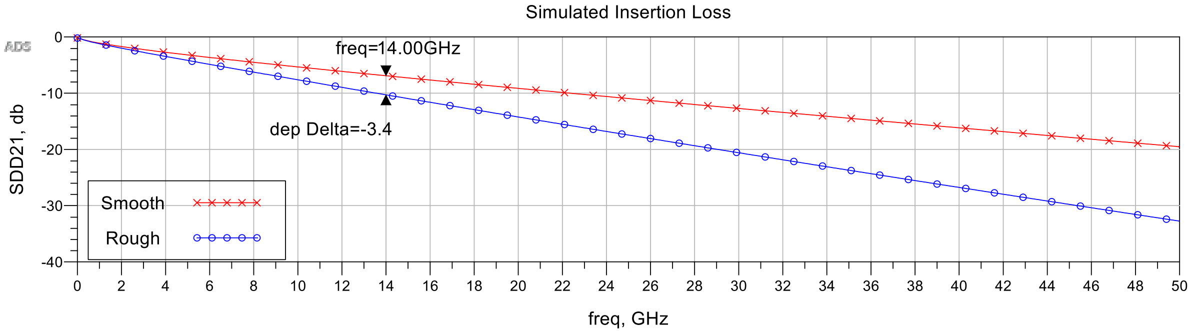


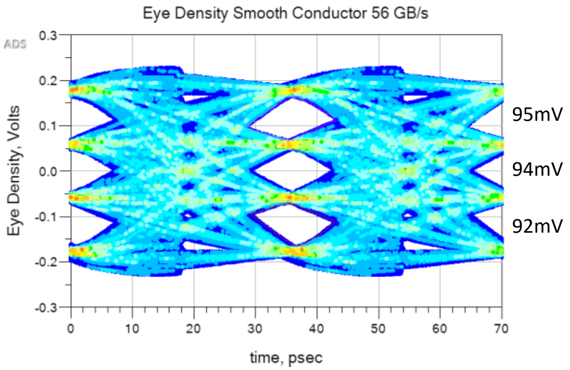
Important to model dielectric and conductor loss accurately

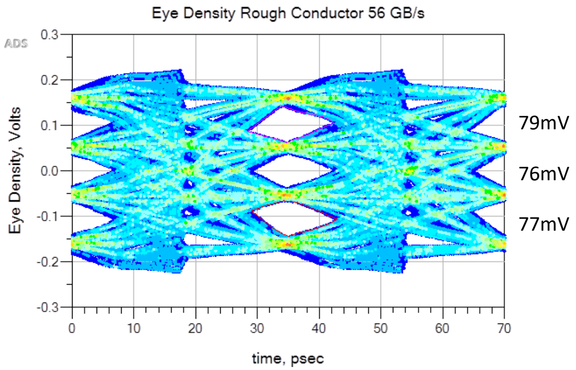
$$IL_{total}\left(f\right)=IL_{diel}\left(f\right)+K_{SR}(f)\times IL_{conductor}\left(f\right)$$

Simulated with Keysight ADS [6]

Failure To Model Roughness Can Be Problematic



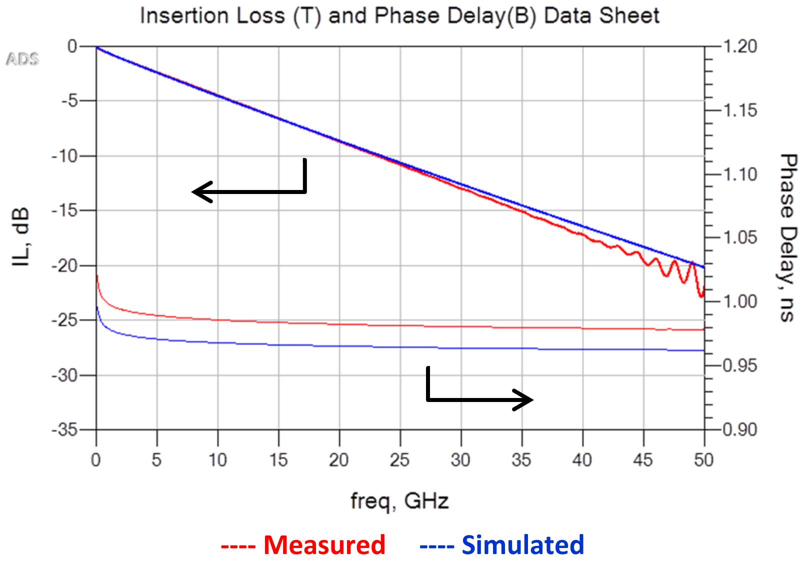




With just 3.4dB delta @14 GHz => 17% reduction averaged across all 3 eye heights with rough copper @56GB/s

Simulated with Keysight ADS [6]

Dielectric Properties

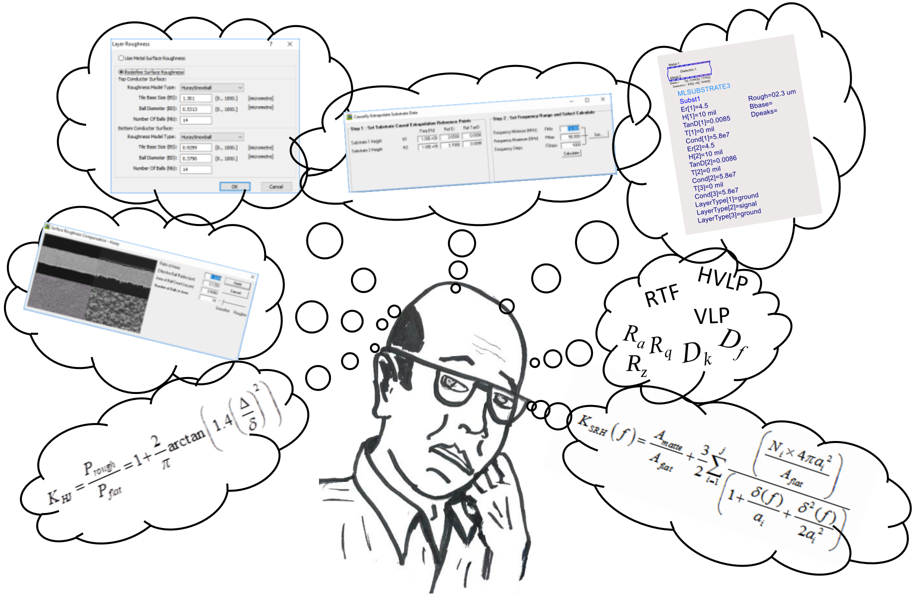


Failure to correct D_k from data sheet due to conductor roughness => inaccuracy in simulated IL & Phase Delay

Simulated with Keysight ADS [6]

EDA Tool Challenges

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



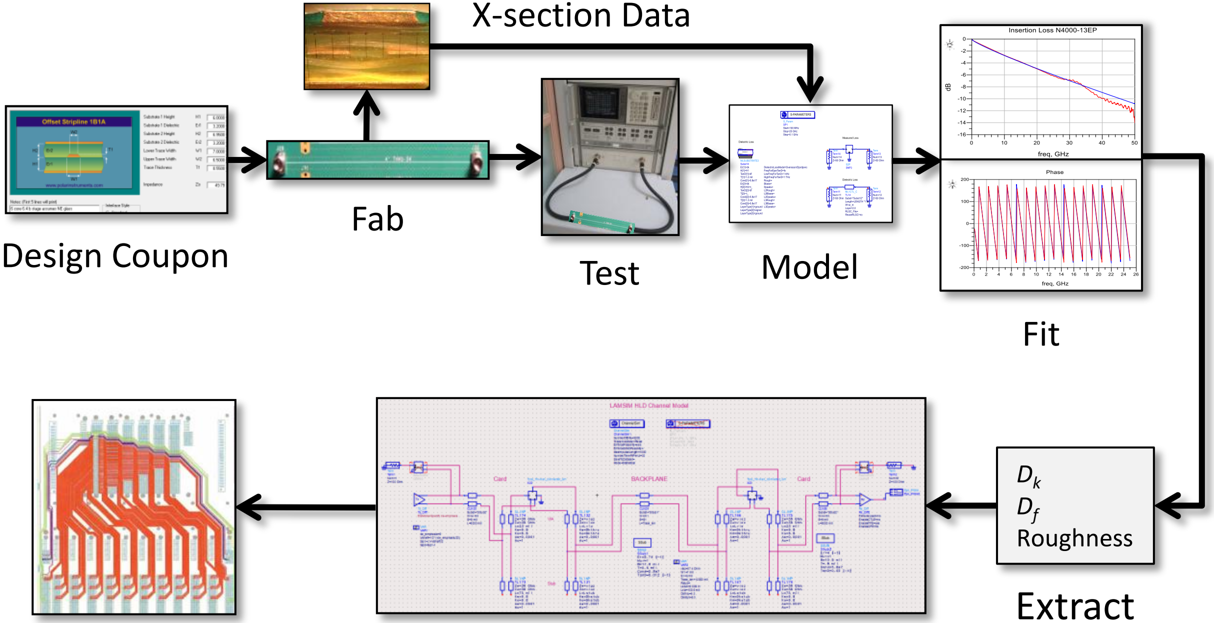
```
Metal-1
Dialectric-1
Metal-2
MLSUBSTRATE3
Subst1
Er[1]=4.5
H[1]=10 mil
TanD[1]=0.0085
T[1]=0 mil
Cond[1]=5.8e7
Er[2]=4.5
H[2]=10 mil
TanD[2]=0.0086
T[2]=0 mil
Cond[2]=5.8e7
T[3]=0 mil
Cond[3]=5.8e7
LayerType[1]=ground
LayerType[2]=signal
LayerType[3]=ground
Rough=02.3 um
Bbase=
Dpeaks=
```

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

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

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

Design Feedback Method



X-section Data

Design Coupon

Fab

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

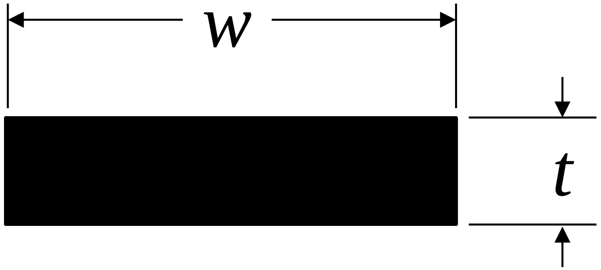
“Sometimes an OK answer NOW! is better than a good answer late….” **– Eric Bogatin**

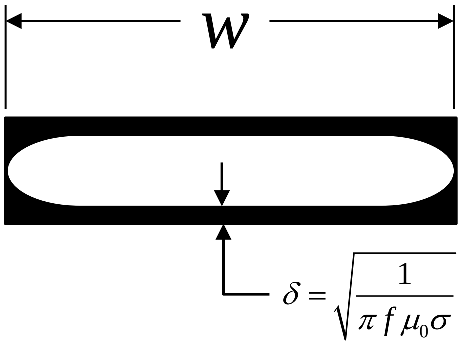
What You Will Learn

- ✓ How to apply my Cannonball stack model to determine roughness parameters for Huray model from data sheets
- ✓ How to determine D_{keff} due to roughness from data sheets
- ✓ How to apply these parameters in popular field solvers.
- ✓ Impact of causal metal model to simulated results
- ✓ Impact of Oxide/Oxide Alternative treatments on roughness, insertion loss and impedance
- ✓ How to pull it all together and compare simulated transmission line interconnect models with case studies

Overview

Current Distribution Through a Conductor





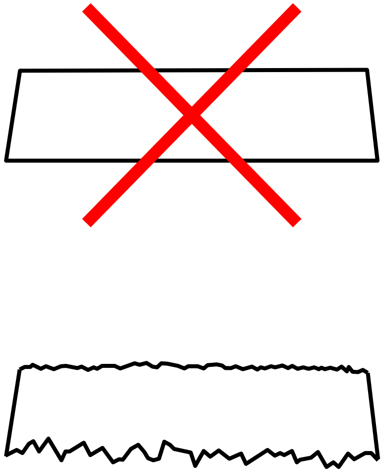
$$\delta = \sqrt{\frac{1}{\pi f \mu_0 \sigma}}$$

DC current is uniform through cross-sectional area of conductor

AC current above ~10MHz flows mainly along “skin” of the conductor

μ_0 = Permeability of free space in H/m σ = Conductivity in S/m.

Conductor Roughness

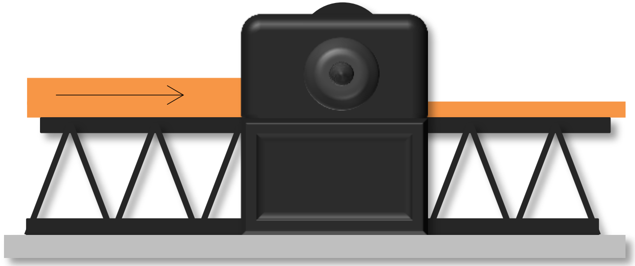


No such thing as a perfectly smooth PCB conductor surface

Roughness is always applied to promote adhesion to the dielectric material

Copper Foil Manufacturing Processes

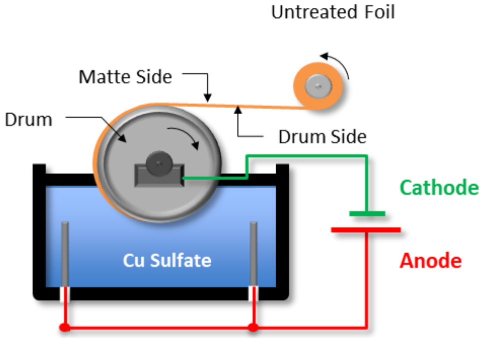
Rolled



- Smoother
- Higher Cost

VS

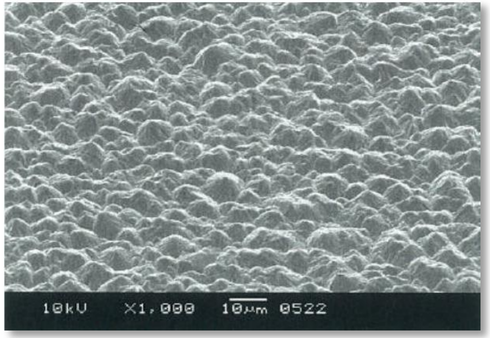
Electro-deposited (ED)



- Rougher
- Lower Cost

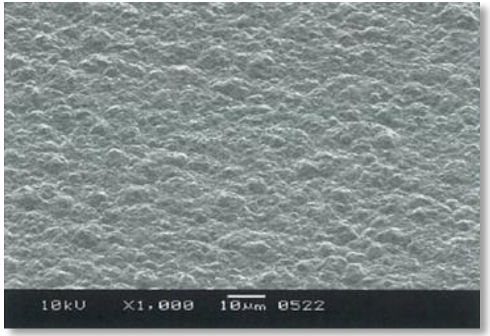
Common ED Roughness Profiles

Standard Profile



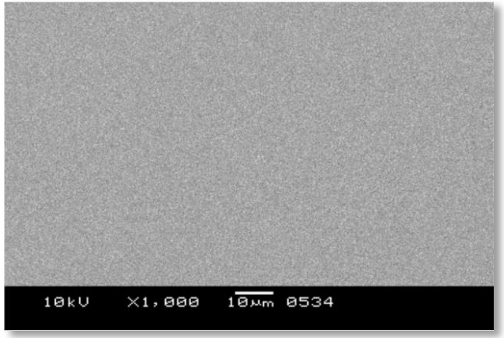
No min/max spec

IPC Very Low Profile(VLP)



$R_z < 5.2\ \mu$m max

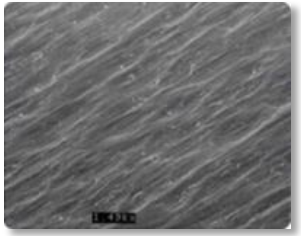
Ultra Low Profile (ULP)Class



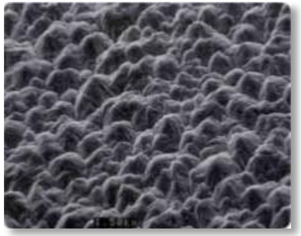
-*Other names: HVLP*, VSP
-No IPC spec
-Typically $R_z < 2\ \mu$m max

SEM Photos Reference [28]

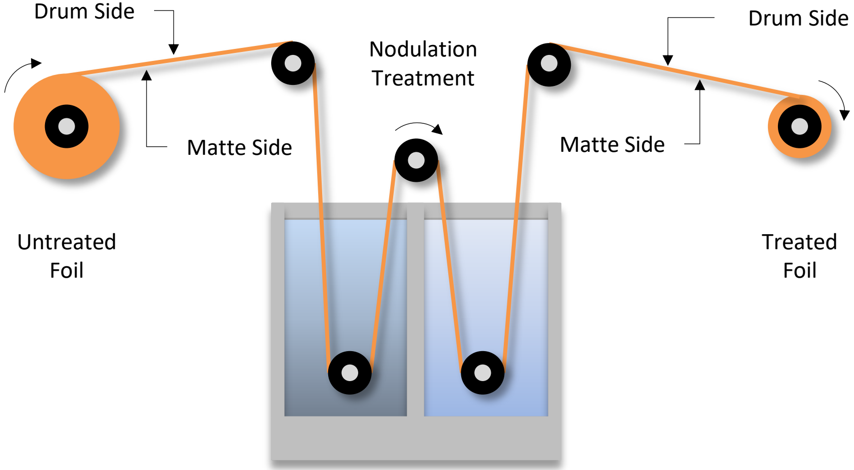
ED Copper Foil Nodulation Treatment



Drum Side Untreated



Matte Side Untreated



Drum Side

Matte Side

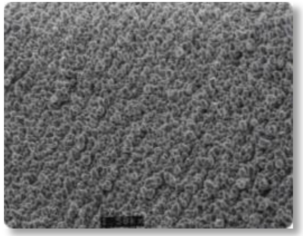
Untreated Foil

Nodulation Treatment

Drum Side

Matte Side

Treated Foil



Drum Side Treated

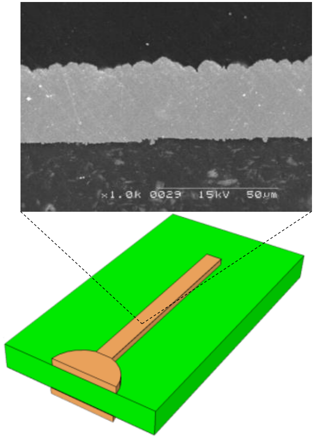
OR

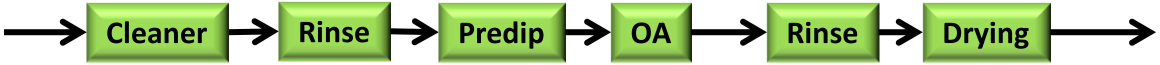
Matte Side Treated

SEM Photos Reference [20]

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

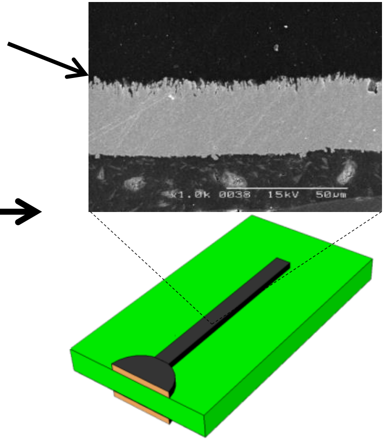
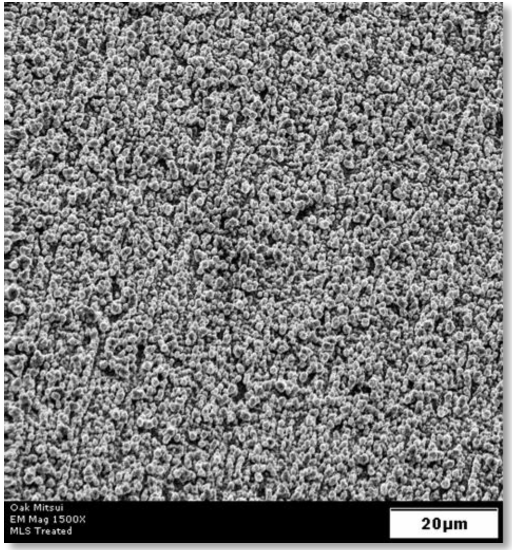


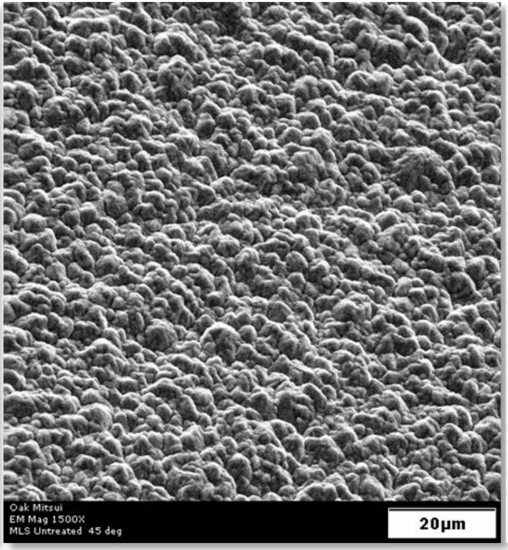
Photo Reference [29]

Reverse Treated Foil (RTF) After Oxide Alternative Treatment



Treated drum side

$R_z = 3.175\ \mu\mathrm{m}$



Untreated matte side

$R_z = 5.715\ \mu\mathrm{m}$

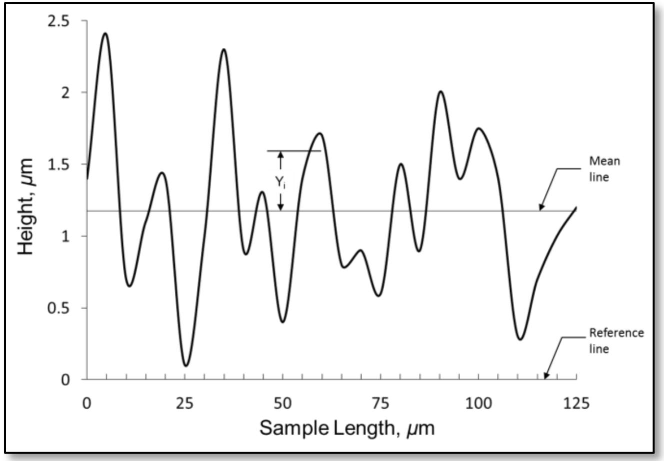
Matte side after OA treatment

$R_z = 4.443\ \mu\mathrm{m}$

Photos courtesy of Oak-mitsui [9]

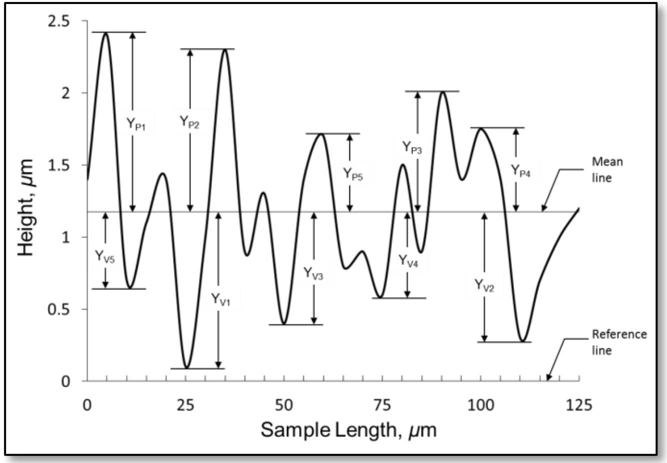
Roughness Parameters

RMS (R_q) / Average (R_a)



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

10-point Mean (R_z)



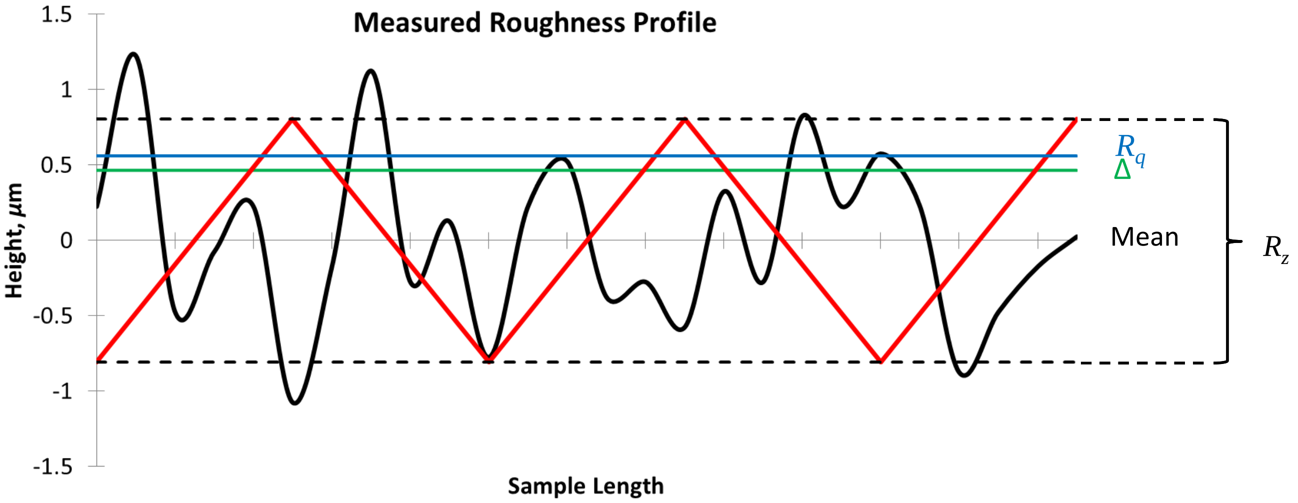
$$R_z = \frac{1}{5}\sum_{i=1}^{5}\left|Y_{Pi}\right| + \frac{1}{5}\sum_{i=1}^{5}\left|Y_{Vi}\right|$$

Modeling Conductor Roughness

“All models are wrong but some are useful…”

- George E. P. Box

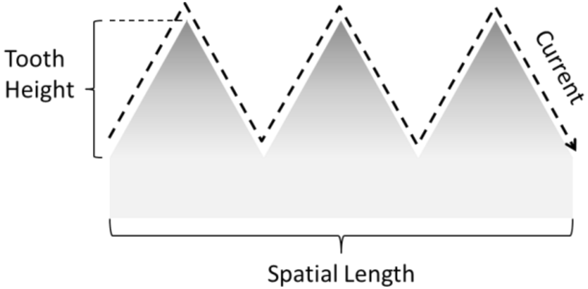
Triangular Roughness Model



If RMS height of triangular profile = Δ, then: $\Delta = \frac{R_z}{2\sqrt{3}}$

Likewise if $\Delta \approx R_q$, then: $R_z \approx R_q\left(2\sqrt{3}\right)$

Hamerstad & Jensen Model



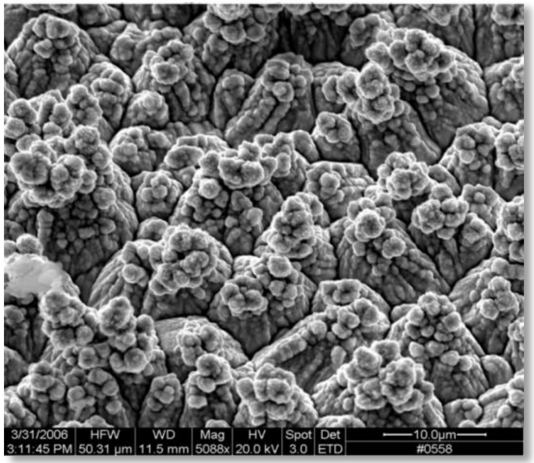
$$K_{HJ}=\frac{P_{rough}}{P_{flat}}=1+\frac{2}{\pi}\arctan\left(1.4\left(\frac{\Delta}{\delta}\right)^2\right)$$

$\Delta =$ RMS tooth height in meters

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

Simulated with Keysight ADS [6]

Huray “*snowball*” Model

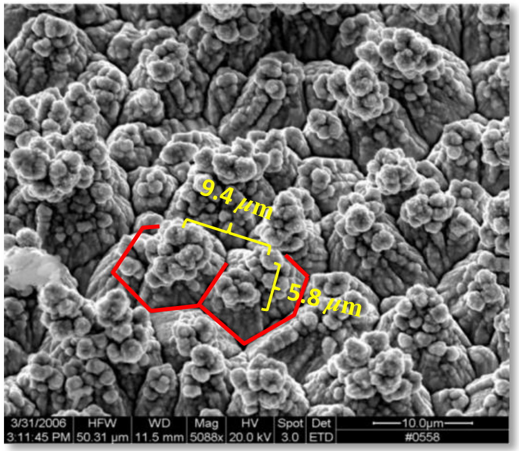


SEM Photo Reference [15]

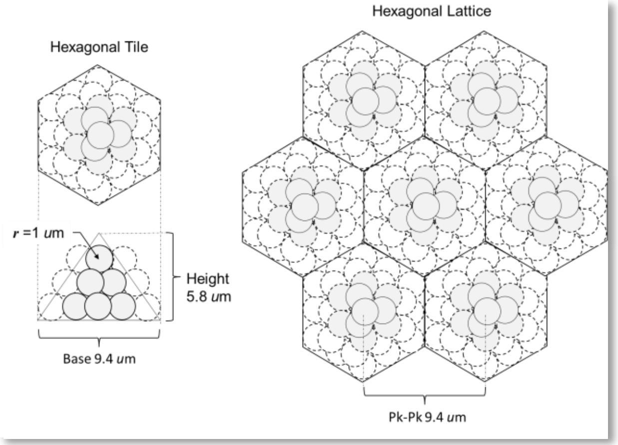
Based on non-uniform distribution of spheres resembling “snowballs” applied to a matte base

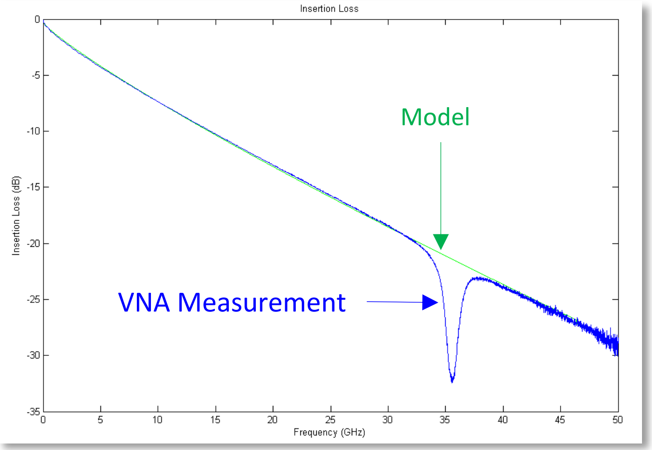
$$K_{SRH}\left(f\right)=\frac{P_{rough}}{P_{flat}}\approx\frac{A_{matte}}{A_{flat}}+\frac{3}{2}\sum_{i=1}^{j}\left(\frac{N_i\times 4\pi a_i^{\,2}}{A_{flat}}\right)\left(1+\frac{\delta(f)}{a_i}+\frac{\delta^2(f)}{2a_i^{\,2}}\right)^{-1}$$

Huray Model Prior Art



SEM Photo Reference [15]





Plot Reference [15]

Assumes stacked "snowballs" arranged in hexagonal lattice

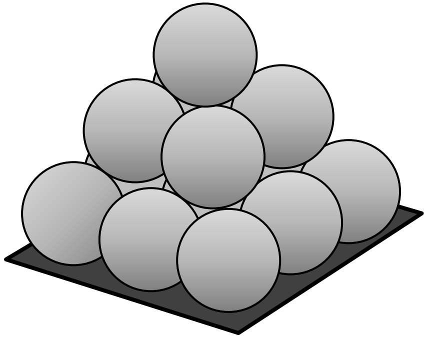
11 spheres min; 38 spheres max of radius 1μm to fit within hex tile area and height of 5.8μm

Fit equation parameters to measured data

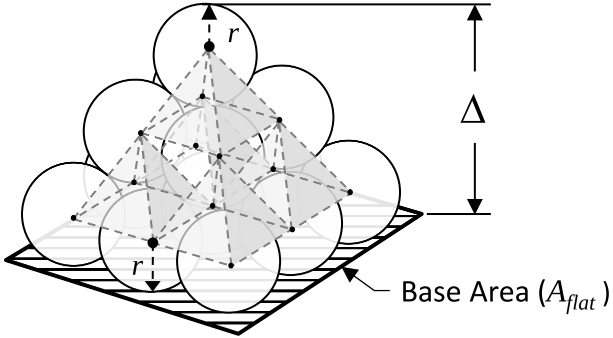
Cannonball-Huray Model

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

$$K_{CH}(f)\approx 1+\frac{3}{2}\frac{\left(\dfrac{14\times 4\pi r^2}{36r^2}\right)}{\left(1+\dfrac{\delta(f)}{r}+\dfrac{\delta^2(f)}{2r^2}\right)} \Rightarrow \boxed{K_{CH}(f)\approx 1+\left[\frac{2.33\pi}{\left(1+\dfrac{\delta(f)}{r}+\dfrac{\delta^2(f)}{2r^2}\right)}\right]}$$



N_i=14 Spheres



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

Applying Cannonball-Huray Model For Popular EDA Tools

Tool	Parameters
• Polar Si9000e [5]; Mentor Hyperlynx [19] include the Cannonball-Huray model as an option	R_Z
• Ansys [25]; Cadence [26] tools require surface ratio (sr) and nodule radius (r) as input parameters	$sr = \left(\frac{14\times 4\pi r^2}{A_{flat}}\right) = \left(\frac{14\times 4\pi r^2}{36r^2}\right) = 1.56\pi \approx 4.9$ $r \approx 0.06R_Z$
• Simbeor [22] requires roughness factor ($RF1$) and sphere radius ($SR1$)	$RF1 = 1 + \frac{3}{2}\left(\frac{N4\pi r^2}{A_{flat}}\right) = 1 + \frac{3}{2}\left(\frac{14\cdot 4\pi (r_{avg})^2}{36(r_{avg})^2}\right) \approx 8.33$ $SR1 = r \approx 0.06R_Z$

Modeling D_{keff} Due to Surface Roughness

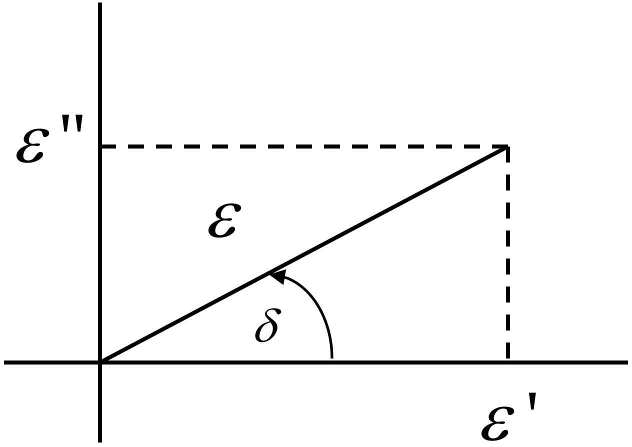
Dielectric Material Terms

Complex dielectric constant ε defined as:

$$\varepsilon = \varepsilon^{'} - j\varepsilon^{''} \qquad \tan(\delta) = \frac{\varepsilon^{''}}{\varepsilon'}$$

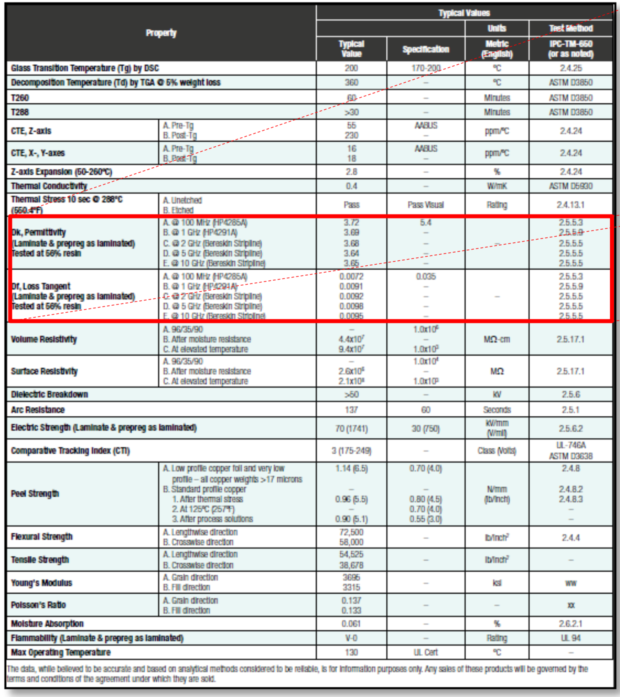
If real part ε' = D_k and tan(δ) = D_f then:

$$D_f = \frac{\varepsilon^{''}}{D_k}$$



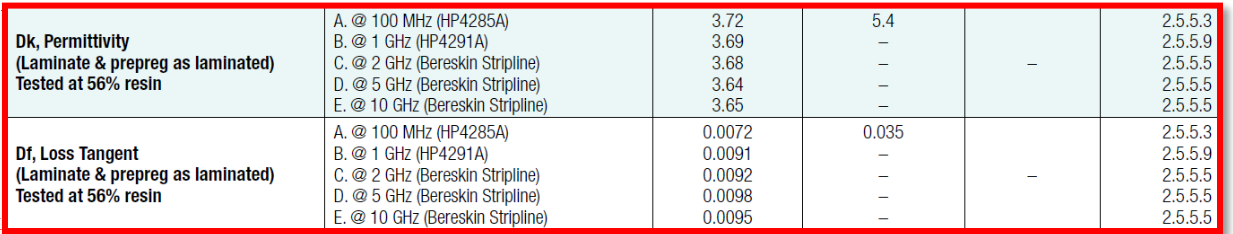
$\delta =$ loss angle

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.

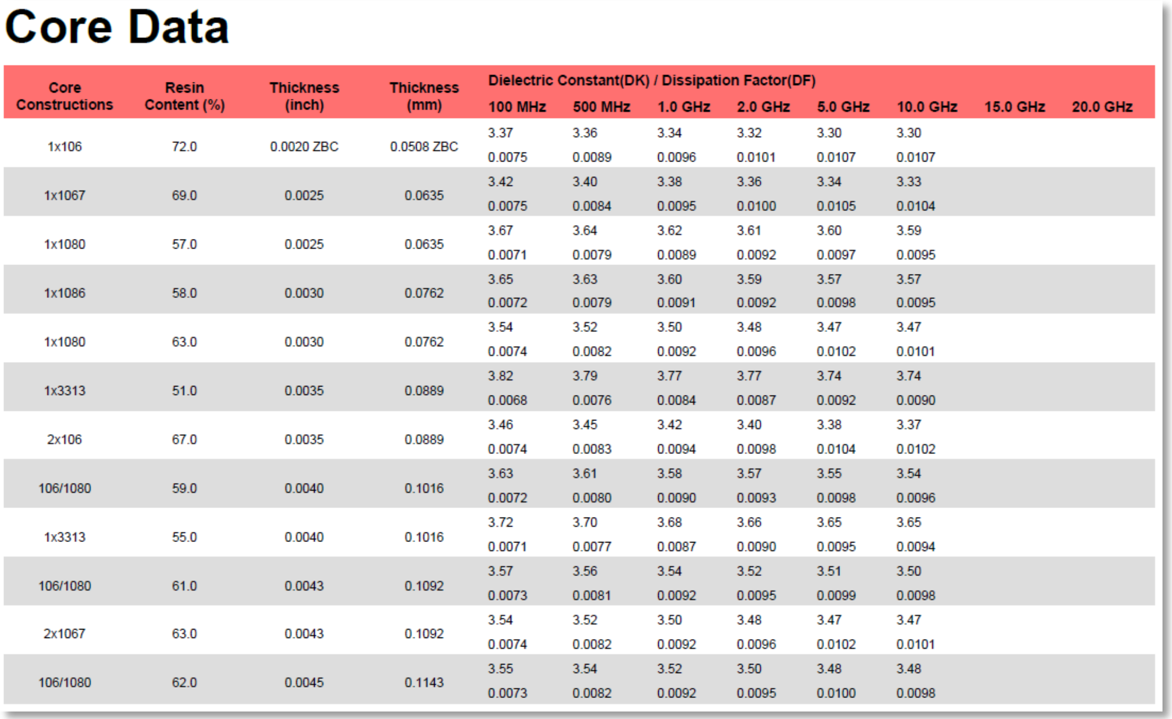


Dk, Permittivity (Laminate & prepreg as laminated) Tested at 56% resin	A. @ 100 MHz (HP4285A) B. @ 1 GHz (HP4291A) C. @ 2 GHz (Bereskin Stripline) D. @ 5 GHz (Bereskin Stripline) E. @ 10 GHz (Bereskin Stripline)	3.72 3.69 3.68 3.64 3.65	5.4 – – – –	–	2.5.5.3 2.5.5.9 2.5.5.5 2.5.5.5 2.5.5.5
Df, Loss Tangent (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 D_k/D_f numbers from marketing data sheets for stackup and channel modeling will give inaccurate results

Reference: Isola [10]

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		

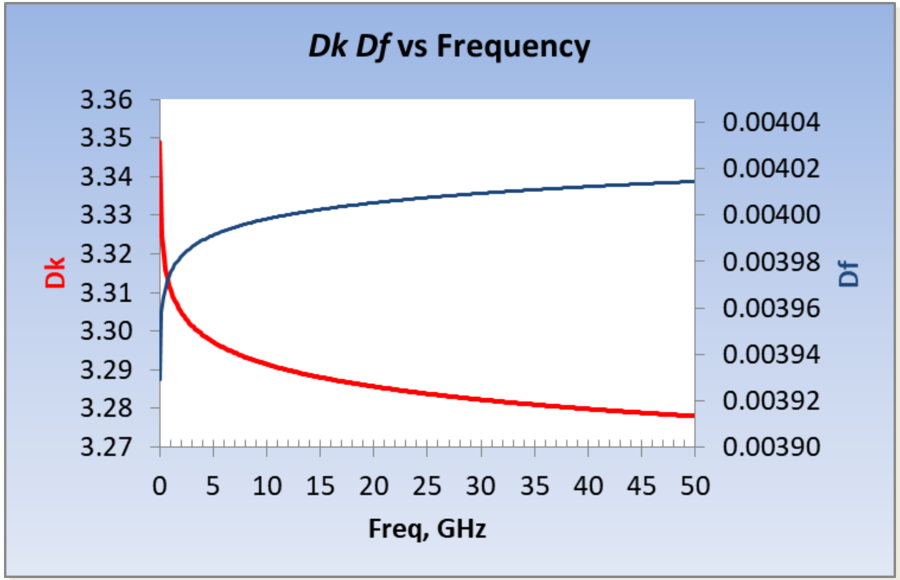
Provides:

- ✓ Actual core/prepreg thicknesses
- ✓ Resin content
- ✓ $D_k(f)$ / $D_f(f)$ for different glass styles

Reference: Isola [10]

Causal Dielectric Model

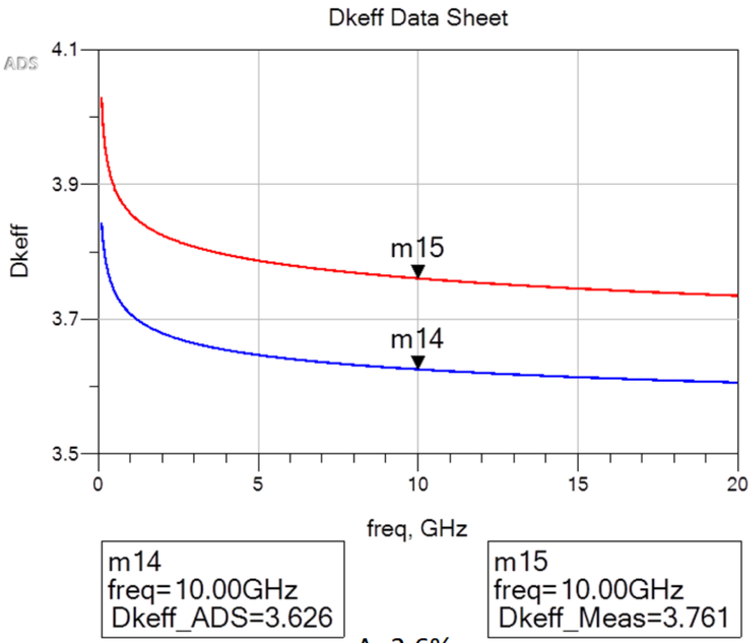
Because Complex Dk has real and imaginary components => Causal Dielectric model



Most EDA tools include wideband Debye model

- Input $D_k(f)\,/D_f(f)$ at a single frequency near Nyquist of baud rate

Dielectric Modeling Issue



m14
freq=10.00GHz
Dkeff_ADS=3.626

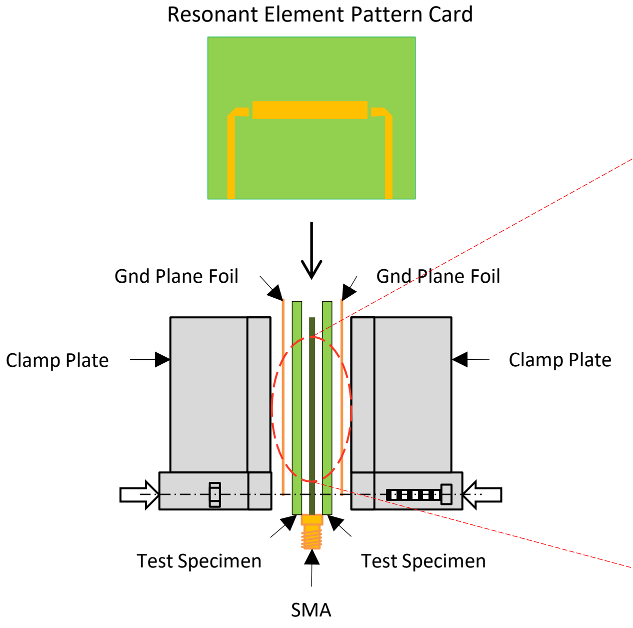
m15
freq=10.00GHz
Dkeff_Meas=3.761

Δ -3.6%

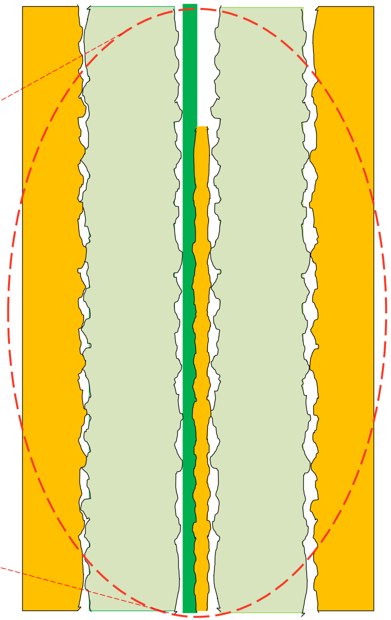
When Data Sheet D_k is not the same as Effective D_k

Simulated with Keysight ADS [6]

IPC-TM-650 Clamped Stripline Resonator Test Method



Side View (Unclamped) N.T.S.



Side View (Clamped) N.T.S.

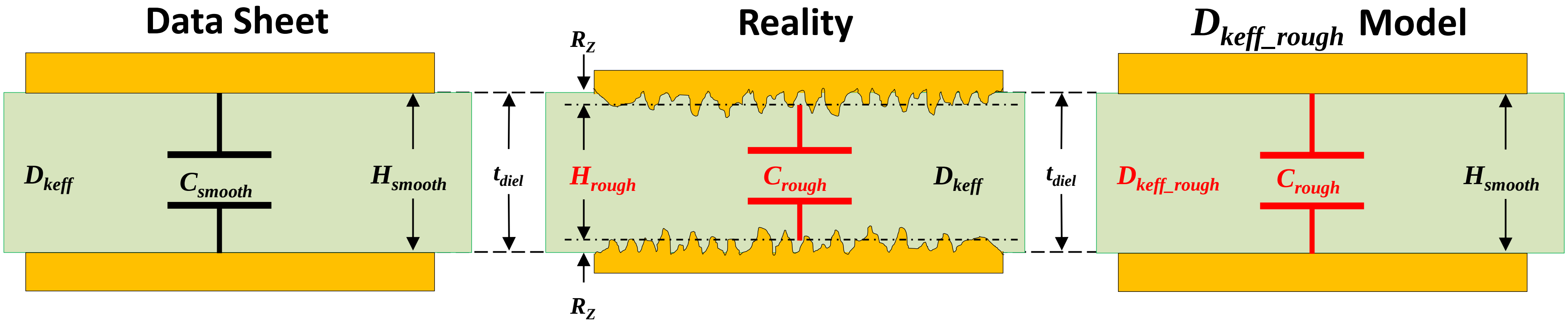
Issue:

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



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

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

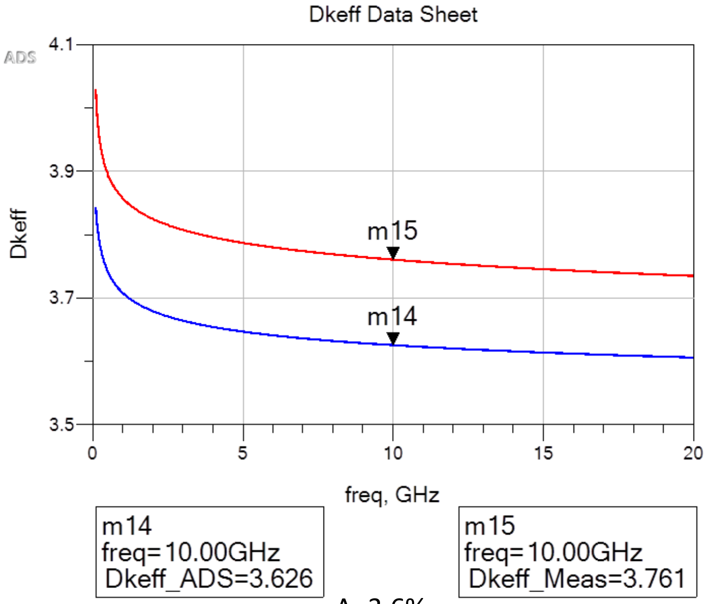
$$\boxed{C_{rough} = D_{keff\_rough}\left(\frac{\varepsilon_0 A}{H_{smooth}}\right)}$$

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

⇨

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

FR408HR/RTF Simulation Results for D_{keff}

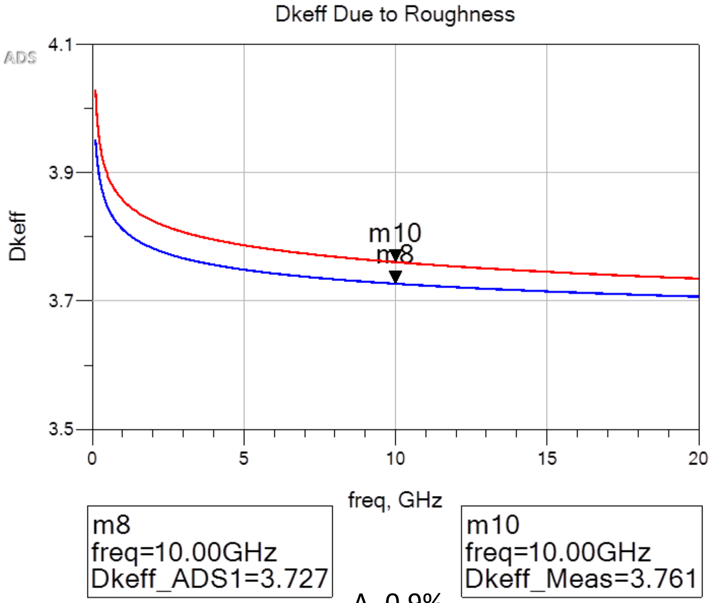


m14
freq=10.00GHz
Dkeff_ADS=3.626

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

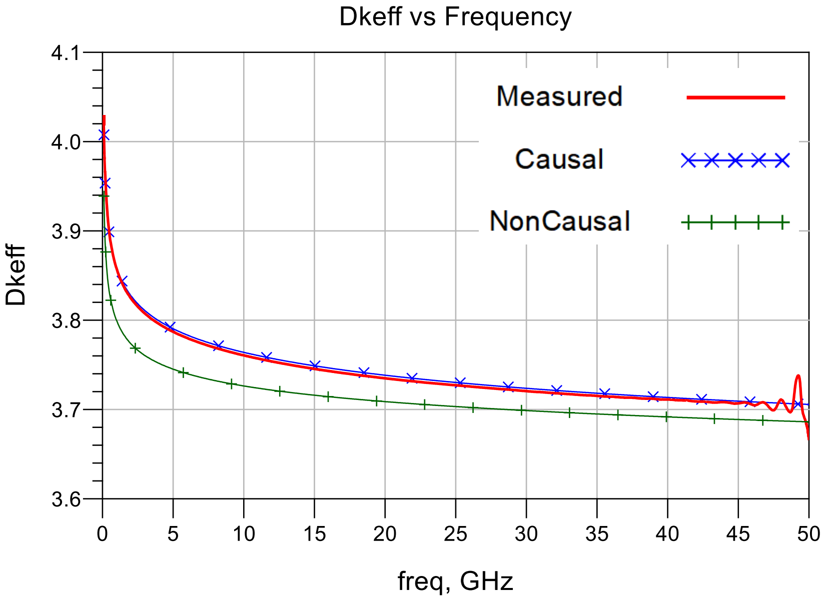
Simulated with Keysight ADS [6]

Causal Roughness Correction Factors

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

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

FR408HR/RTF Simulation Results for D_{keff}



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

✓Excellent Results!

Modeled with Hyperlynx [19] and Simulated with Keysight ADS [6]

HDPUG Oxide Alternative Study Results

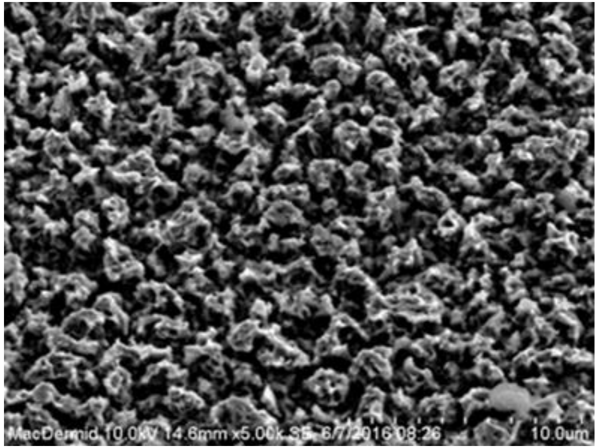
	Sample	R_q μm*
	Base CU	0.305
Etch	A	0.547
	B	0.548
	C	0.440
Non-Etch	D	0.286
	E	0.317
	F	0.313

R_q data reference [17]

In 2016 the High-density Packaging User Group (HDPUG) [16] undertook a project to evaluate the high frequency loss impacts of a variety of OA treatments on a Megtron-6 (Meg-6) test platform using HVLP base foil on core laminates prior to lamination.

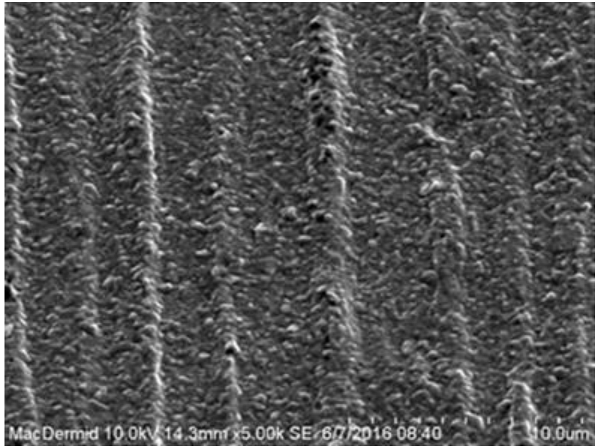
Typical Etch vs Non-Etch OA Treatments

Drum Side



Etch Samples A, B, C

Drum Side

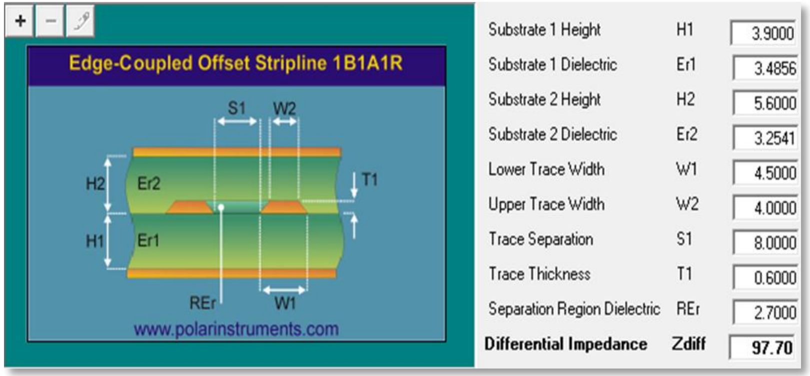


Non-etch Samples D, E, F

Photo Credit [16]

Impact of Oxide Alternative Case Study

Megtron-6 / HVLP Foil 4.5-8-4.5 Geometry



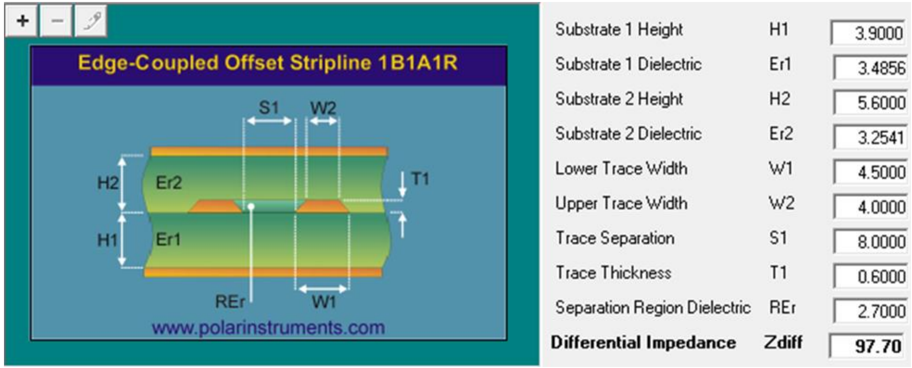
Substrate 1 Height H1 3.9000
Substrate 1 Dielectric Er1 3.4856
Substrate 2 Height H2 5.6000
Substrate 2 Dielectric Er2 3.2541
Lower Trace Width W1 4.5000
Upper Trace Width W2 4.0000
Trace Separation S1 8.0000
Trace Thickness T1 0.6000
Separation Region Dielectric REr 2.7000
Differential Impedance Zdiff 97.70

Sample	OA R_q* (μm)	OA R_z** (μm)	Matte R_z (μm)	D_{keff} Core @12GHz	D_{keff} Prepreg @12GHz	D_f @12GHz
Base CU	**0.3050**	1.0566	1.5000	3.4856	3.2541	0.004
A	**0.5470**	1.8949	1.5000	3.4856	3.2984	0.004
B	**0.5480**	1.8983	1.5000	3.4856	3.2986	0.004
C	**0.4400**	1.5242	1.5000	3.4856	3.2787	0.004
D	**0.2860**	0.9907	1.5000	3.4856	3.2507	0.004
E	**0.3170**	1.0981	1.5000	3.4856	3.2563	0.004
F	**0.3130**	1.0843	1.5000	3.4856	3.2556	0.004

* Rq data reference [17]; ** $R_z \approx R_q(2\sqrt{3})$

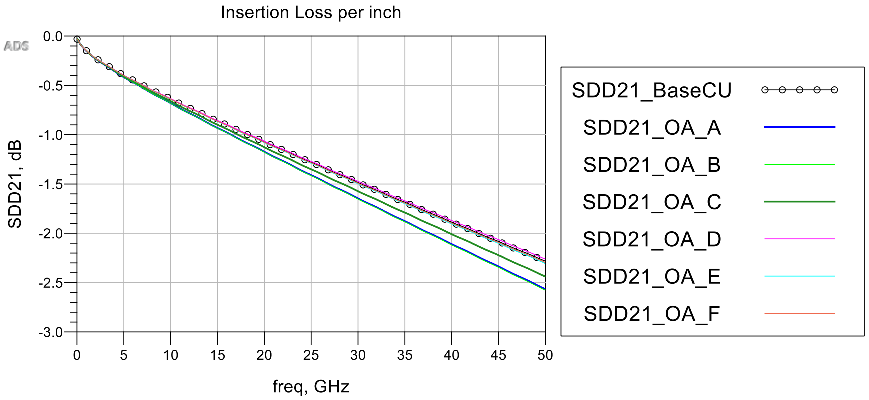
Impact of Oxide Alternative on IL & Impedance

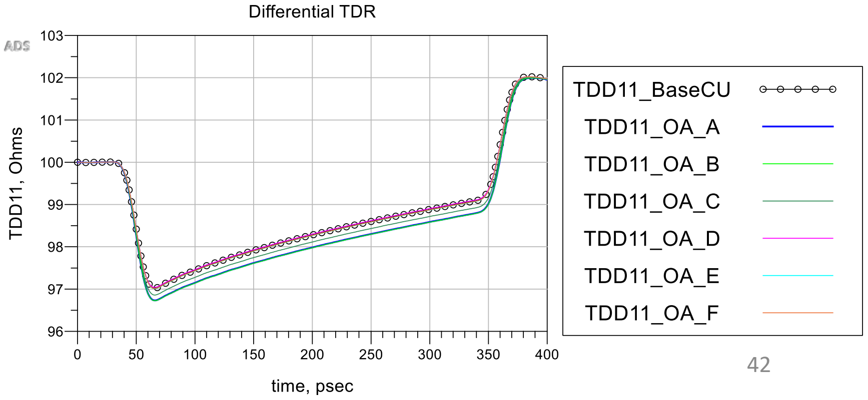
Megtron-6 / HVLP Foil 4.5-8-4.5 Geometry



Substrate 1 Height	H1	3.9000
Substrate 1 Dielectric	Er1	3.4856
Substrate 2 Height	H2	5.6000
Substrate 2 Dielectric	Er2	3.2541
Lower Trace Width	W1	4.5000
Upper Trace Width	W2	4.0000
Trace Separation	S1	8.0000
Trace Thickness	T1	0.6000
Separation Region Dielectric	REr	2.7000
Differential Impedance	**Zdiff**	**97.70**

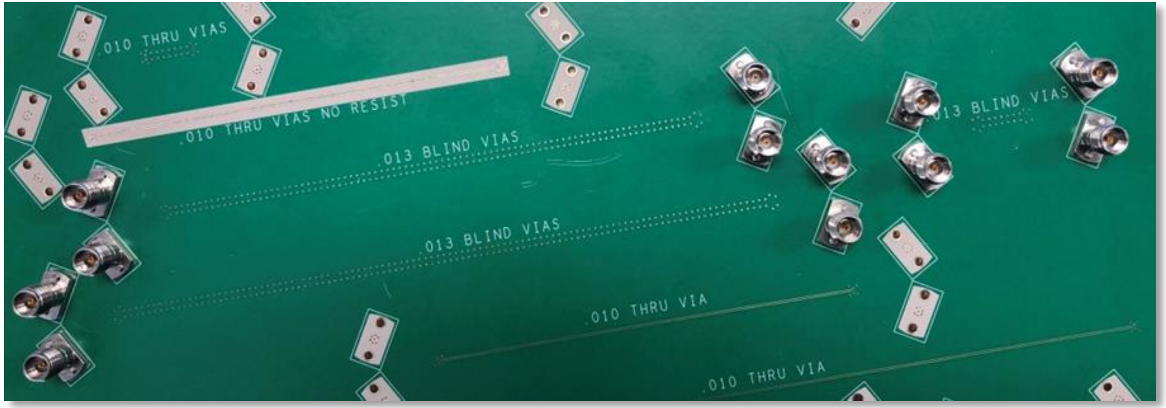
- 0.07 dB/inch delta between OA sample B and sample D @14GHz 0.16dB/inch delta @ 28GHz
- May not be an issue for 56GB but may be for future 112G depending on interface





Model Validation Case Studies

Megtron-4 RTF Case Study

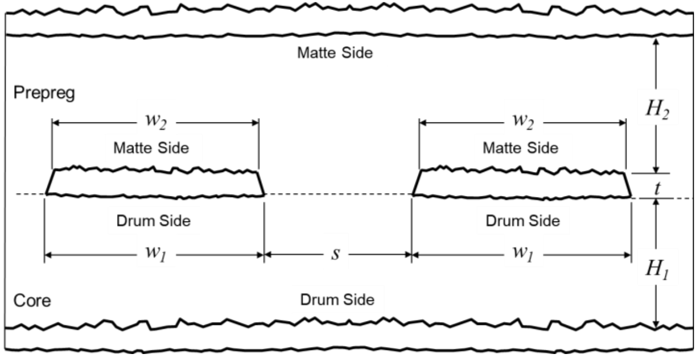


Features:

- Megtron-4
- 1067 Core/prepreg
- ½ oz RTF
- 1”; 6”; 5”; Diff pairs

Test board and data courtesy of Ciena Corporation [18]

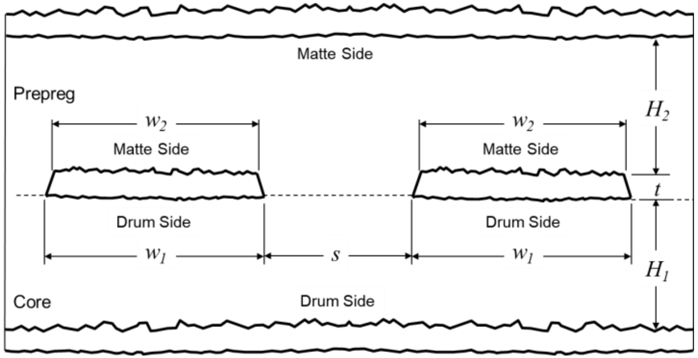
Meg-4/RTF Data Sheet & Test Board Design Parameters



Parameter	Value
D_k Core/Prepreg @ 10GHz	3.55/3.41
D_f Core/Prepreg @ 10GHz	0.008/0.008
R_z Drum side	2.5 μm
R_z Before Micro-etch-Matte side	3.4μm
R_z After 50 μin (1.27 μm) Micro-etch treatment -Matte side	2.13 μm
Trace Thickness, t	0.63 mils (31.73 μm)
Trace Width Base (W_1)	3.5 mils (88.9 μm)
Trace Width Top (W_2)	3 mils (76.2 μm)
Space (s)	4.5 mils (114.3 μm)
Core thickness, H_1	3.9 mils (99.06 μm)
Prepreg thickness, H_2	3.95 mils (100.33 μm)
De-embedded trace length	5.00 in (15.24 cm)

Test board and data courtesy of Ciena Corporation [18]

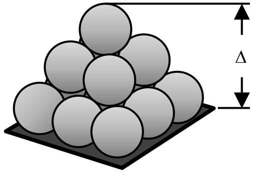
Determine D_{keff} Due to Roughness Core/Prepreg



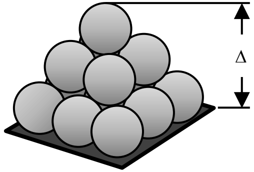
$$D_{keff\_prepreg} = \frac{H_2}{(H_2 - 2R_z)} D_{k2} = \frac{100.33\mu m}{(100.33\mu m - 2(2.13\mu m))} \times 3.41 = 3.56$$

$$D_{keff\_Core} = \frac{H_1}{(H_1 - 2R_z)} D_{k1} = \frac{99.06\mu m}{(99.06\mu m - 2(2.5\mu m))} \times 3.55 = 3.74$$

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



Matte-side



Drum-side

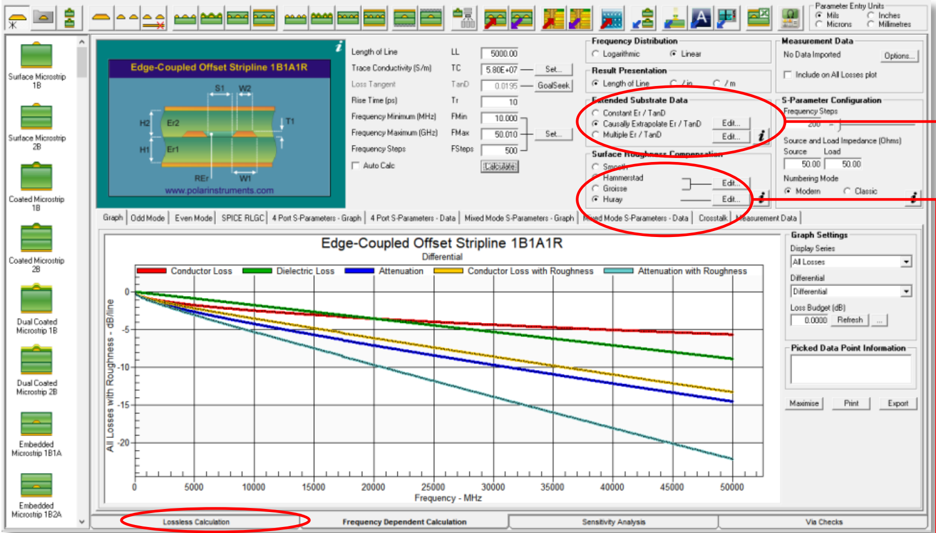
$$\begin{aligned} r_{\_matte} &\approx 0.06 R_{z\_matte} \\ &\approx 0.06 \times 2.13 \\ &\approx 0.128\mu m \end{aligned}$$

$$\begin{aligned} r_{\_drum} &\approx 0.06 R_{z\_drum} \\ &\approx 0.06 \times 2.50 \\ &\approx 0.150\mu m \end{aligned}$$

$$\begin{aligned} r_{avg} &= \frac{r_{\_matte} + r_{\_drum}}{2} \\ &\approx \frac{0.150 + 0.128}{2} \\ &\approx 0.139\mu m \end{aligned}$$

$$\begin{aligned} A_{flat} &= 36\left(r_{avg}\right)^2 \\ &= 36(0.139\mu m)^2 \\ &= 0.696\mu m^2 \end{aligned}$$

Input Design Parameters Polar Si9000e



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

Length of Line	LL	5000.00
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	50.010
Frequency Steps	FSteps	500

☐ Auto Calc

Frequency Distribution: ○ Logarithmic ● Linear

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

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

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

Measurement Data: No Data Imported

☐ Include on All Losses plot

S-Parameter Configuration: Frequency Steps 200

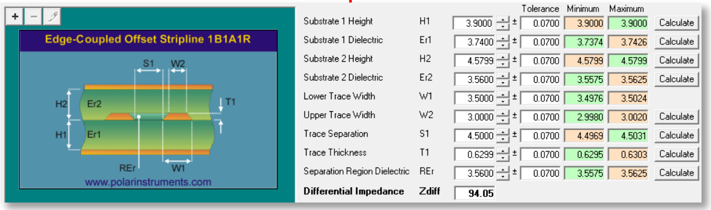
Source and Load Impedance (Ohms): Source 50.00 Load 50.00

Numbering Mode: ● Modern ○ Classic

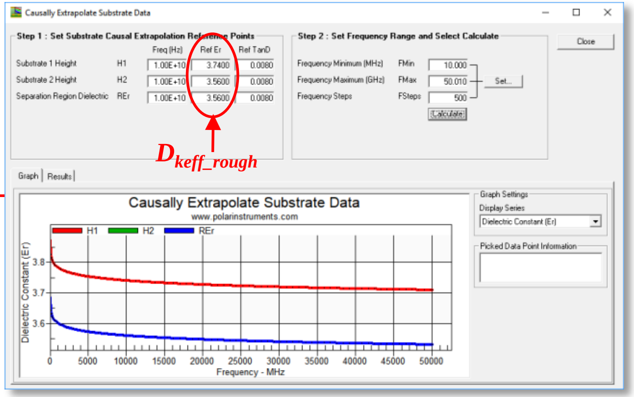
Display Series: All Losses

Differential: Differential

Loss Budget (dB): 0.0000 Refresh



				Tolerance	Minimum	Maximum	
Substrate 1 Height	H1	3.9000	±	0.0700	3.9000	3.9000	Calculate
Substrate 1 Dielectric	Er1	3.7400	±	0.0700	3.7374	3.7426	Calculate
Substrate 2 Height	H2	4.5799	±	0.0700	4.5799	4.5799	Calculate
Substrate 2 Dielectric	Er2	3.5600	±	0.0700	3.5575	3.5625	Calculate
Lower Trace Width	W1	3.5000	±	0.0700	3.4976	3.5024	
Upper Trace Width	W2	3.0000	±	0.0700	2.9980	3.0020	Calculate
Trace Separation	S1	4.5000	±	0.0700	4.4969	4.5031	Calculate
Trace Thickness	T1	0.6299	±	0.0700	0.6295	0.6303	Calculate
Separation Region Dielectric	REr	3.5600	±	0.0700	3.5575	3.5625	Calculate
Differential Impedance	**Zdiff**	**94.05**					



Step 1 : Set Substrate Causal Extrapolation Reference Points

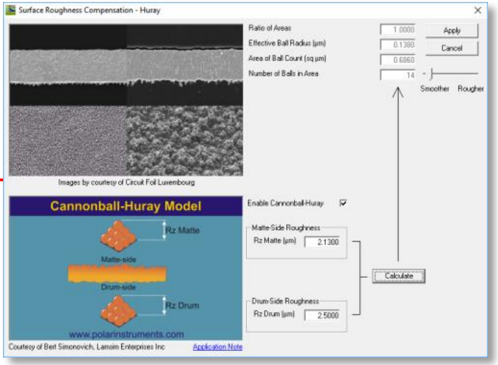
		Freq (Hz)	Ref Er	Ref TanD
Substrate 1 Height	H1	1.00E+10	3.7400	0.0080
Substrate 2 Height	H2	1.00E+10	3.5600	0.0080
Separation Region Dielectric	REr	1.00E+10	3.5600	0.0080

D_{keff_rough}

Step 2 : Set Frequency Range and Select Calculate

Frequency Minimum (MHz)	FMin	10.000
Frequency Maximum (GHz)	FMax	50.010
Frequency Steps	FSteps	500

Display Series: Dielectric Constant (Er)



Ratio of Areas	1.0000
Effective Ball Radius (µm)	0.1380
Area of Ball Count (sq µm)	0.6860
Number of Balls in Area	14

Images by courtesy of Circuit Foil Luxembourg

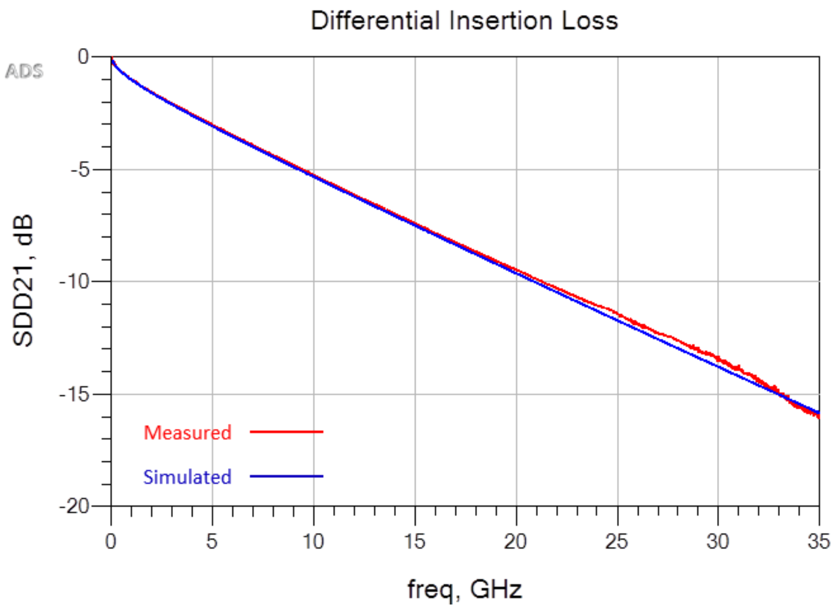
Enable Cannonball-Huray ☑

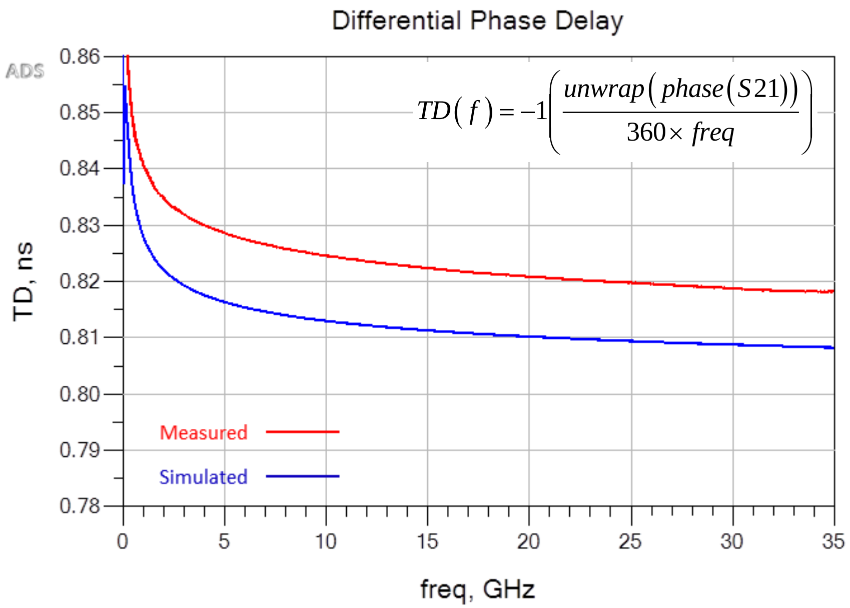
Matte-Side Roughness: Rz Matte (µm) 2.1300

Drum-Side Roughness: Rz Drum (µm) 2.5000

Courtesy of Bert Simonovich, Lamsim Enterprises Inc

Simulated vs Measured Non-causal Metal Model





$$TD(f) = -1\left(\frac{unwrap(phase(S21))}{360 \times freq}\right)$$

✓ Excellent Results

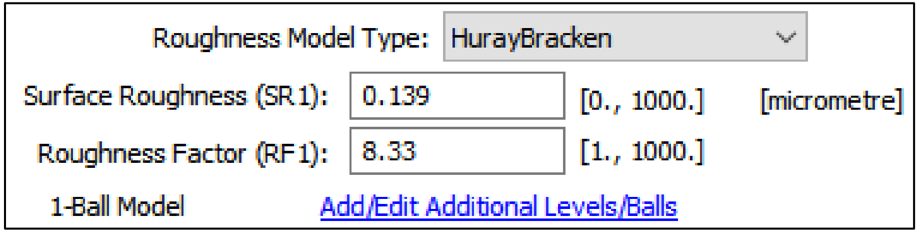
Modeled with Polar Si9000e [5] and Simulated with Keysight ADS [6]

Simbeor Huray-Bracken Causal Metal Model

$$RF1 = 1 + \frac{3}{2}\left(\frac{N4\pi r^2}{A_{flat}}\right) = 1 + \frac{3}{2}\left(\frac{14 \cdot 4\pi (r_{avg})^2}{36 (r_{avg})^2}\right) \approx 8.33$$

$$SR1 = \frac{r_{\_matte} + r_{\_drum}}{2} \approx \frac{0.150 + 0.128}{2}$$

$$\approx 0.139\,\mu m$$

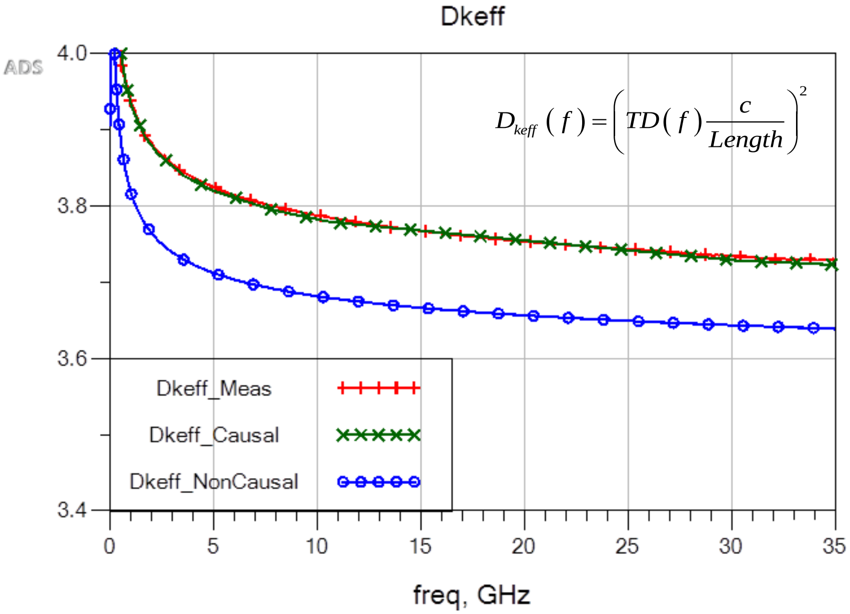


Roughness Model Type: HurayBracken

Surface Roughness (SR1): 0.139 [0., 1000.] [micrometre]

Roughness Factor (RF1): 8.33 [1., 1000.]

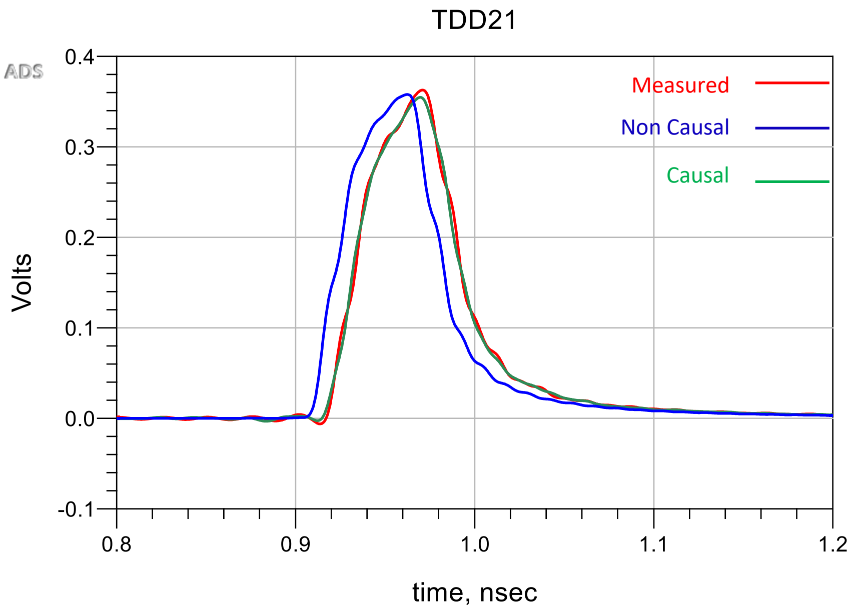
1-Ball Model

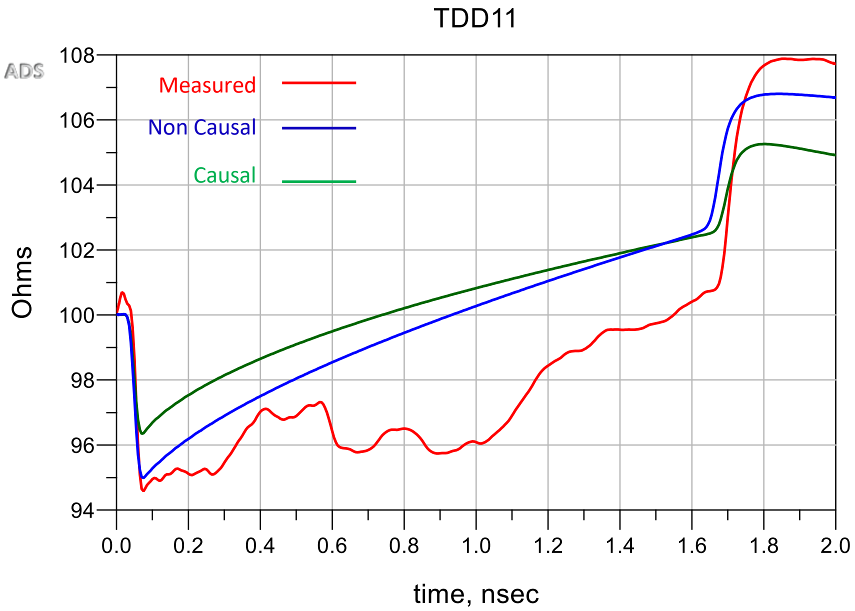


$$D_{keff}(f) = \left(TD(f)\frac{c}{Length}\right)^2$$

✓Excellent Correlation!

Meg-4/RTF Case Study Single Bit Response and TDR



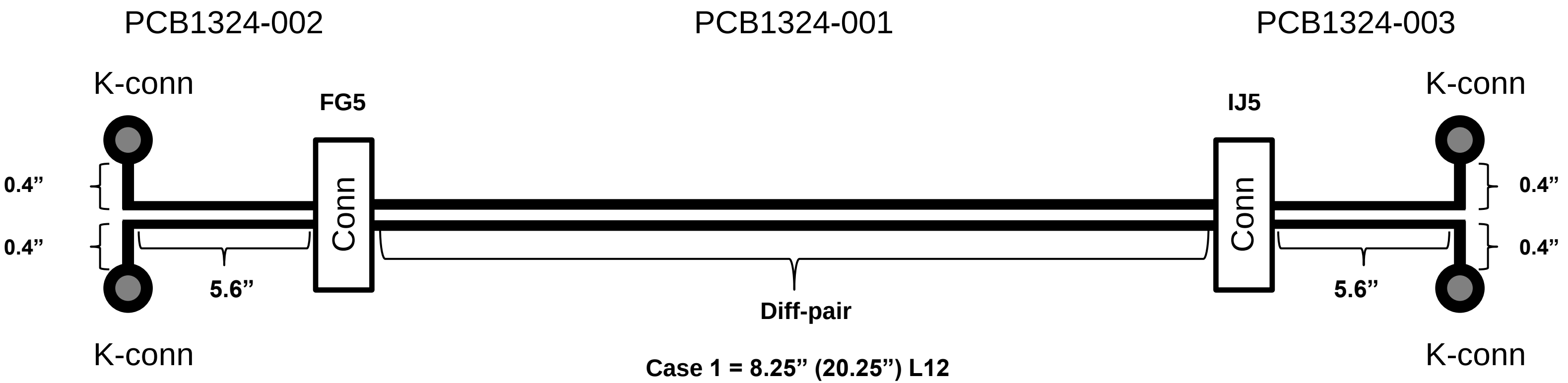


BUT how well does this method work to model a practical backplane channel?

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

Topology Model N4000-13EPSI Summary



PCB1324-002

PCB1324-001

PCB1324-003

K-conn

FG5

IJ5

K-conn

Conn

Conn

0.4”

0.4”

0.4”

0.4”

5.6”

5.6”

Diff-pair

K-conn

K-conn

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

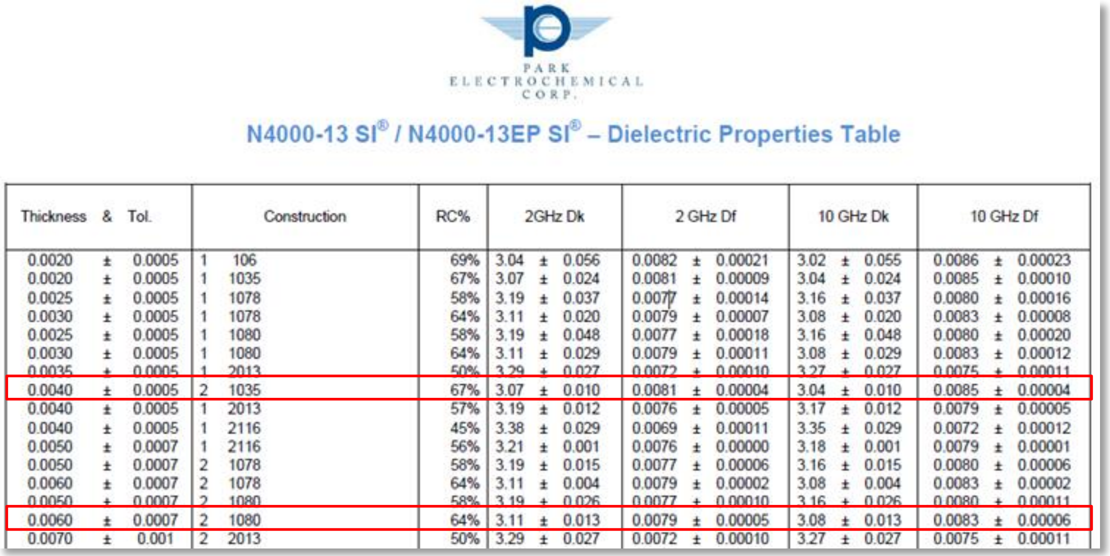
W = 4.9mils
S = 6.1mils
t = 0.6 mils

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

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

K-conn
(2.92mm)

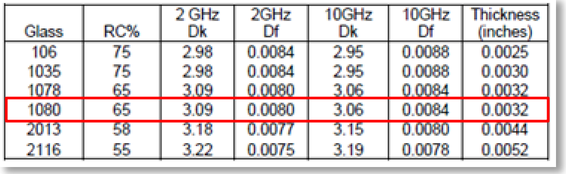
Data Sheet Parameters



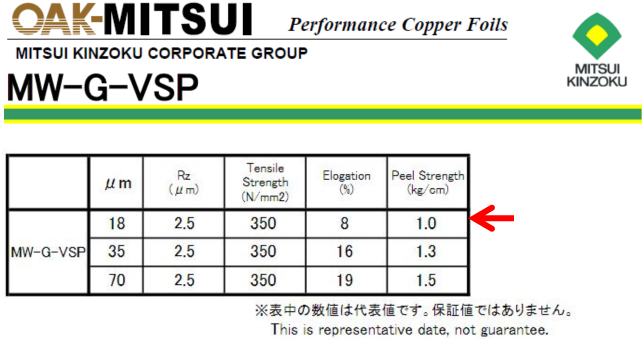
PARK ELECTROCHEMICAL CORP.

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
DC Core	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
BP Core	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



	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
BP/DC Prepreg	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



OAK-MITSUI *Performance Copper Foils*

MITSUI KINZOKU CORPORATE GROUP

MITSUI KINZOKU

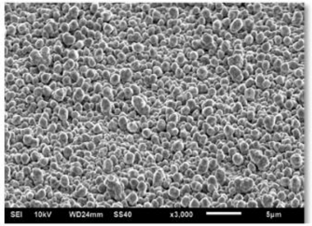
MW−G−VSP

	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

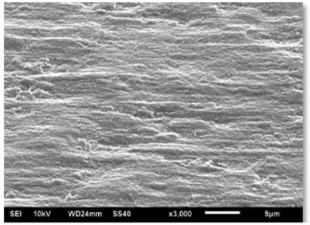
※表中の数値は代表値です。保証値ではありません。

This is representative date, not guarantee.

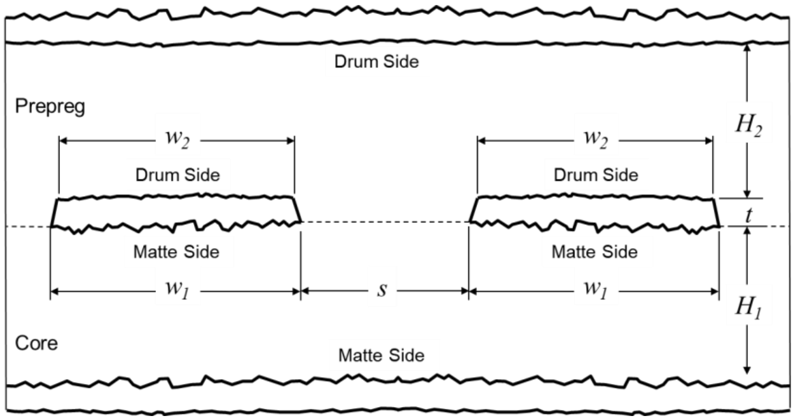
ラミ面/Laminate side



レジ面 / resist side



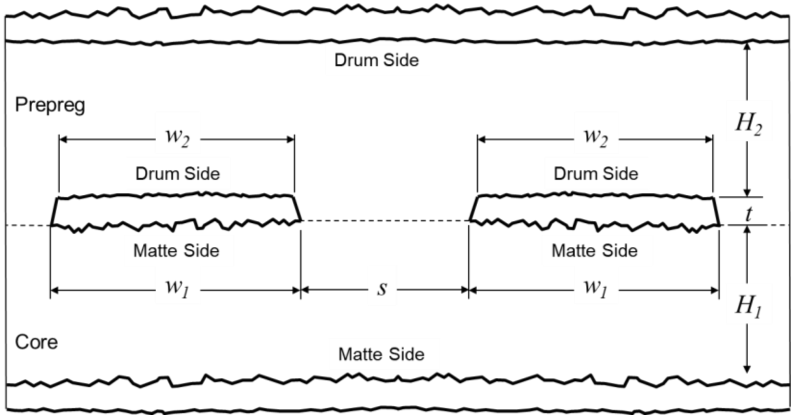
ExaMax Demonstrator Platform
Data Sheet Design Parameters Summary



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	6.2 mils	6.2mils

**OA Treatment Sample C [17]

Determine D_{keff} Due to Roughness Core/Prepreg



Daughter Card

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

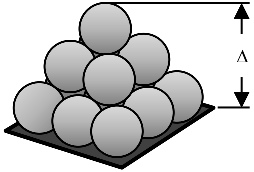
$$D_{keff\_core} = \frac{H_{smooth}}{\left(H_{smooth} - 2R_{z\_matte}\right)} \times D_{k\_core}$$
$$= \frac{4.0mils \times 25.4}{\left(4.0mils \times 25.4 - 2 \times 2.5\mu m\right)} \times 3.04$$
$$= 3.20$$

Backplane

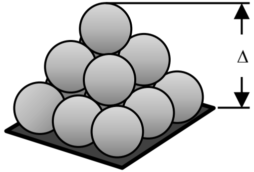
$$D_{keff\_prepreg} = \frac{H_{smooth}}{\left(H_{smooth} - 2R_{z\_drum}\right)} \times D_{k\_prepreg}$$
$$= \frac{6.2mils \times 25.4}{\left(6.2mils \times 25.4 - 2 \times 1.5\mu m\right)} \times 3.06$$
$$= 3.12$$

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

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



Drum-side



Matte-side

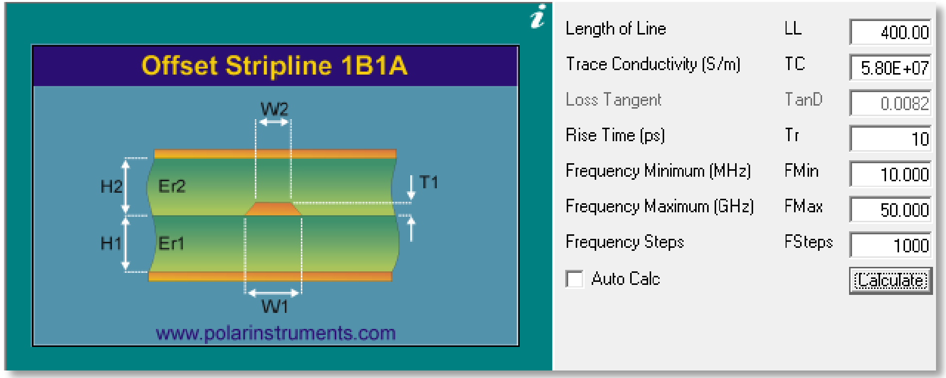
$$r_{drum} \approx 0.06 R_{z\_drum} \approx 0.090\,\mu m$$

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

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

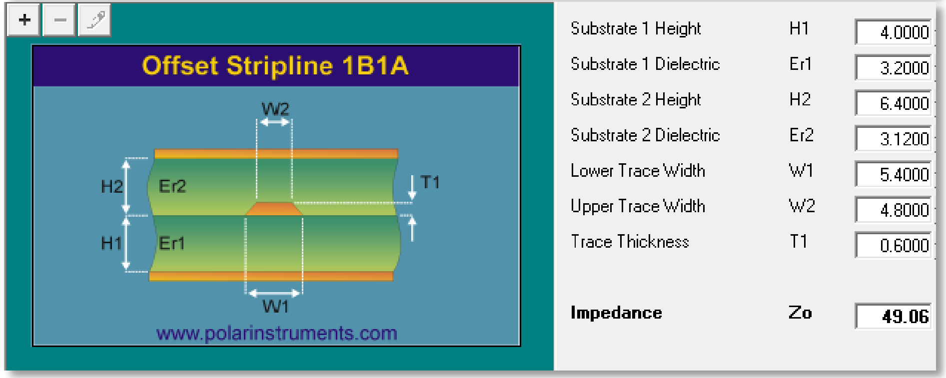
$$A_{flat} \approx 36\left(r_{avg}\right)^2 \approx 0.514\,\mu m^2$$

Polar ExaMax Daughter Card SE Trace Parameters

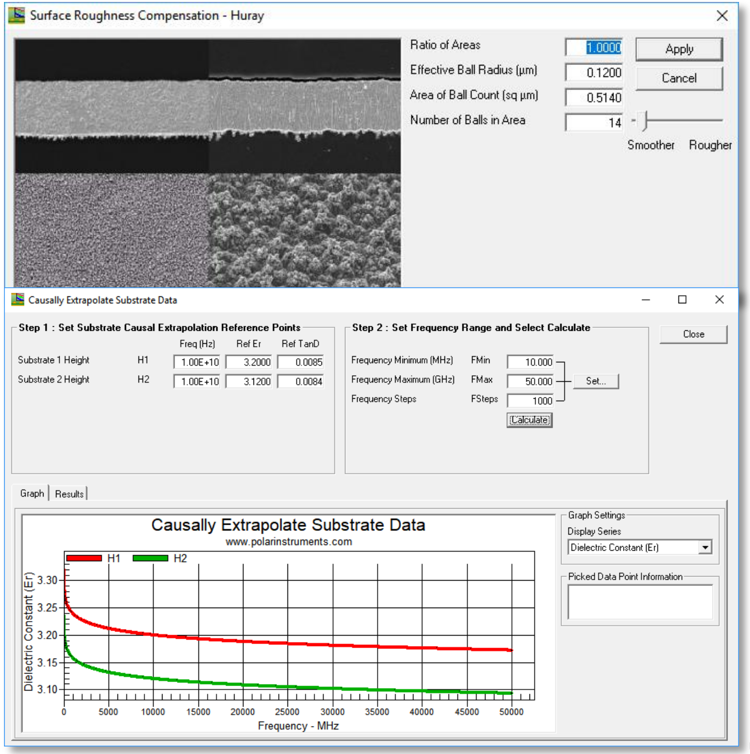


Length of Line	LL	400.00
Trace Conductivity (S/m)	TC	5.80E+07
Loss Tangent	TanD	0.0082
Rise Time (ps)	Tr	10
Frequency Minimum (MHz)	FMin	10.000
Frequency Maximum (GHz)	FMax	50.000
Frequency Steps	FSteps	1000

☐ 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**



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	3.2000	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

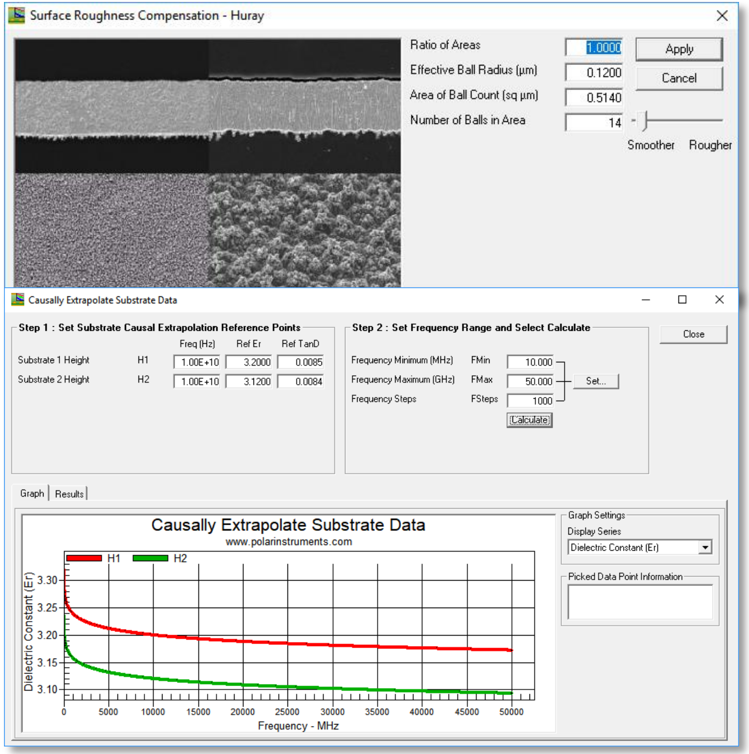
Display Series: Dielectric Constant (Er)

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**



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

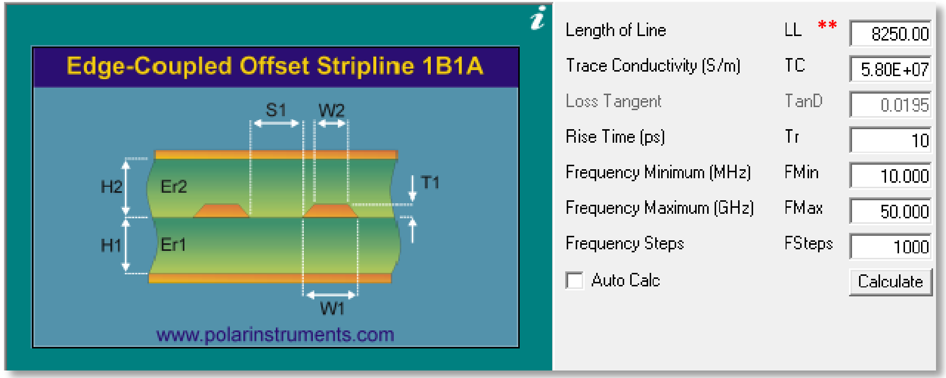
		Freq (Hz)	Ref Er	Ref TanD
Substrate 1 Height	H1	1.00E+10	3.2000	0.0085
Substrate 2 Height	H2	1.00E+10	3.1200	0.0084

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)

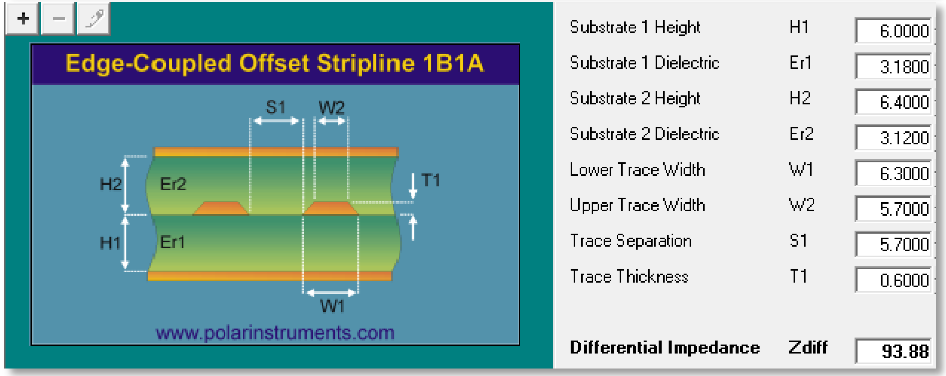
Polar ExaMax Backplane Diff Trace Parameters



Edge-Coupled Offset Stripline 1B1A

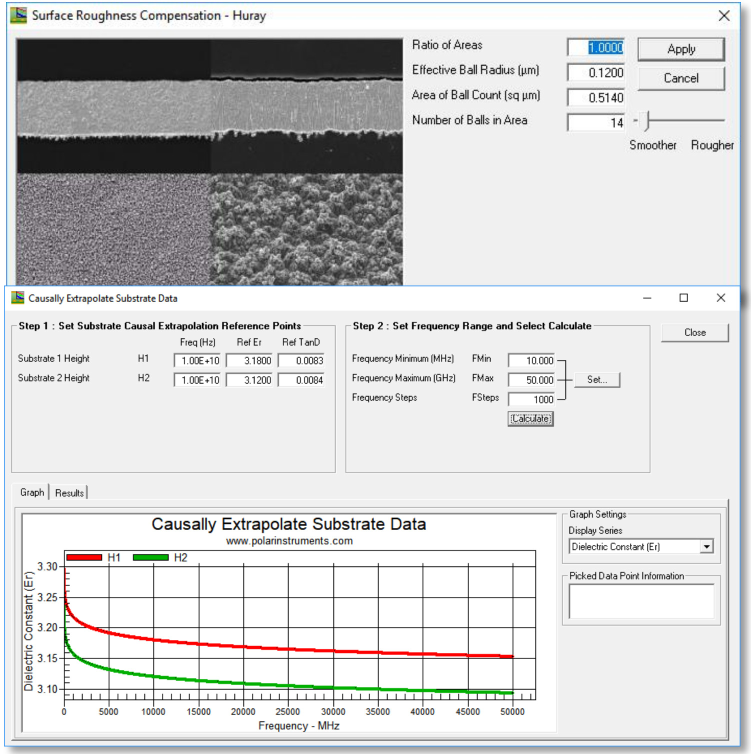
Length of Line	LL **	8250.00
Trace Conductivity (S/m)	TC	5.80E+07
Loss Tangent	TanD	0.0195
Rise Time (ps)	Tr	10
Frequency Minimum (MHz)	FMin	10.000
Frequency Maximum (GHz)	FMax	50.000
Frequency Steps	FSteps	1000

☐ Auto Calc



Edge-Coupled Offset Stripline 1B1A

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

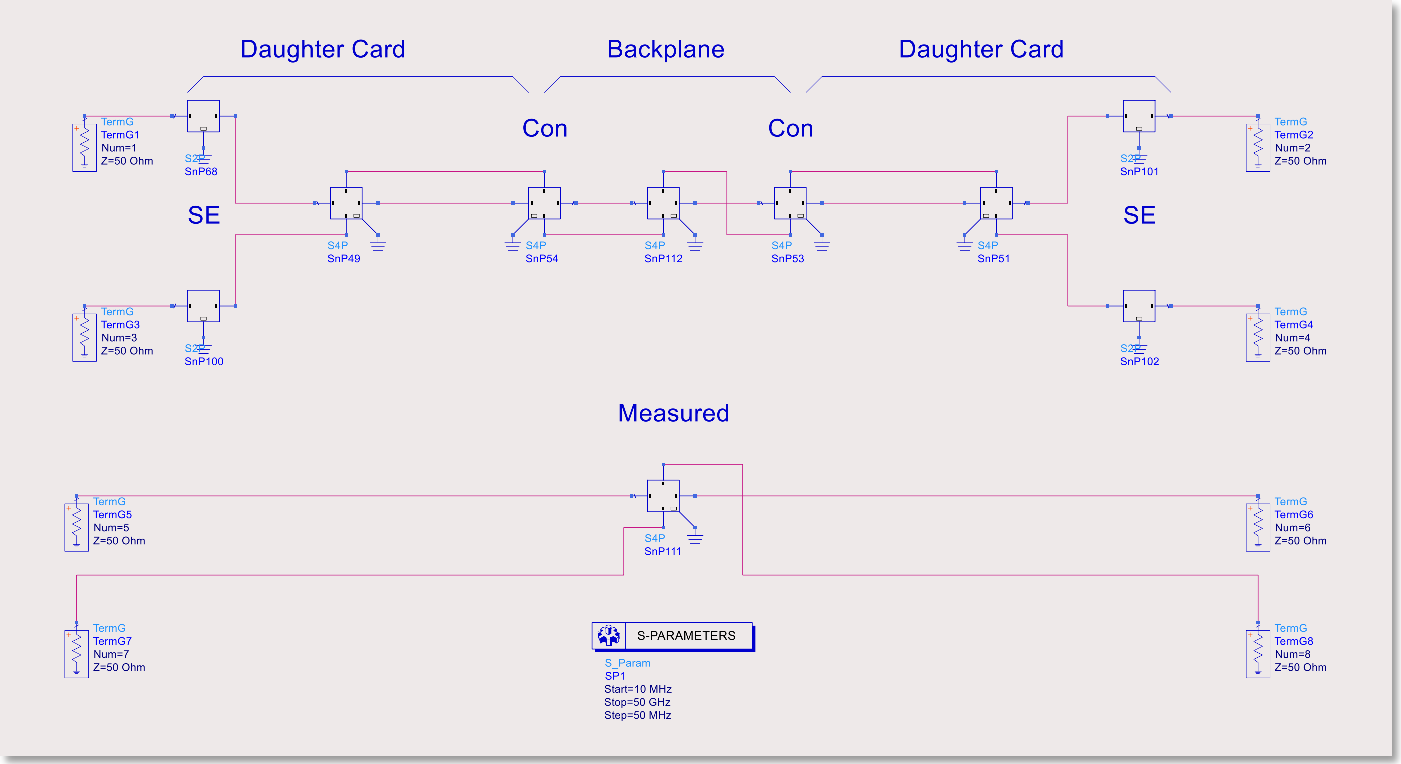
Frequency Minimum (MHz)	FMin	10.000
Frequency Maximum (GHz)	FMax	50.000
Frequency Steps	FSteps	1000

Graph Settings
Display Series: Dielectric Constant (Er)

Picked Data Point Information

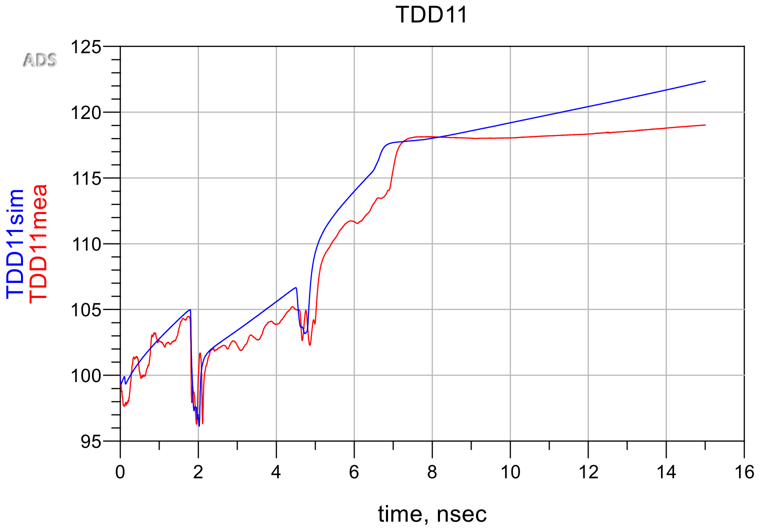
****Length of Line (LL) Adjusted for 8.25”; 14.80”; 20.22”; 26.70”**

Generic Topology Model



Modeled with Keysight ADS [6]

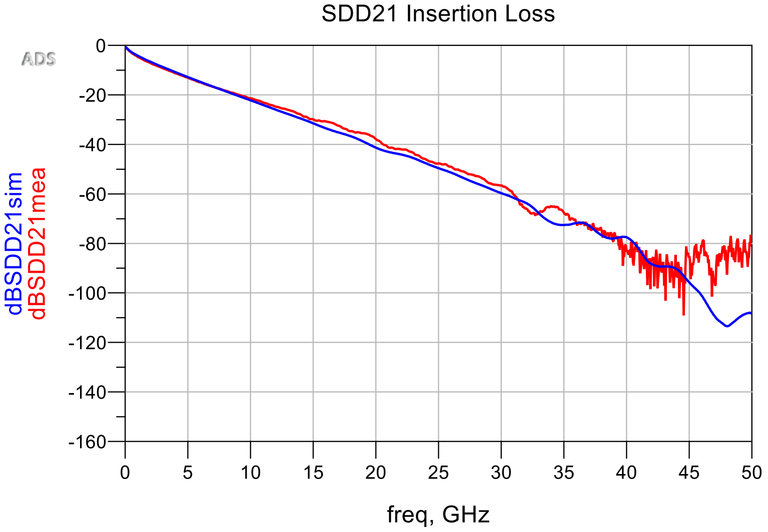
ExaMax Backplane Case 1 Total Length = 20.25”

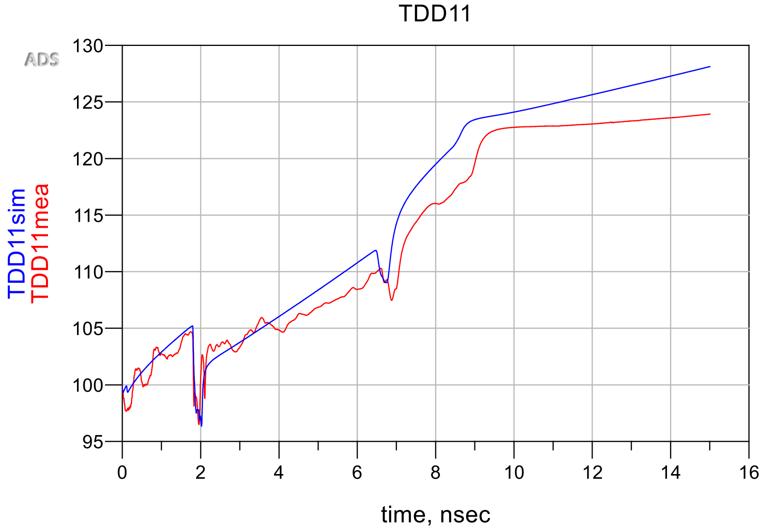


---- Measured
---- Simulated

Simulated with Keysight ADS [6]

ExaMax Backplane Case 2 Total Length = 26.80”


SDD21 Insertion Loss

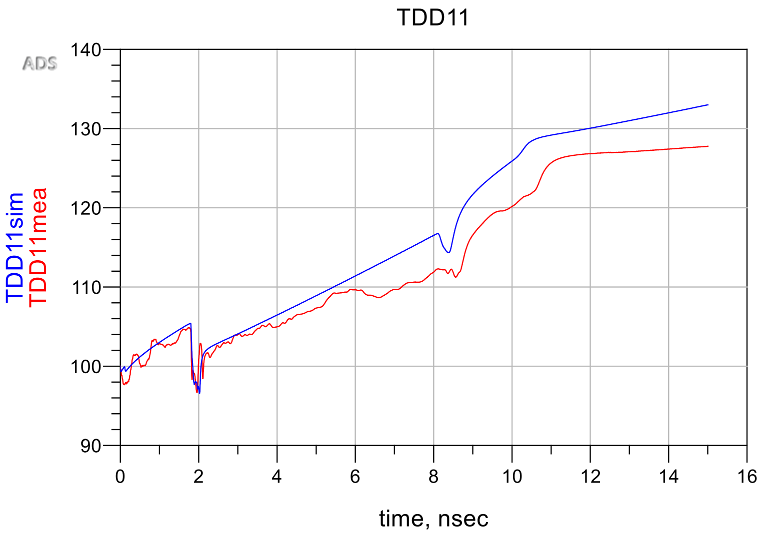

TDD11

---- Measured

---- Simulated

Simulated with Keysight ADS [6]

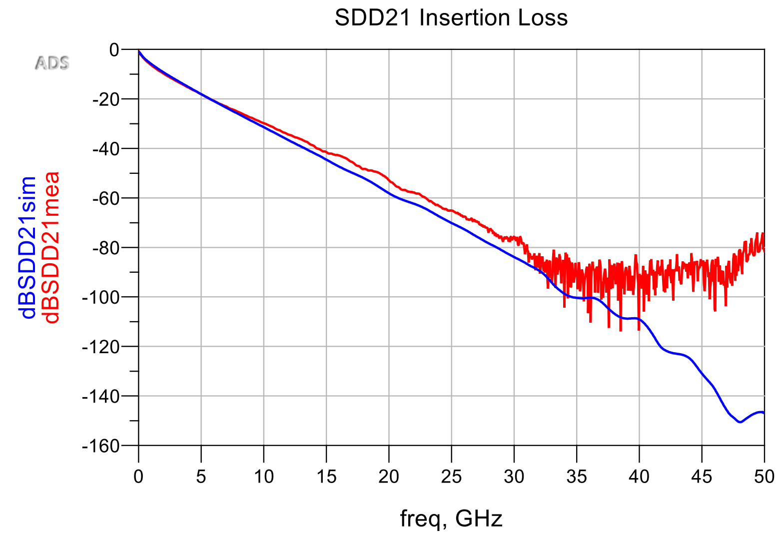
ExaMax Backplane Case 3 Total Length = 32.22”

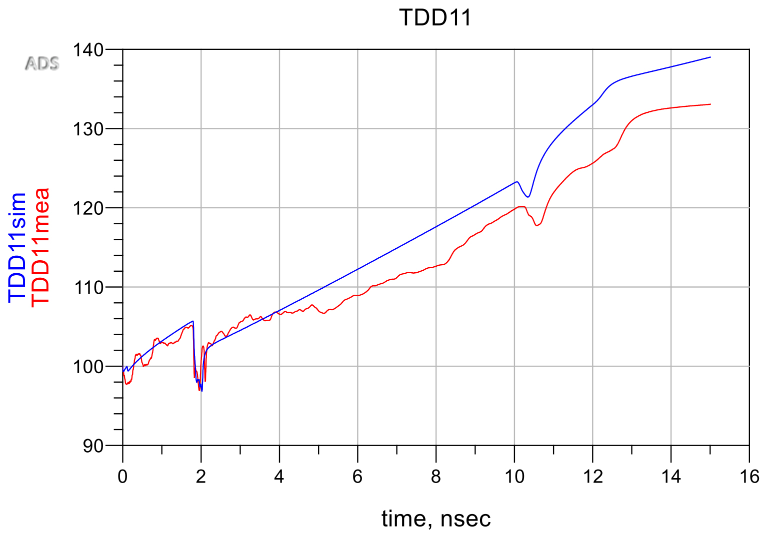


---- Measured
---- Simulated

Simulated with Keysight ADS [6]

ExaMax Backplane Case 4 Total Length = 38.70”

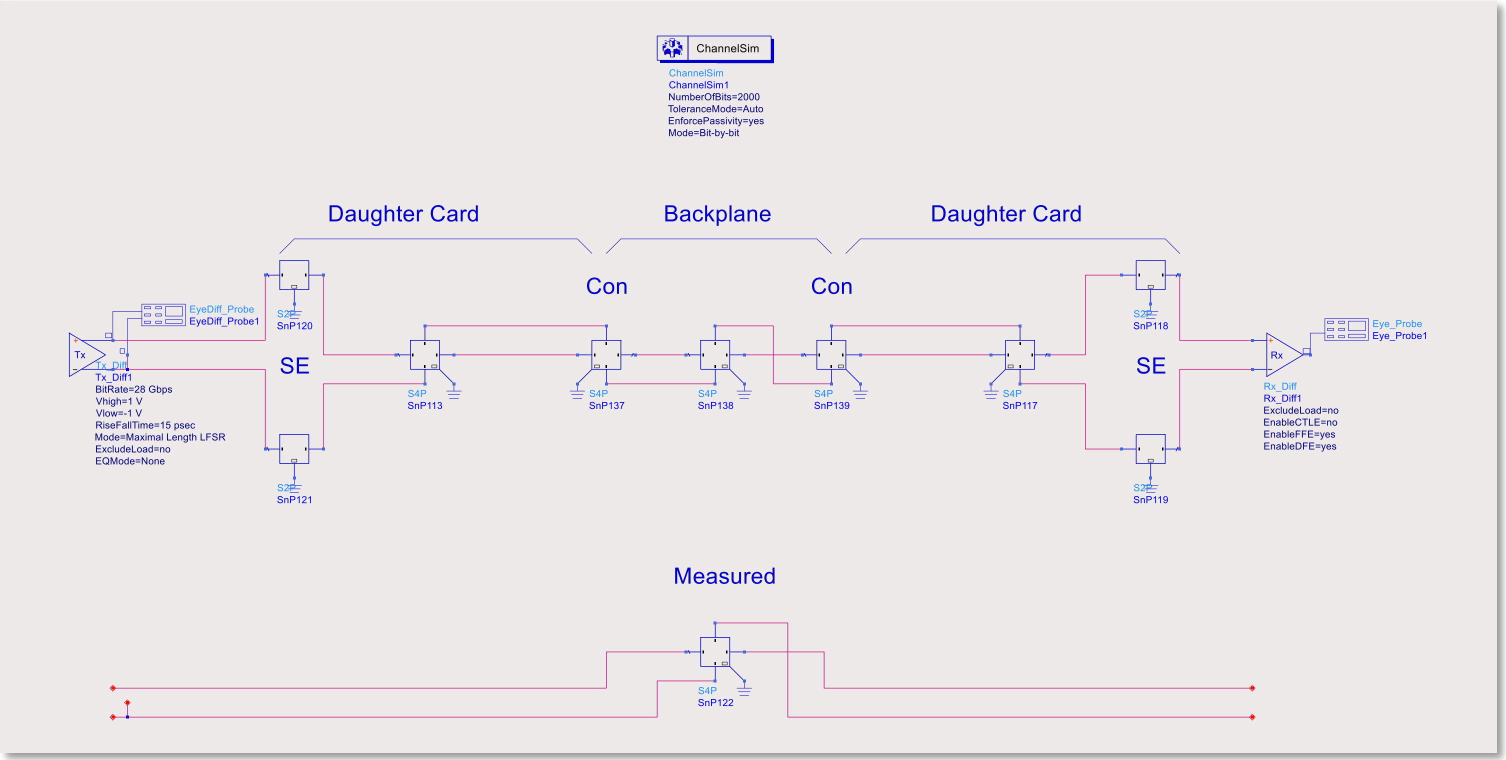




---- Measured
---- Simulated

Simulated with Keysight ADS [6]

Generic Channel Model



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

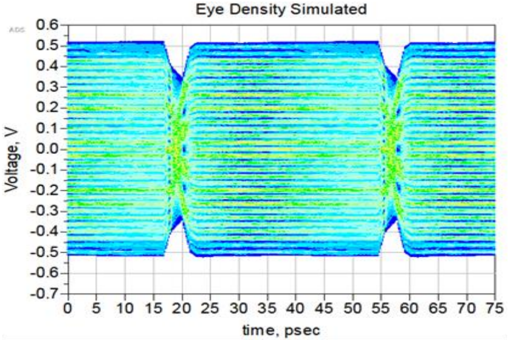
Tx_Diff
Tx_Diff1
BitRate=28 Gbps
Vhigh=1 V
Vlow=-1 V
RiseFallTime=15 psec
Mode=Maximal Length LFSR
ExcludeLoad=no
EQMode=None

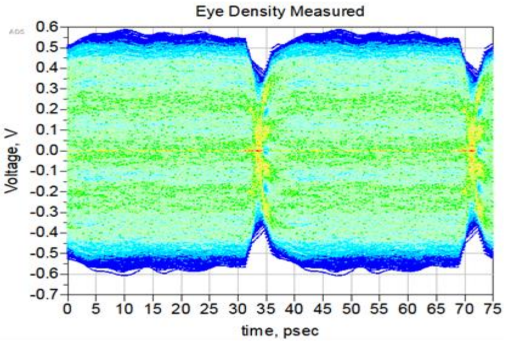
Rx_Diff
Rx_Diff1
ExcludeLoad=no
EnableCTLE=no
EnableFFE=yes
EnableDFE=yes

Modeled with Keysight ADS [6]

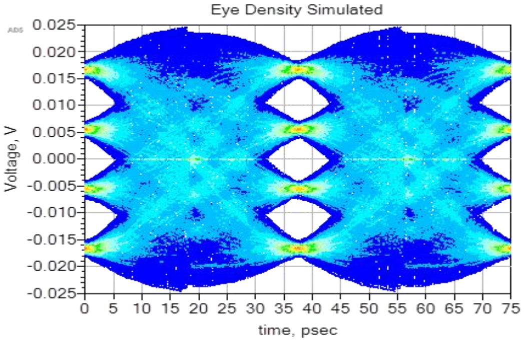
Channel Simulation 53.12 GB/s Case 1 20.25”

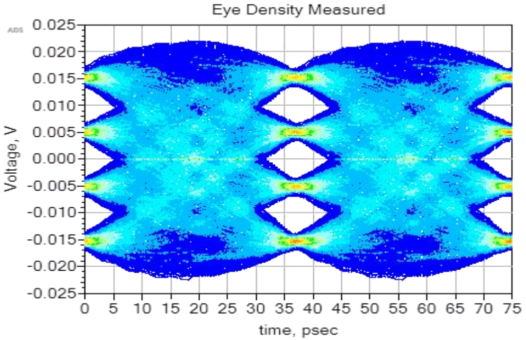
Near-end





Far-end





permute(HeightAtBER0)	permute(HeightAtBER1)	permute(HeightAtBER2)
7.447 m	7.090 m	7.224 m

permute(WidthAtBER0)	permute(WidthAtBER1)	permute(WidthAtBER2)
7.718 p	7.718 p	7.718 p

permute(HeightAtBER0)	permute(HeightAtBER1)	permute(HeightAtBER2)
6.404 m	6.280 m	6.451 m

permute(WidthAtBER0)	permute(WidthAtBER1)	permute(WidthAtBER2)
7.530 p	7.342 p	7.530 p

Simulated with Keysight ADS [6]

Summary

- ✓ By using dielectric material properties, copper foil and oxide alternative roughness parameters 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.
- ✓ Even though some models are wrong, they can still be useful for getting that answer now rather than later.

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