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February 24–26, 2026
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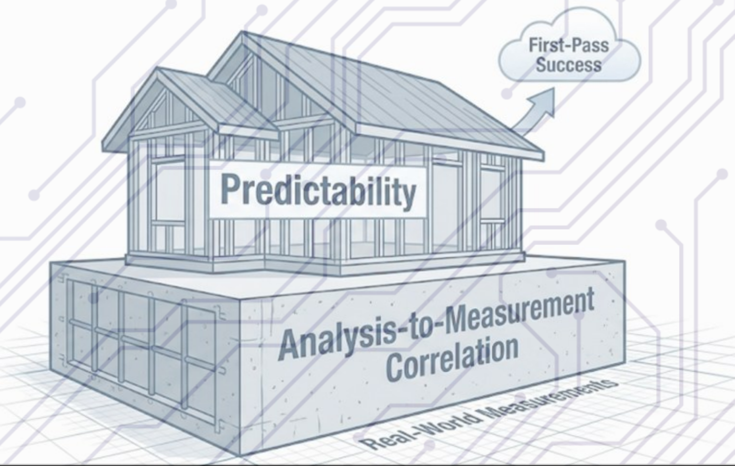
Expo
February 25–26, 2026

How to Design Predictable Interconnects up to 448 Gbps

Yuriy Shlepnev, Simberian Inc.
Alex Manukovsky, Intel Israel
Joshua Nutzati, Intel

Tuesday, February 24
2:00 PM - 4:30 PM Pacific Time (US & Canada)
Ballroom H



SPEAKERS

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How to Design Predictable Interconnects up to 448 Gbps

Part I

1. SI Dreams and Nightmares
2. The Inconvenient Reality of Interconnects
3. Some good practices - Towards 448 Gbps

Predictable Interconnects

1 Mostly

Step1- First Simulate

Step2- Lab Measurement

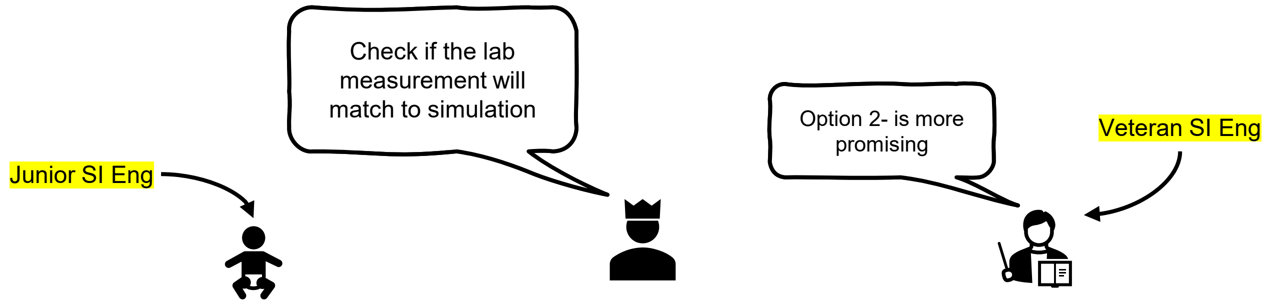
Step3- Check if it Matches

2 Sometimes

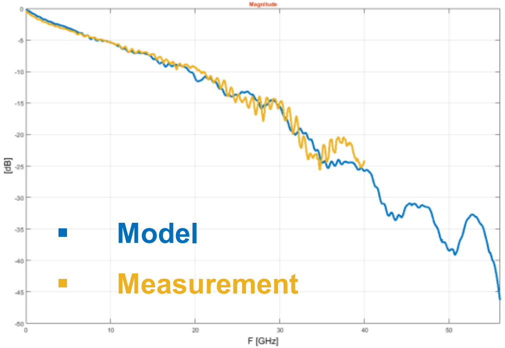
Step1- Lab Measurement First

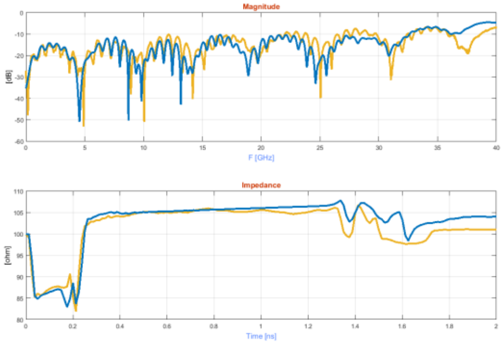
Step2- Simulation

Step3- Check if it Matches

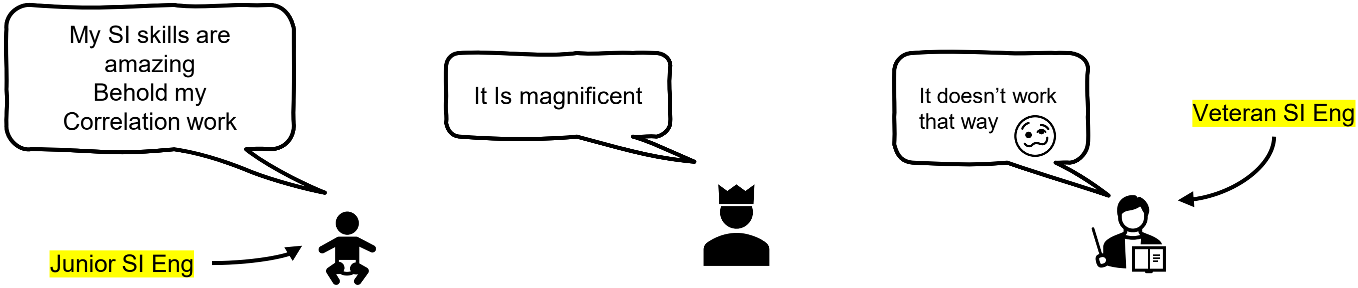


Predictable Interconnects





Don't Believe In Fairytales



Step One - Acknowledging the Challenge

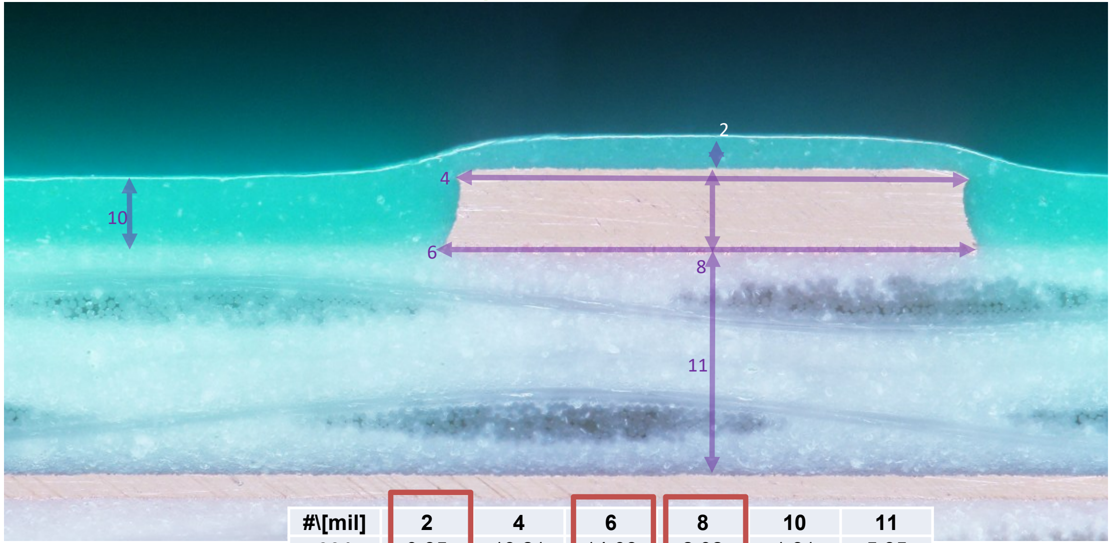
1. Case study 1- Microstrip Geometry
2. Case Study 2- Coupon Structure
3. Case Study 3 -Probing PAD (Via)Structure

Case study 1 Microstrip Geometry

- 10 PCBs
- Same Lot

Some Variations are more familiar to SI Engineers

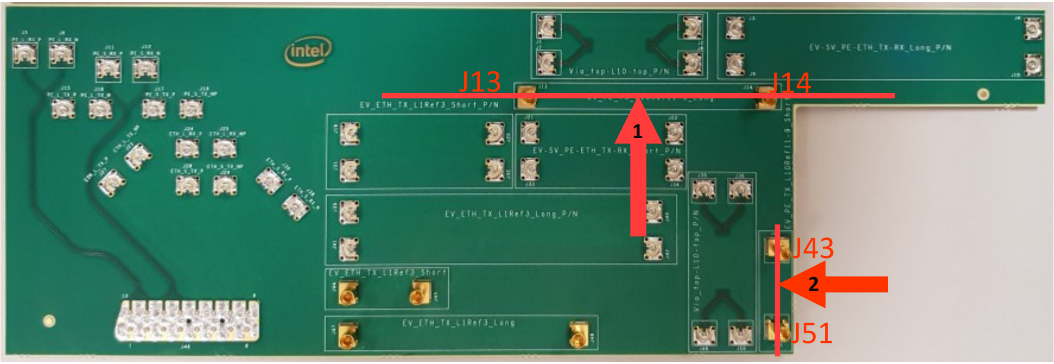
Covered in Depth in Literature [2]



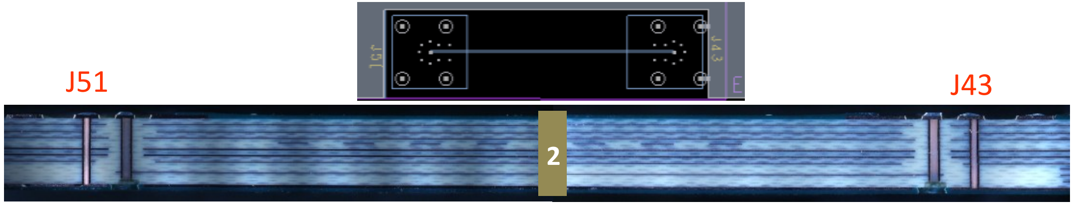
#\[mil]	2	4	6	8	10	11
001	0.85	13.21	14.08	2.02	1.81	5.85
002	0.90	13.11	14.01	2.20	2.05	5.81
003	0.89	13.42	14.04	2.03	1.77	5.81
004	0.86	13.44	14.11	2.15	1.94	5.90
005	0.87	13.57	14.29	2.08	1.86	5.90
006	1.00	13.69	14.32	2.13	1.90	5.94
007	0.82	13.59	14.16	2.05	1.91	5.95
008	1.01	13.98	13.69	2.10	1.84	5.95
009	0.89	13.57	14.20	2.29	1.92	5.97
010	0.85	13.60	14.07	2.00	1.86	6.00
Max	**1.01**	**13.98**	**14.32**	**2.29**	**2.05**	**6.00**
Min	**0.82**	**13.11**	**13.69**	**2.00**	**1.77**	**5.81**
Average	**0.89**	**13.52**	**14.10**	**2.11**	**1.89**	**5.91**
	21%	6%	4%	14%	15%	3%

Case Study 2 -Coupon Structure

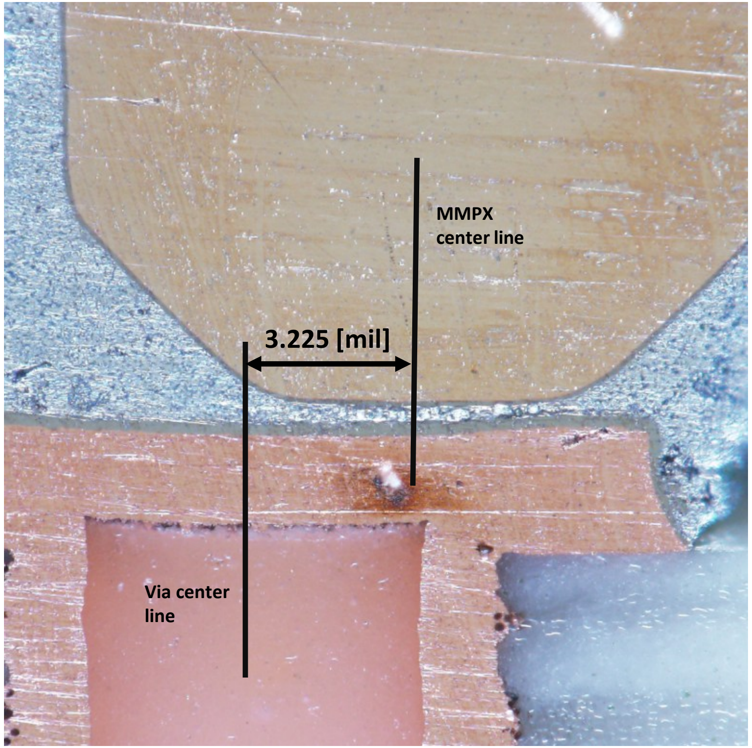
What could possibly go wrong?

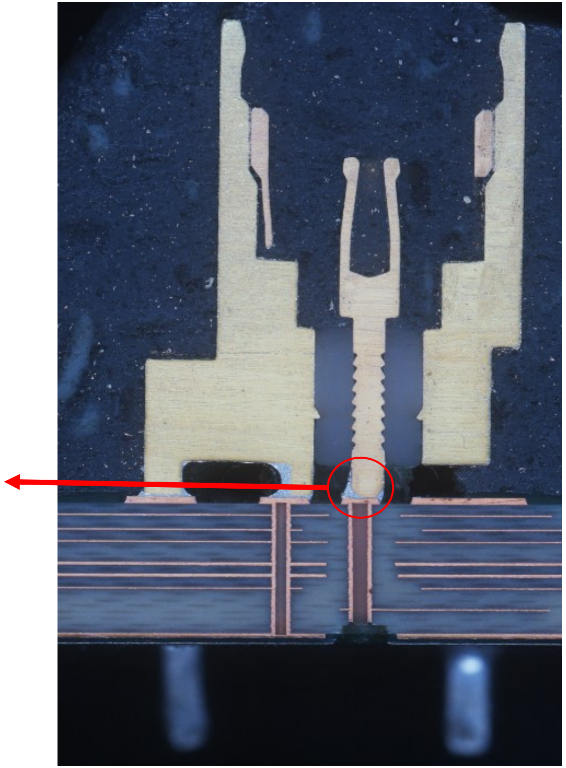


Coupon Structure
NS vs EW orientation
Same Via Structure
Same PCB



Connector pin to Via Offset



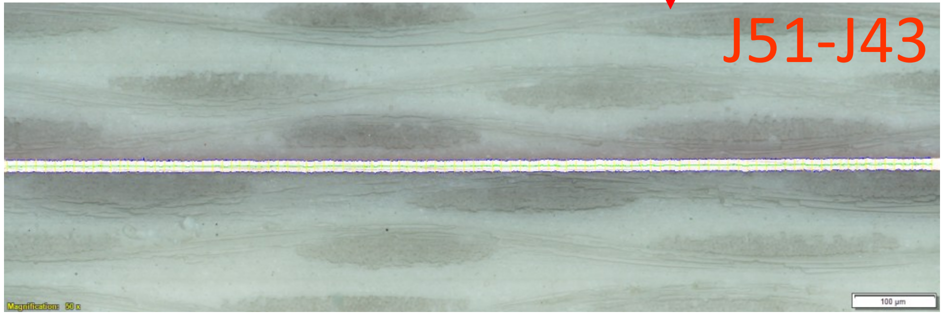


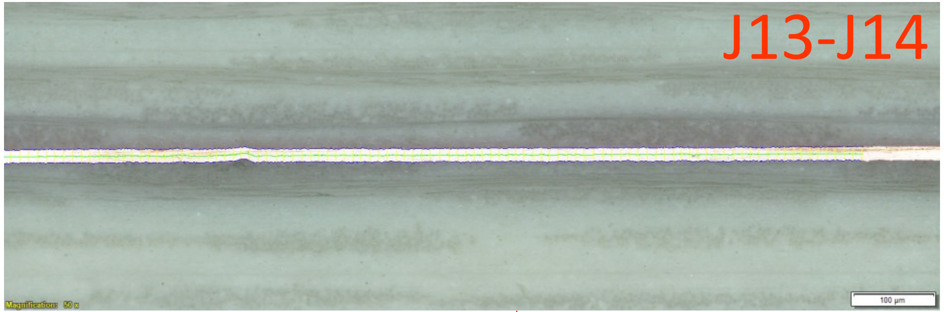
Isotropic Weave Spread

Resulted in 2Ω
Impedance Difference [2]

NS –Non Spread Weave

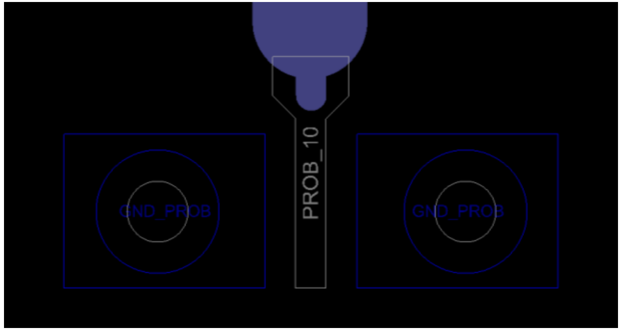
EW -Spread Weave



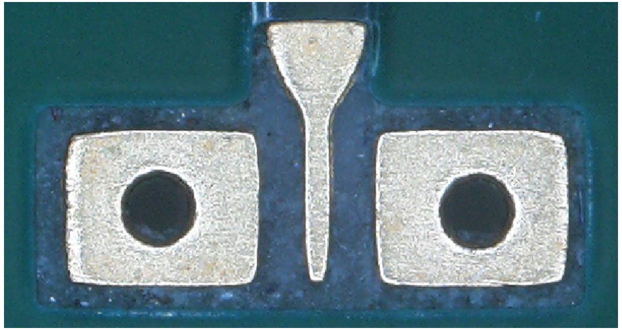


Case Study 3- Probing PAD Structure

What could possibly go wrong?



Design

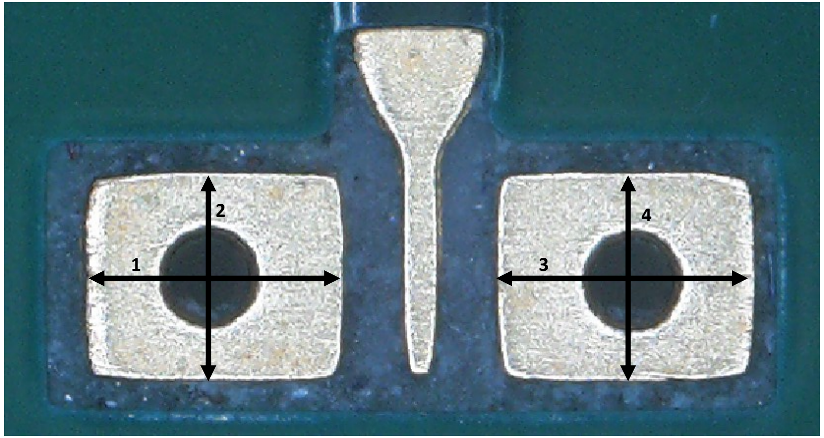


Reality

Post Manufactured PCB Reality Might Be Different than Intended

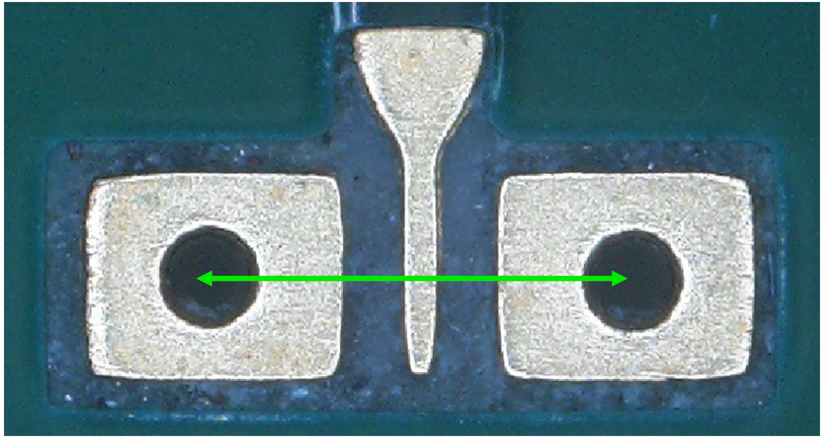
- 10 PCB Samples
- Same Lot

Measured Gnd Pads Dimensions



	1	2	3	4
001	23.91	18.91	23.44	19.12
002	23.46	18.08	23.28	18.47
003	23.07	17.93	23.13	17.66
004	23.23	18.62	22.77	18.57
005	23.37	18.50	23.39	18.53
006	22.62	17.79	22.55	17.93
007	23.10	18.63	23.48	18.25
008	23.28	18.33	22.92	18.08
009	23.42	17.71	22.52	18.17
010	23.23	18.56	23.68	18.81
Design	26	20	26	20
AVG	23.27	18.31	23.12	18.36
Min	22.62	17.71	22.52	17.66
Max	23.91	18.91	23.68	19.12
var	1.29	1.2	1.16	1.46
Max error	3.38	2.29	3.48	2.34

Measured Via center to Via center distance [mil]



	Measured
001	39.16
002	39.62
003	41.72
004	39.07
005	39.72
006	40.74
007	39.82
008	39.30
009	39.55
010	39.71
AVG	39.84
min	39.07
max	41.72
delta	2.65
MAX error	1.72

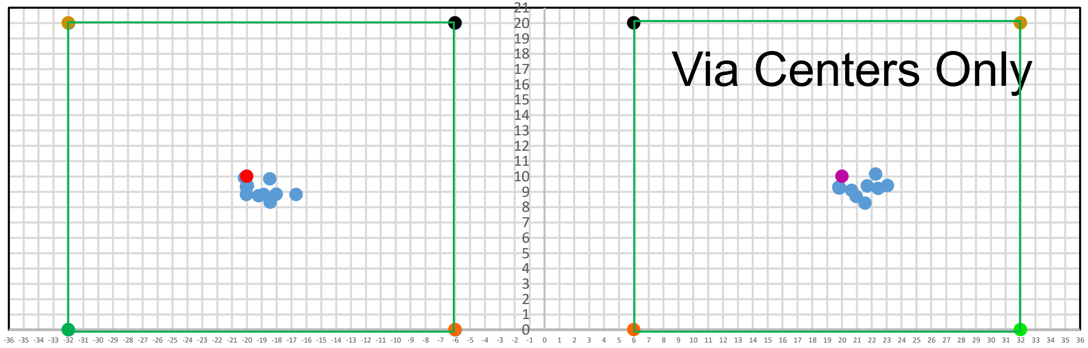
Via Location Measured vs Designed

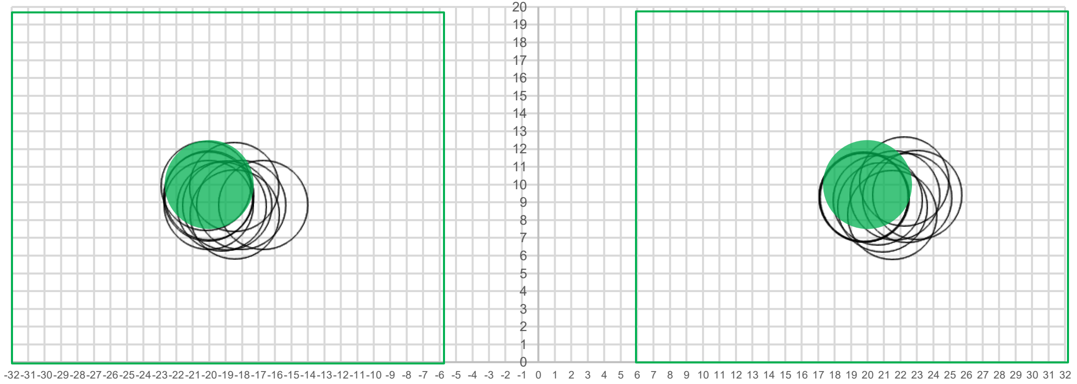
Left via

Coupon	X	Y
001	-20.0	9.3
002	-16.7	8.8
003	-20.0	8.8
004	-20.2	9.9
005	-18.9	8.8
006	-18.5	9.9
007	-18.4	8.3
008	-19.2	8.7
009	-18.0	8.8
010	-20.0	9.4
Design	-20	10
AVG	-18.99	9.07
min	-20.2	8.3
max	-16.7	9.9
delta	3.5	1.6
MAX error	-3.3	1.7

Right via

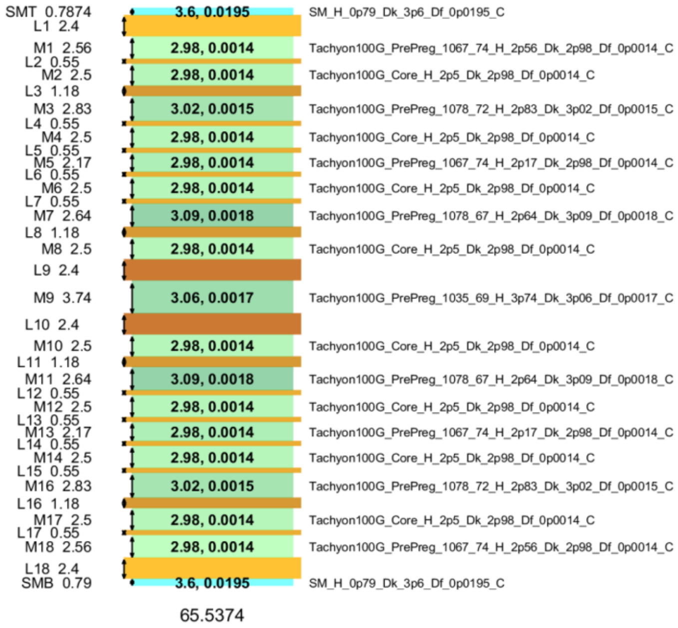
Coupon	X	Y
001	19.8	9.3
002	23.0	9.4
003	22.4	9.2
004	19.8	9.3
005	20.9	8.7
006	22.2	10.2
007	21.5	8.3
008	20.6	9.1
009	21.7	9.4
010	19.8	9.3
Design	20	10
AVG	21.17	9.22
min	19.8	8.3
max	23	10.2
delta	3.2	1.9
MAX error	-3	1.7



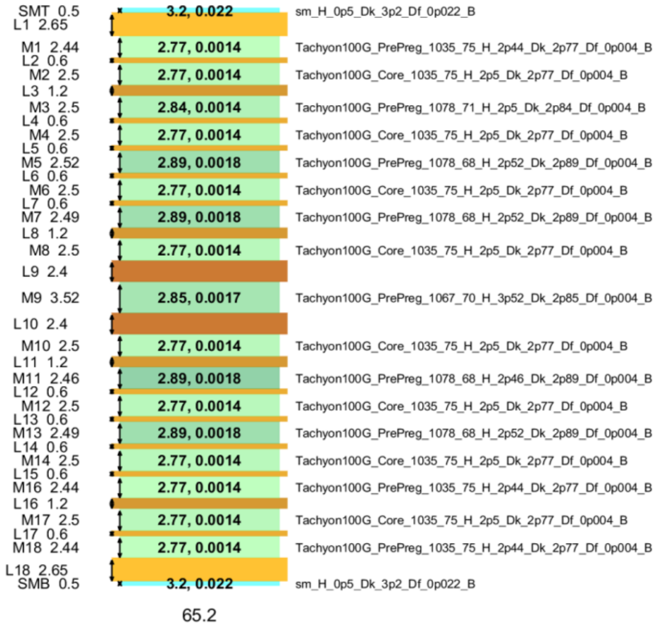


Vias Variations- Single design Two fab Vendors

Stackup 1



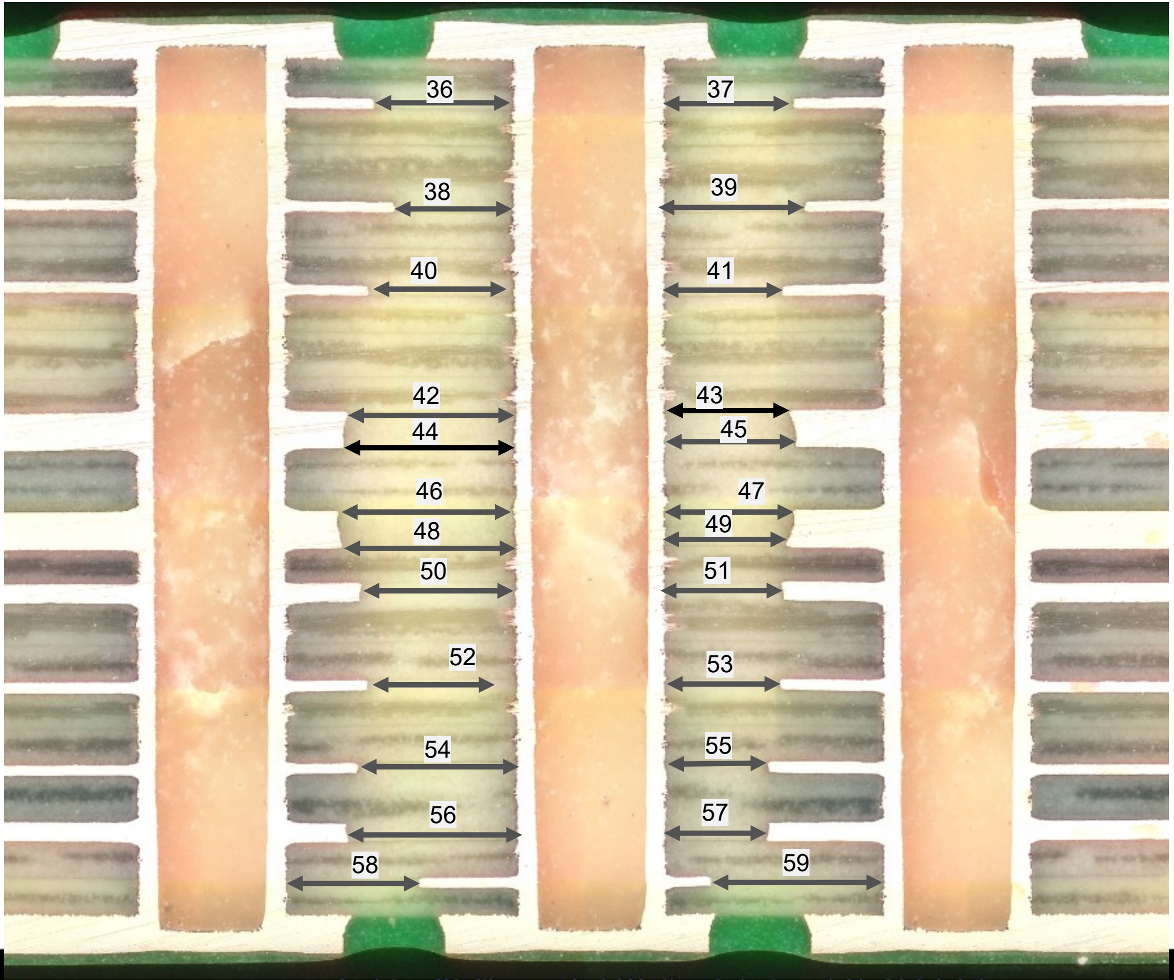
Stackup 2



Vias for each layer were designed to satisfy the low reflection condition for two stackups simultaneously – see details in A. Manukovsky, Y. Shlepnev, J. Nutzati, A. Kuntsevych, I. Peleg, S. Mordooch Via Design for 112 Gbps and Beyond: Theory and Reality, DesignCon 2025

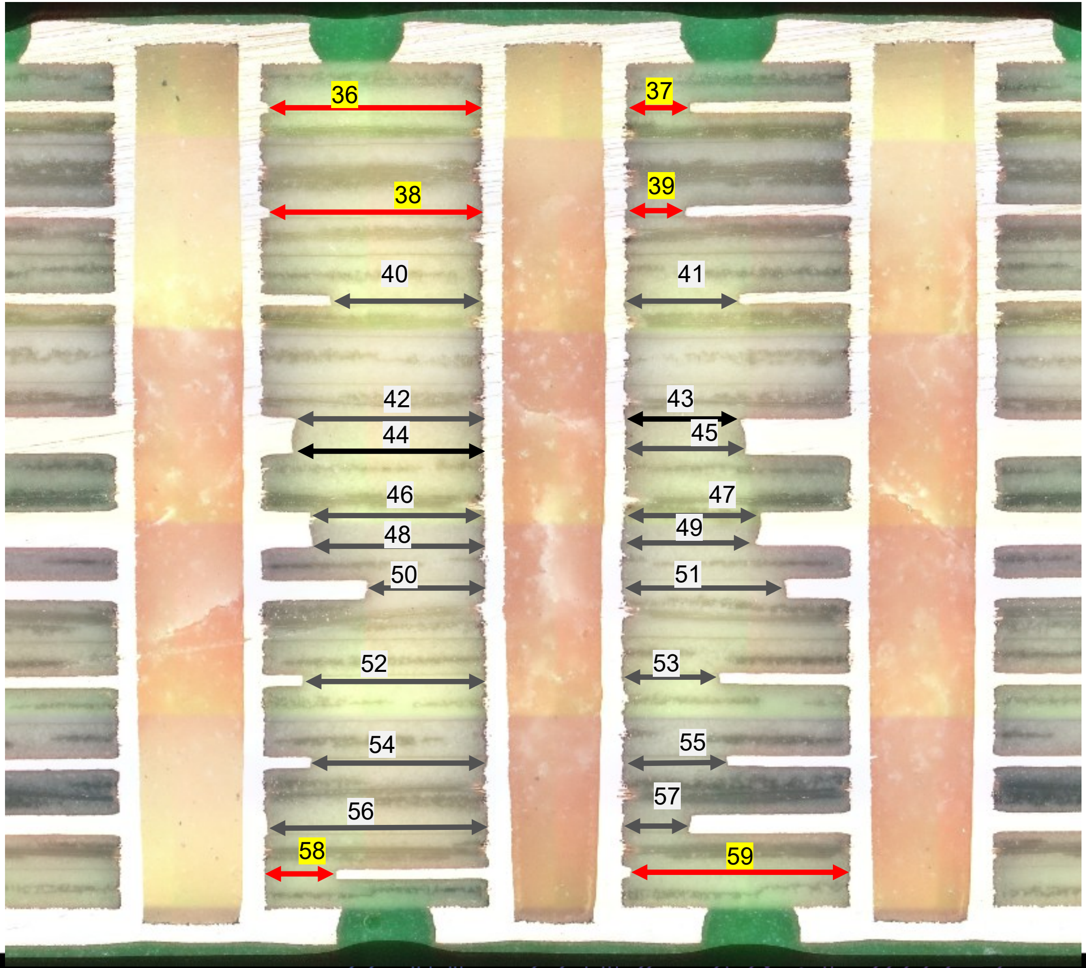
Vendore1_004_line_17_Via

Type	Name	Length (mil)
Horizontal Line	36	9.74
Horizontal Line	37	8.96
Horizontal Line	38	8.34
Horizontal Line	39	9.74
Horizontal Line	40	10.16
Horizontal Line	41	8.23
Horizontal Line	42	11.78
Horizontal Line	43	8.68
Horizontal Line	44	11.93
Horizontal Line	45	9.14
Horizontal Line	46	12.21
Horizontal Line	47	8.99
Horizontal Line	48	12.08
Horizontal Line	49	8.42
Horizontal Line	50	10.83
Horizontal Line	51	8.23
Horizontal Line	52	10.42
Horizontal Line	53	8.01
Horizontal Line	54	11.18
Horizontal Line	55	7.15
Horizontal Line	56	11.97
Horizontal Line	57	7.24
Horizontal Line	58	9.18
Horizontal Line	59	11.95



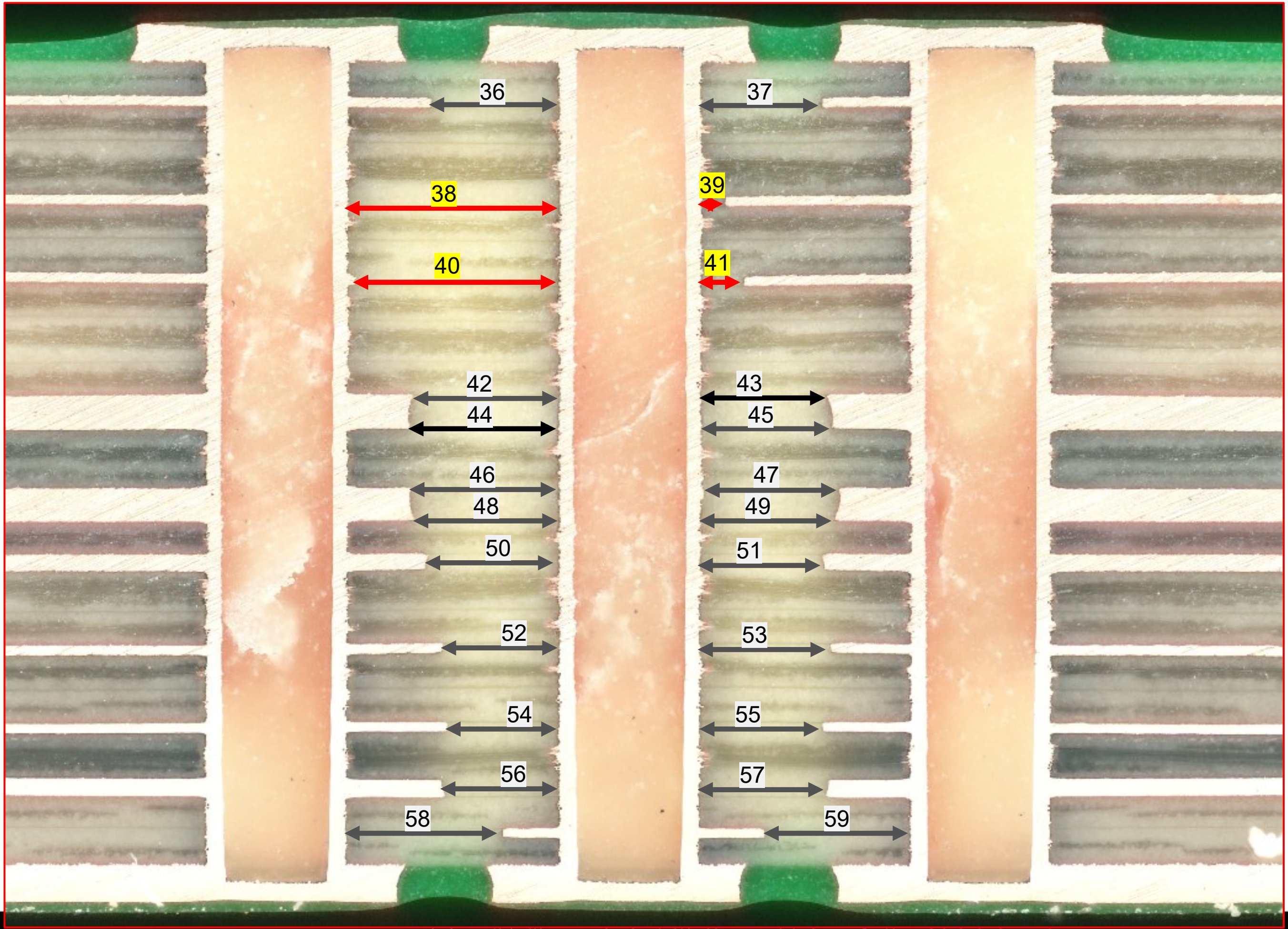
Vendore1_003_line_17_Via

Type	Name	Length [mil]
Horizontal Line	36	15.00
Horizontal Line	37	4.52
Horizontal Line	38	15.00
Horizontal Line	39	4.25
Horizontal Line	40	10.68
Horizontal Line	41	7.92
Horizontal Line	42	13.11
Horizontal Line	43	8.12
Horizontal Line	44	13.37
Horizontal Line	45	8.38
Horizontal Line	46	12.20
Horizontal Line	47	9.52
Horizontal Line	48	12.12
Horizontal Line	49	9.39
Horizontal Line	50	8.33
Horizontal Line	51	11.41
Horizontal Line	52	12.78
Horizontal Line	53	6.82
Horizontal Line	54	12.40
Horizontal Line	55	7.39
Horizontal Line	56	15.47
Horizontal Line	57	4.67
Horizontal Line	58	5.00
Horizontal Line	59	15.36



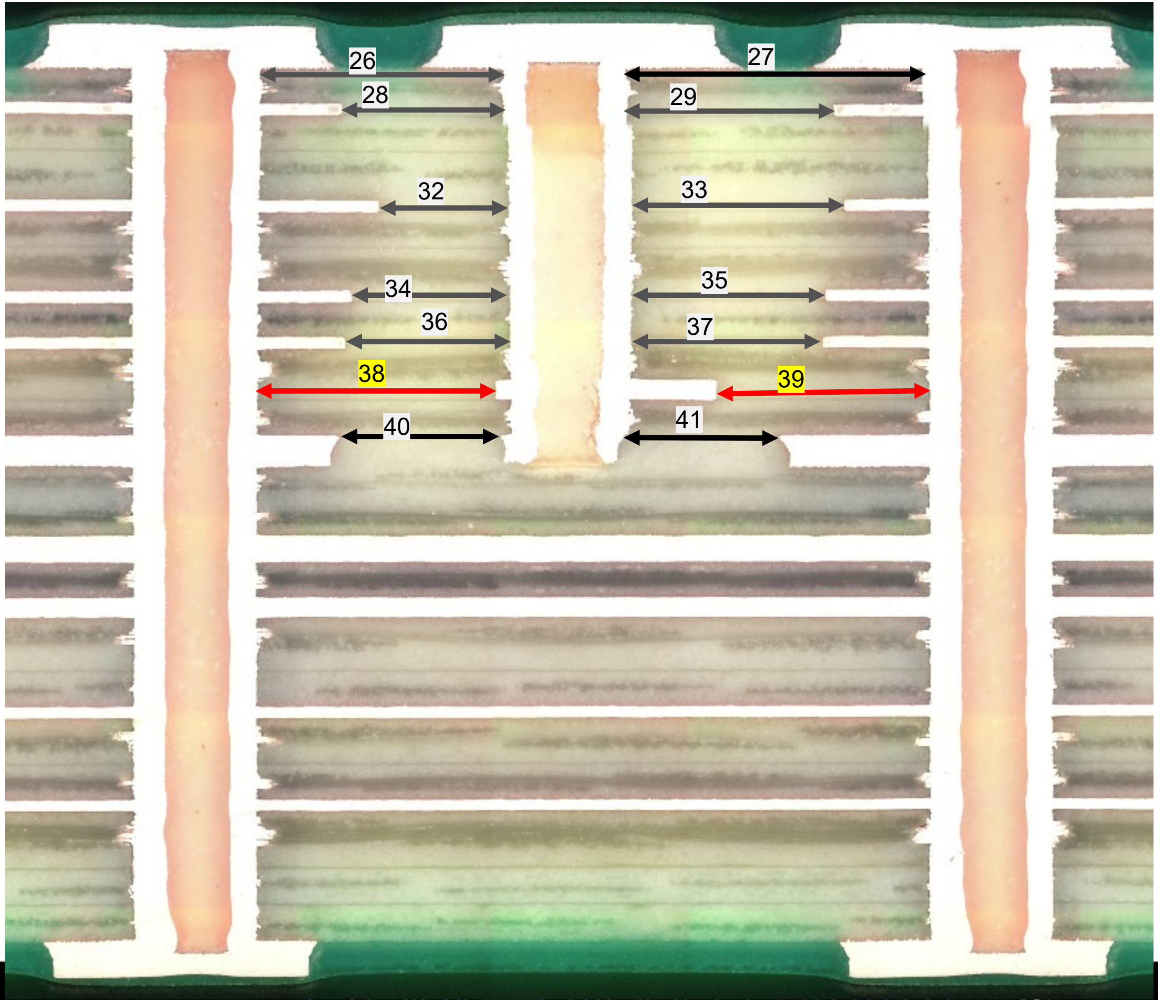
Vendore1_002_line_17_Via

Type	Name	Length (mil)
Horizontal Line	36	9.46
Horizontal Line	37	8.98
Horizontal Line	38	15.66
Horizontal Line	39	1.75
Horizontal Line	40	15.06
Horizontal Line	41	3.18
Horizontal Line	42	10.77
Horizontal Line	43	9.28
Horizontal Line	44	10.91
Horizontal Line	45	9.63
Horizontal Line	46	10.92
Horizontal Line	47	10.12
Horizontal Line	48	10.73
Horizontal Line	49	10.01
Horizontal Line	50	9.78
Horizontal Line	51	9.09
Horizontal Line	52	8.57
Horizontal Line	53	9.56
Horizontal Line	54	8.19
Horizontal Line	55	9.17
Horizontal Line	56	8.61
Horizontal Line	57	9.51
Horizontal Line	58	11.67
Horizontal Line	59	10.72



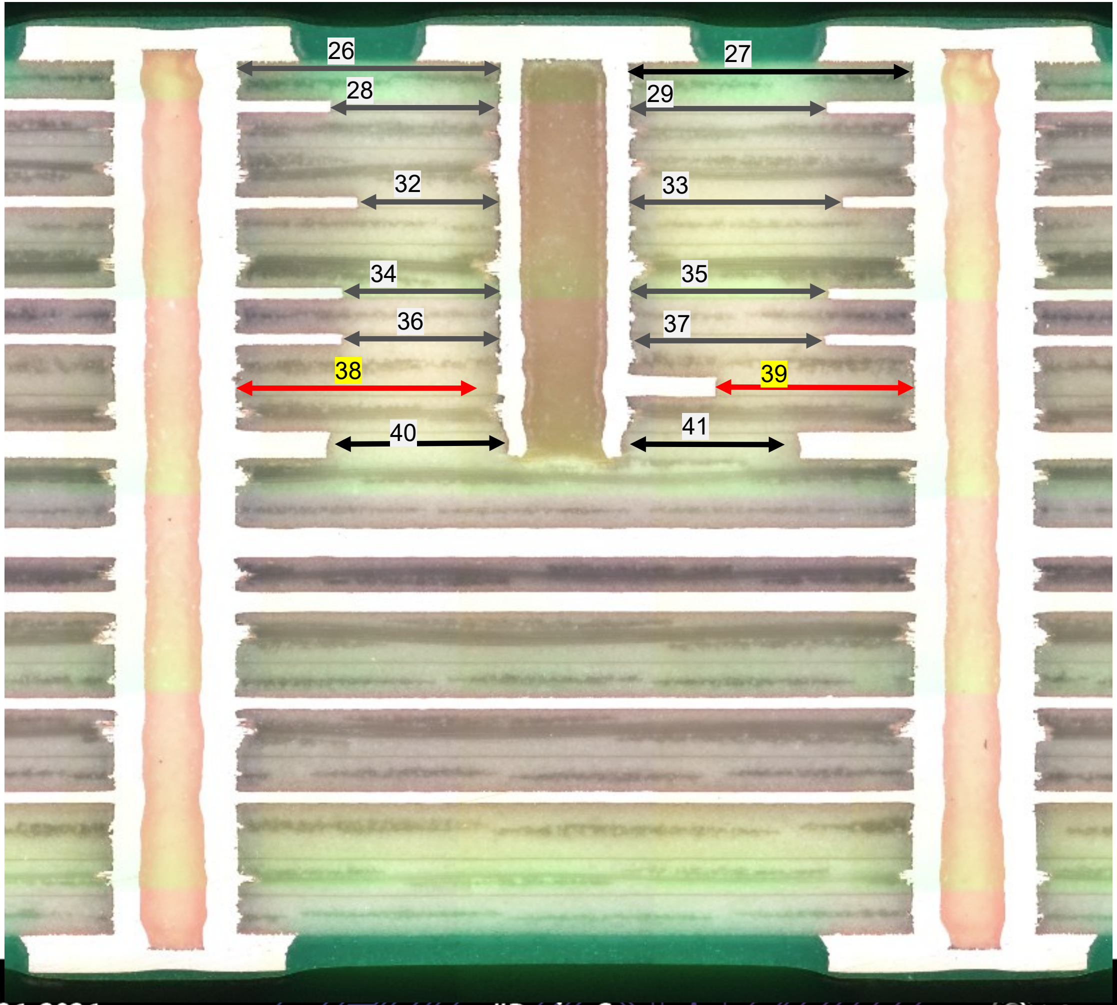
Vendore2_015_line_11_Via

Type	Name	Length [mil]
Horizontal Line	25	4.45
Horizontal Line	26	16.50
Horizontal Line	27	20.14
Horizontal Line	28	11.03
Horizontal Line	29	14.10
Horizontal Line	32	8.88
Horizontal Line	33	14.41
Horizontal Line	34	10.77
Horizontal Line	35	13.22
Horizontal Line	36	11.22
Horizontal Line	37	13.15
Horizontal Line	38	16.26
Horizontal Line	39	14.56
Horizontal Line	40	10.99
Horizontal Line	41	10.51



Vendore2_020_line_11_Via

Type	Name	Length [mil]
Horizontal Line	26	17.89
Horizontal Line	27	19.31
Horizontal Line	28	11.45
Horizontal Line	29	13.42
Horizontal Line	32	9.66
Horizontal Line	33	14.50
Horizontal Line	34	10.78
Horizontal Line	35	13.47
Horizontal Line	36	10.73
Horizontal Line	37	13.21
Horizontal Line	38	17.81
Horizontal Line	39	13.56
Horizontal Line	40	11.96
Horizontal Line	41	11.81



Vendore1_003_line_11_Via

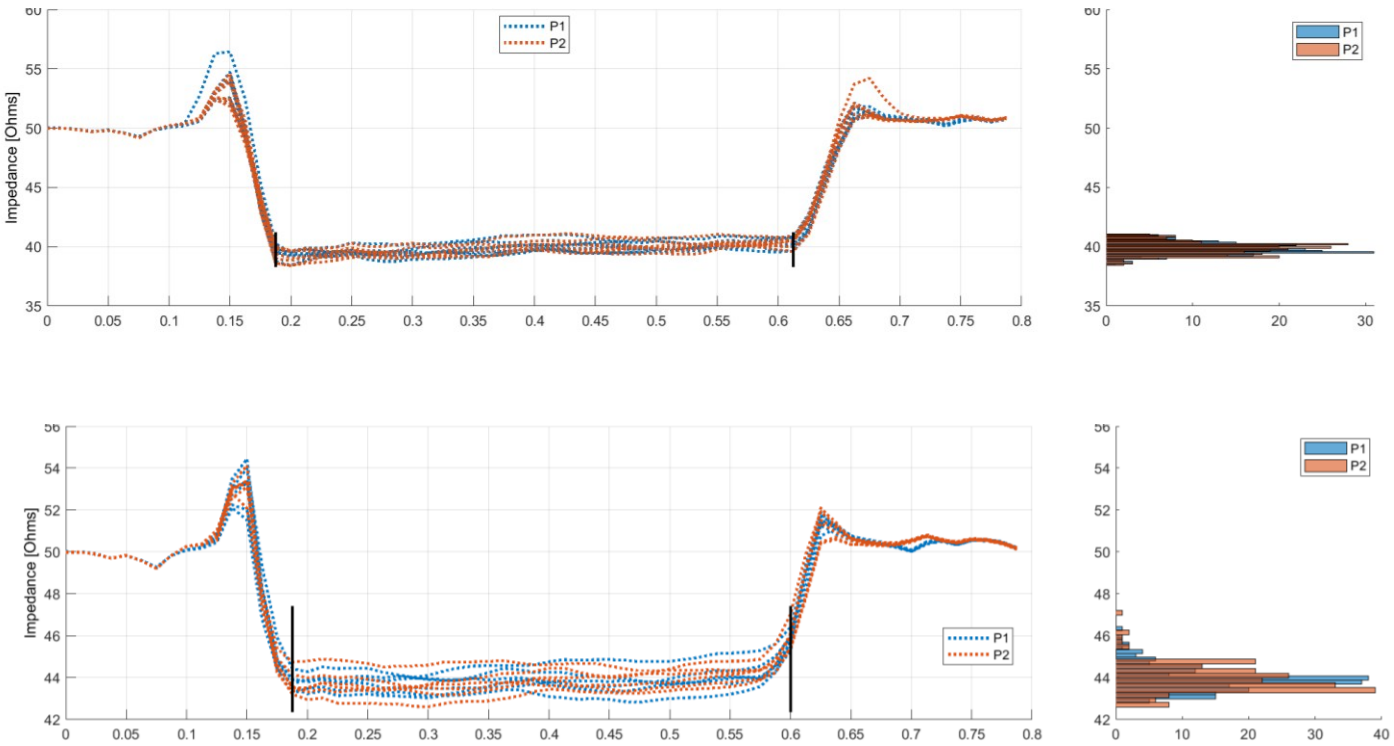
Type	Name 003	
Horizontal Line	26	14.71
Horizontal Line	27	20.86
Horizontal Line	28	13.91
Horizontal Line	29	11.01
Horizontal Line	30	14.86
Horizontal Line	33	10.56
Horizontal Line	34	9.71
Horizontal Line	35	14.31
Horizontal Line	36	9.61
Horizontal Line	37	14.46
Horizontal Line	38	10.46
Horizontal Line	39	12.96
Horizontal Line	40	7.96
Horizontal Line	41	7.86

Vendore1_002_line_11_Via

Type	Name 002	
Horizontal Line	26	19.64
Horizontal Line	27	17.64
Horizontal Line	28	13.63
Horizontal Line	29	12.51
Horizontal Line	32	19.26
Horizontal Line	33	5.13
Horizontal Line	34	19.39
Horizontal Line	35	6.88
Horizontal Line	36	19.26
Horizontal Line	37	7.00
Horizontal Line	38	5.00
Horizontal Line	39	17.26
Horizontal Line	40	8.26
Horizontal Line	41	8.01

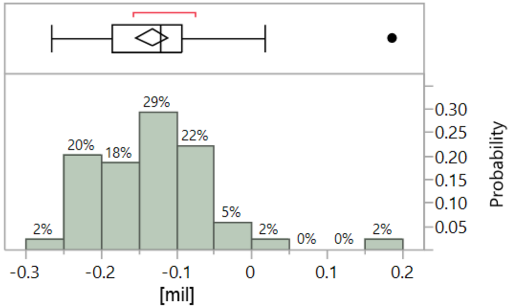
VIA OFFSET

Predictable Transmission Lines

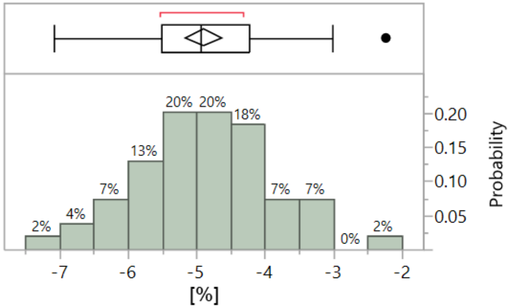


Manufacturing Variation Modeling

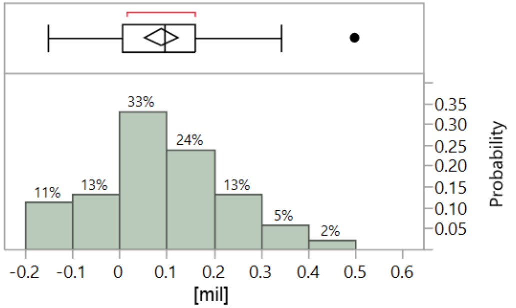
Top Gnd Thickness



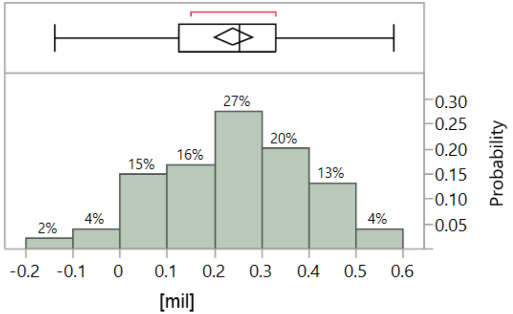
Top Dielectric Height



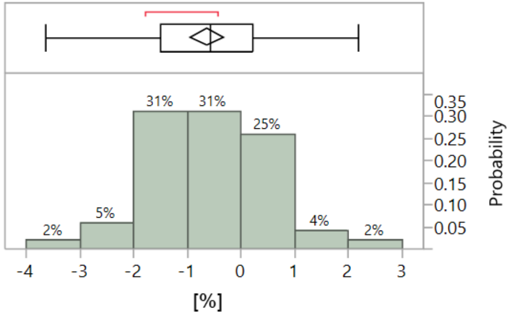
Signal Trace Width



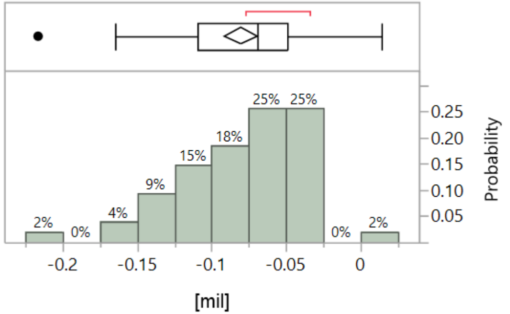
Bottom Gnd Thickness



Bottom Dielectric Height

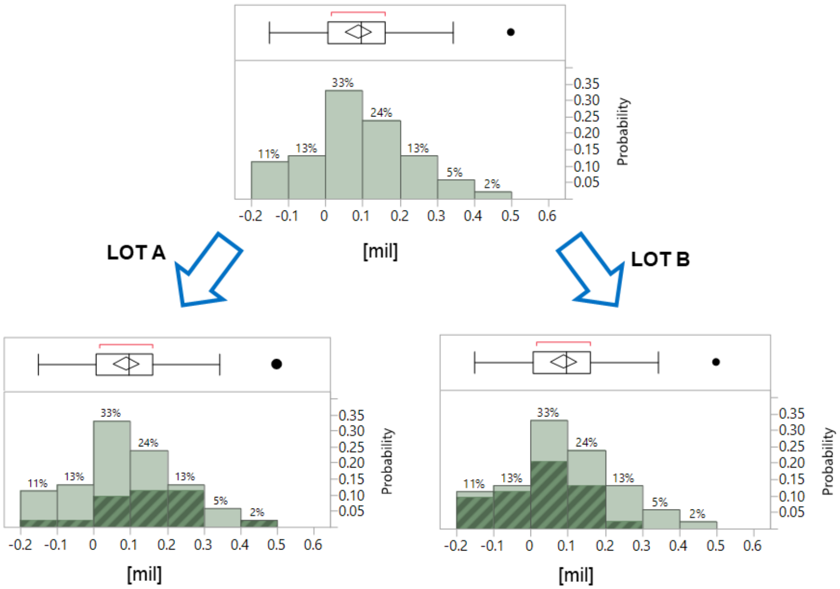


Signal Trace Thickness

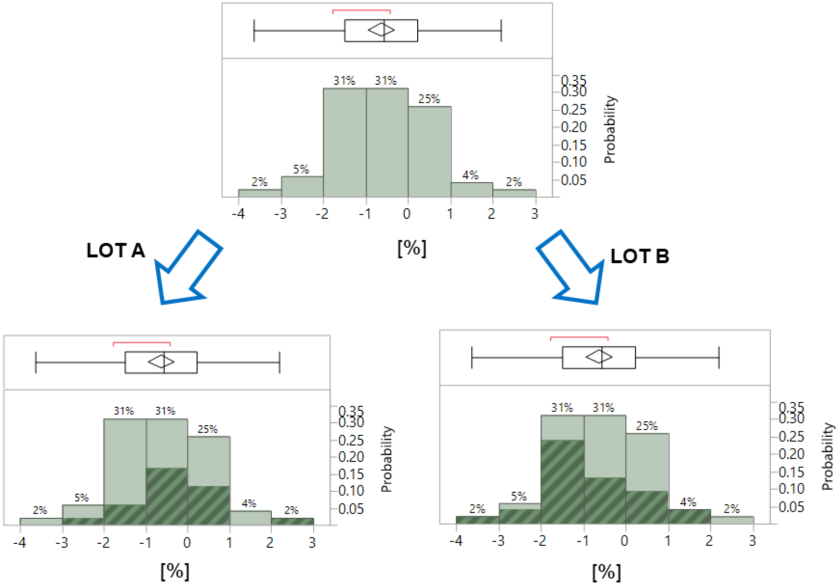


Manufacturing Variation: Lot A vs. Lot B

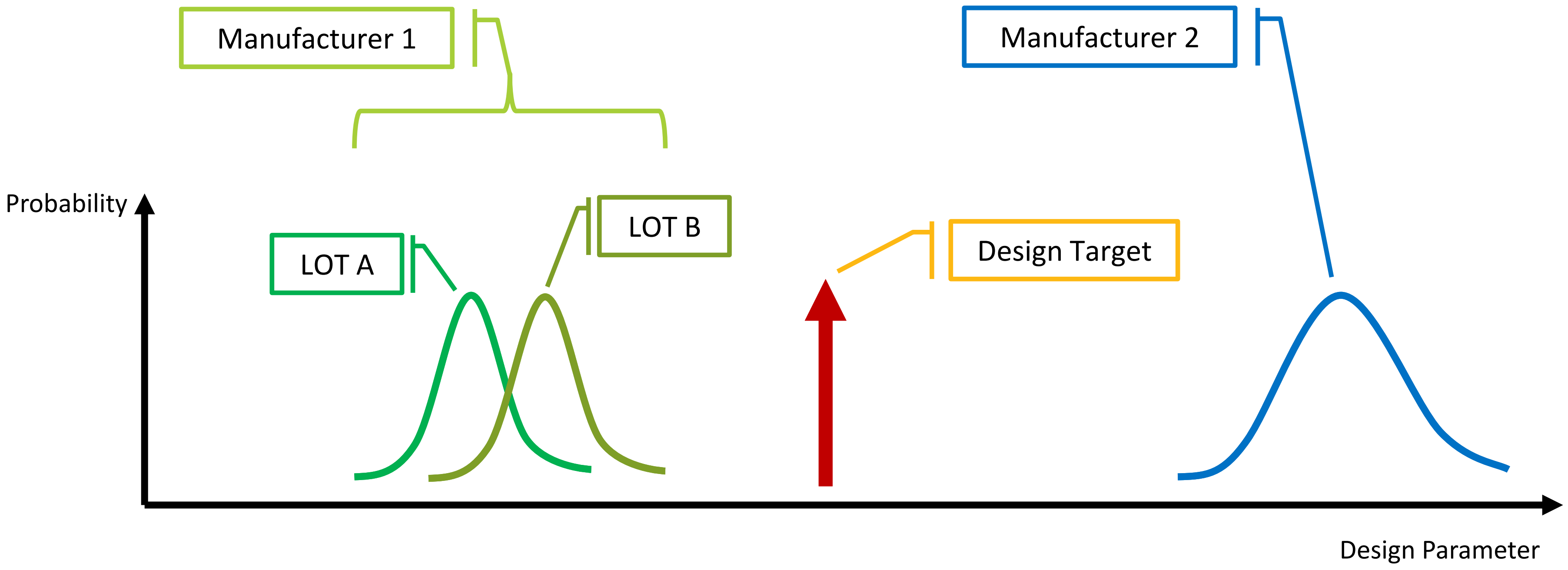
Signal Trace Width



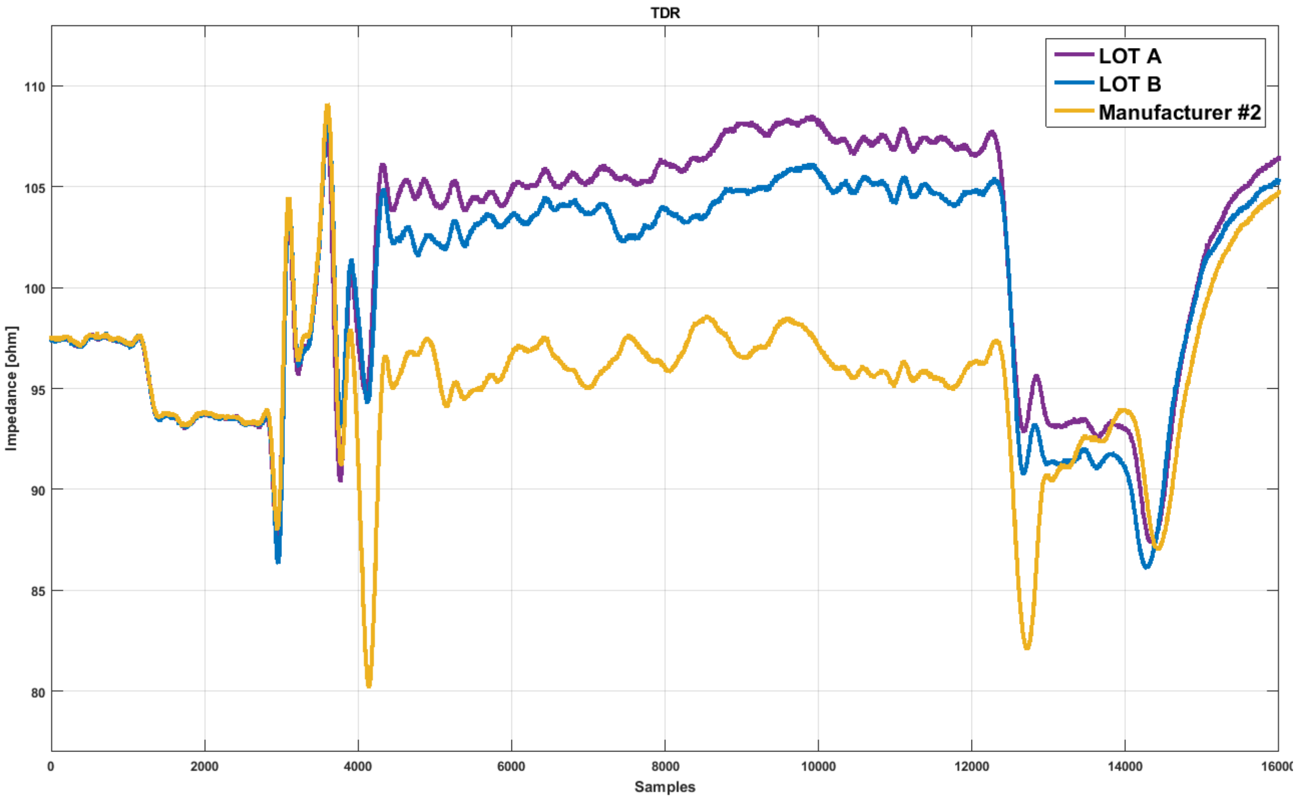
Bottom Dielectric Height



Manufacturing Variation



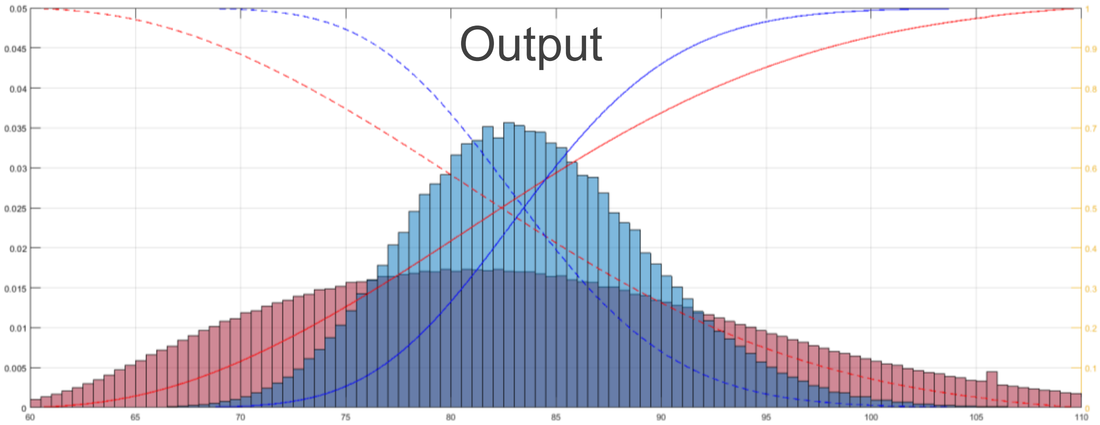
Manufacturing Variation Impact on Design

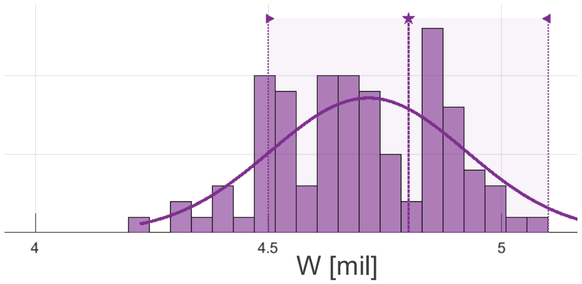


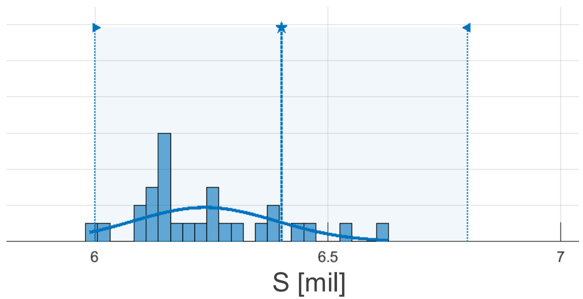
Statistical Approach

- Measure 10 Coupons Transmission line parameters (W,H,T,Dk,Df,etc.)
- Build a statistical probability model of each input (STD, mean ,Variance)
- Generate full factorial DOE table
- Since the various input values possess distinct probabilities of occurrence, the output is weighted based on the overall likelihood of the scenario.
- ApplySame Method as the good old Jitter and BER analysis

Example: Input Value distributions for two parameters







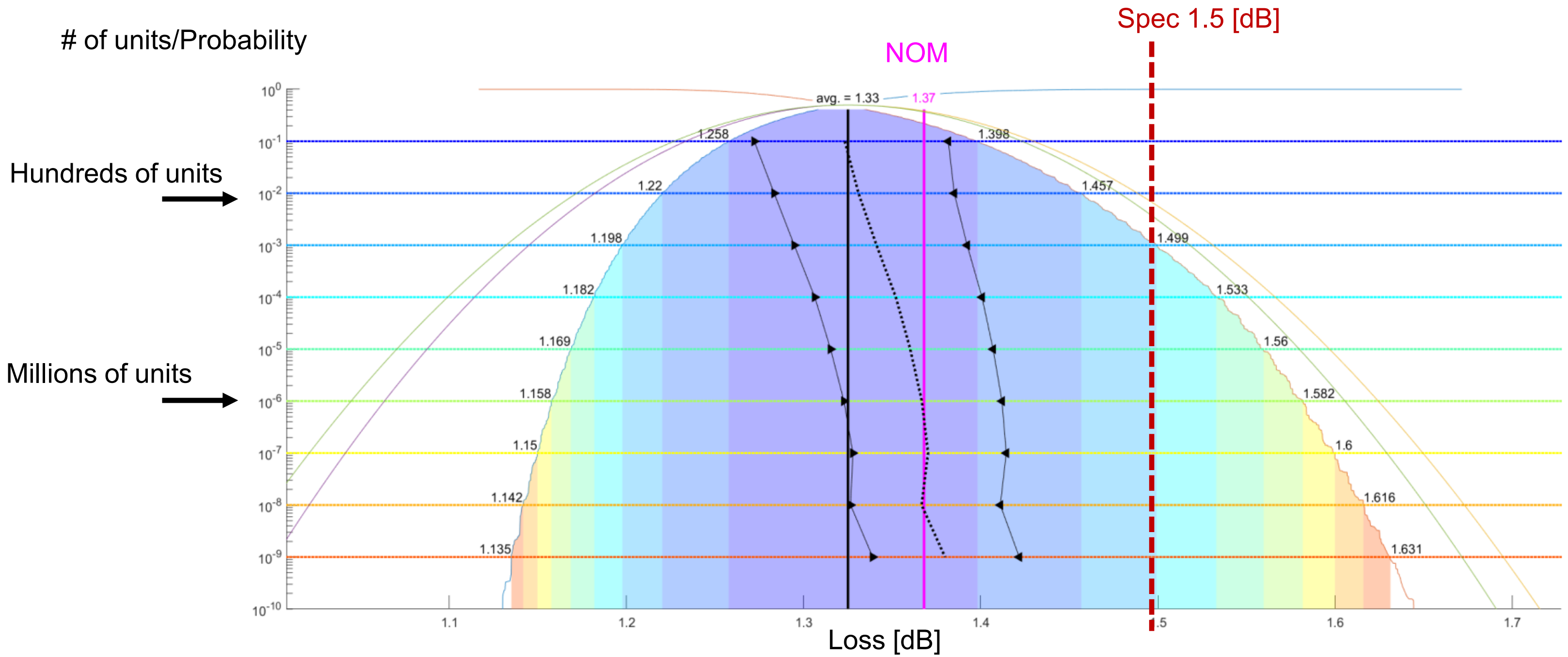
- The Blue Plot is weighted by input combination probability, while the Red Plot is unweighted
- The lines are CDF
    - Dashed –left side CDF
    - Solid –right side CDF

Example: Transmission Line Properties

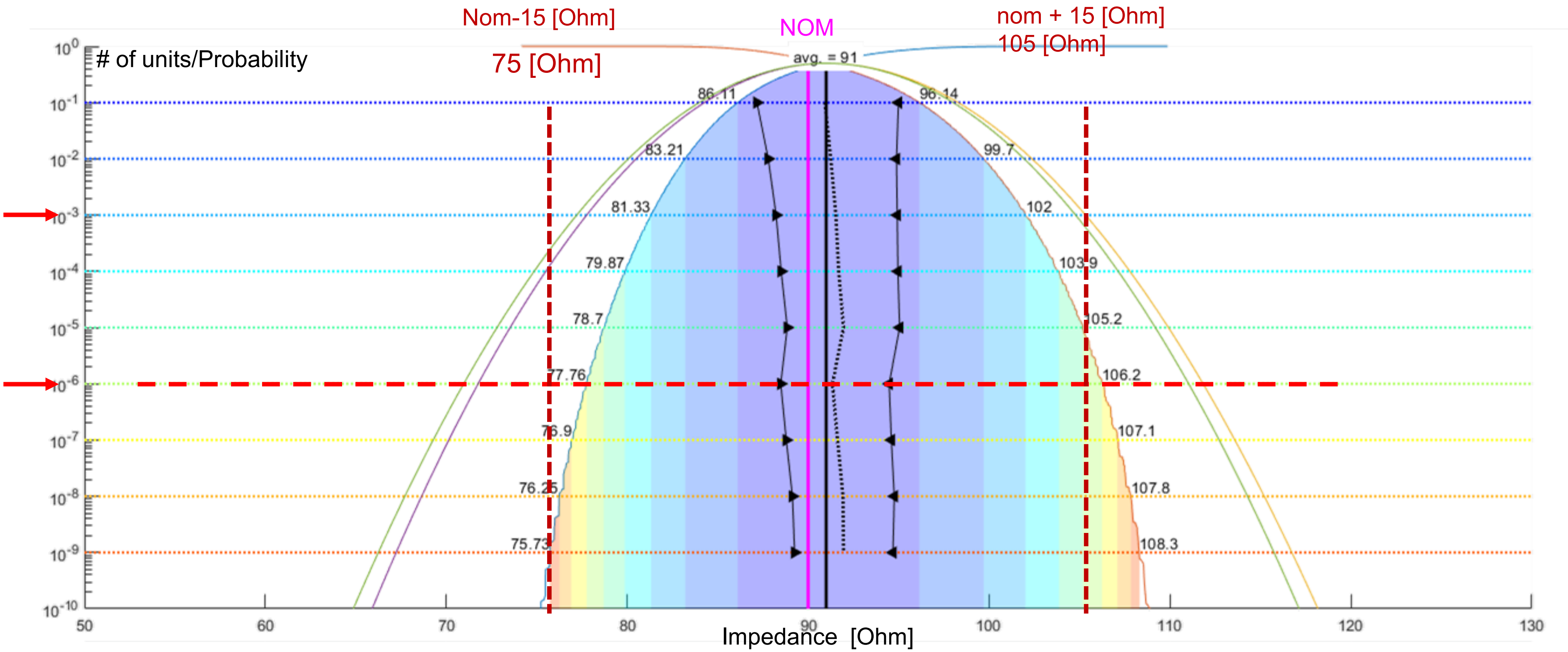
Expected Variation

– Dielectric Height	**-/+20%**
– TW	**-/+4um**
– Copper thickness	**-/+30%**
– Dk **-**	**/+5%**
– Df	**-/+5%**

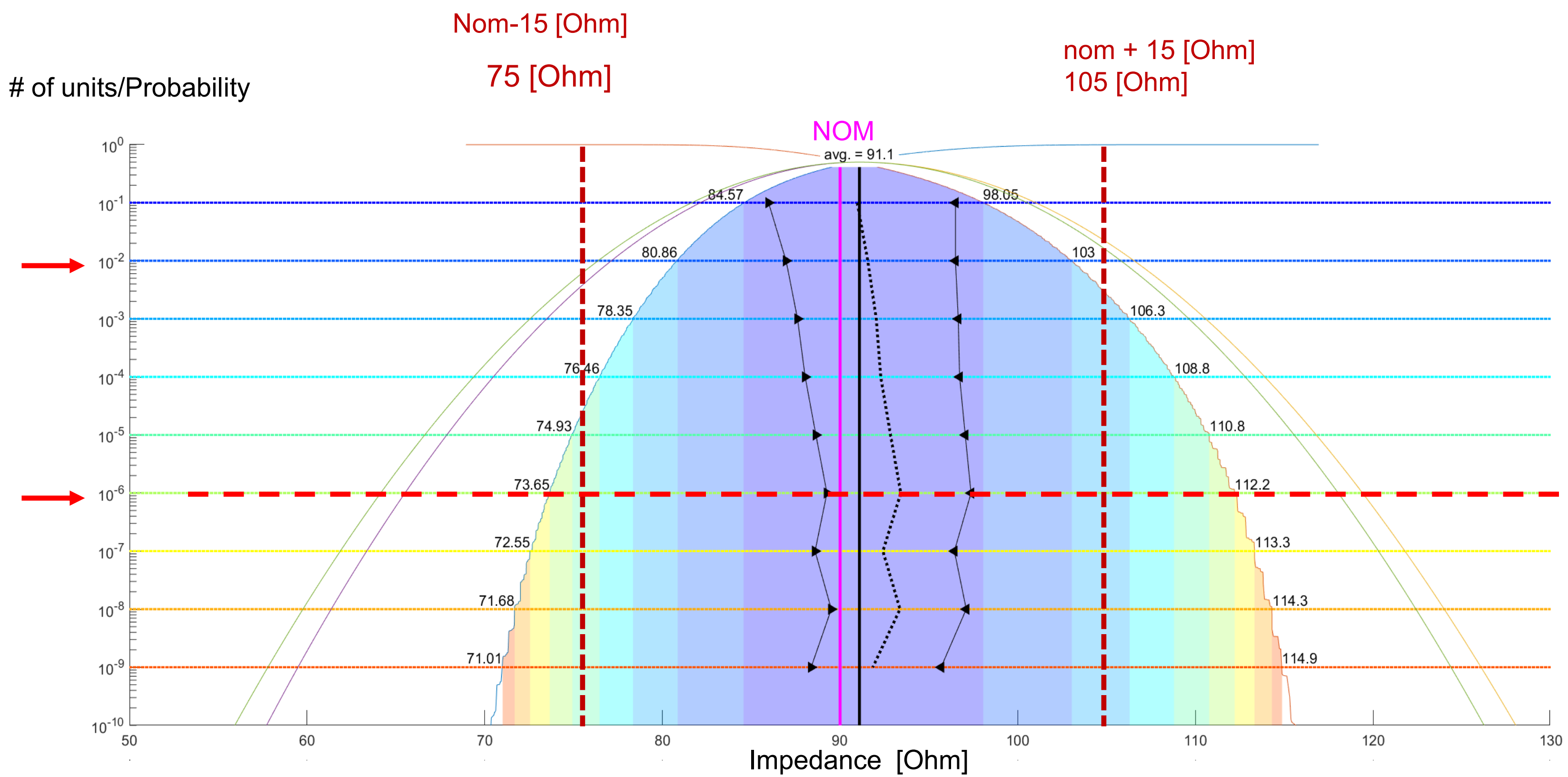
Total Loss probability – Reverse Bathtub



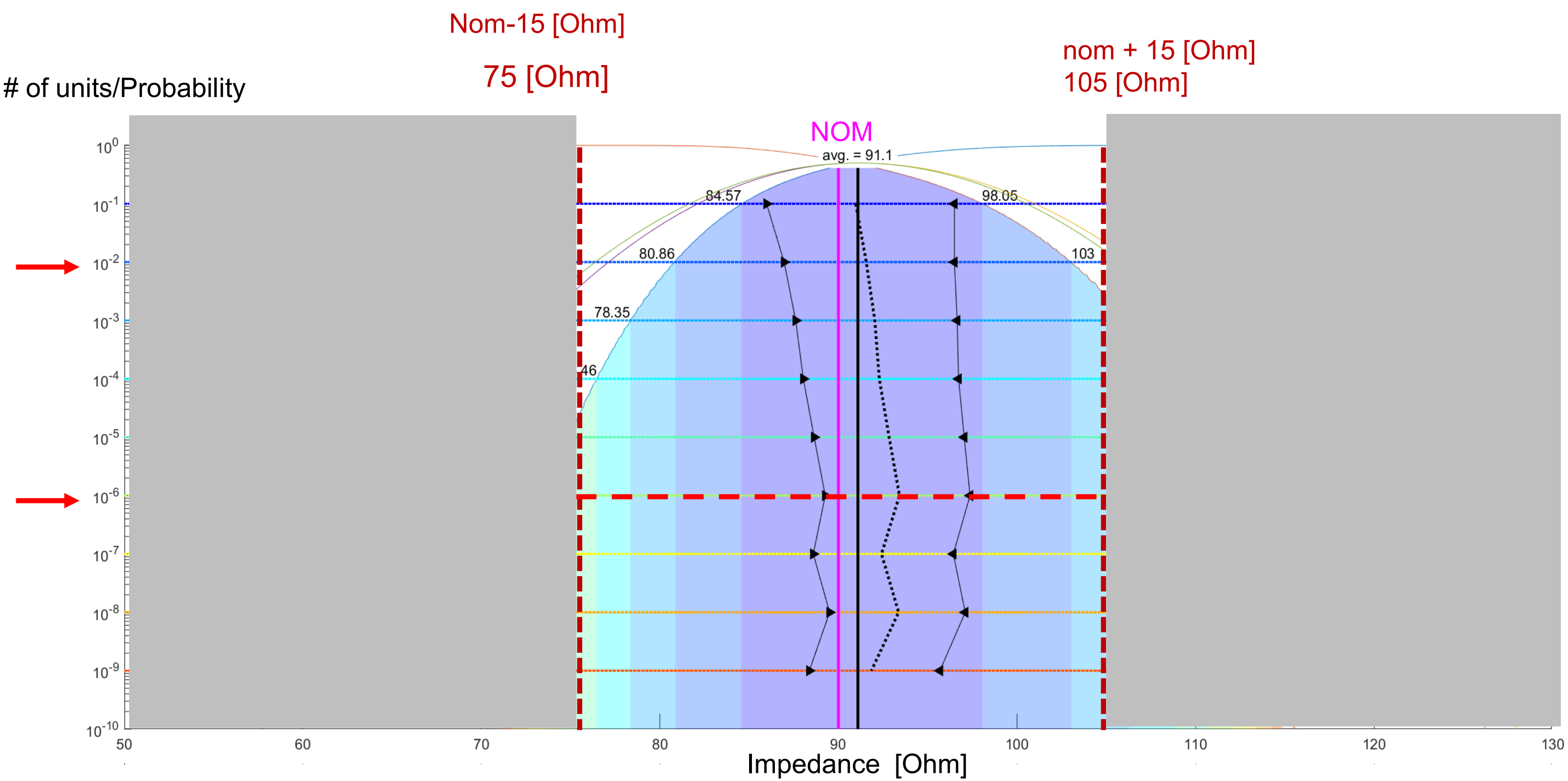
Impedance probability – Reverse Bathtub



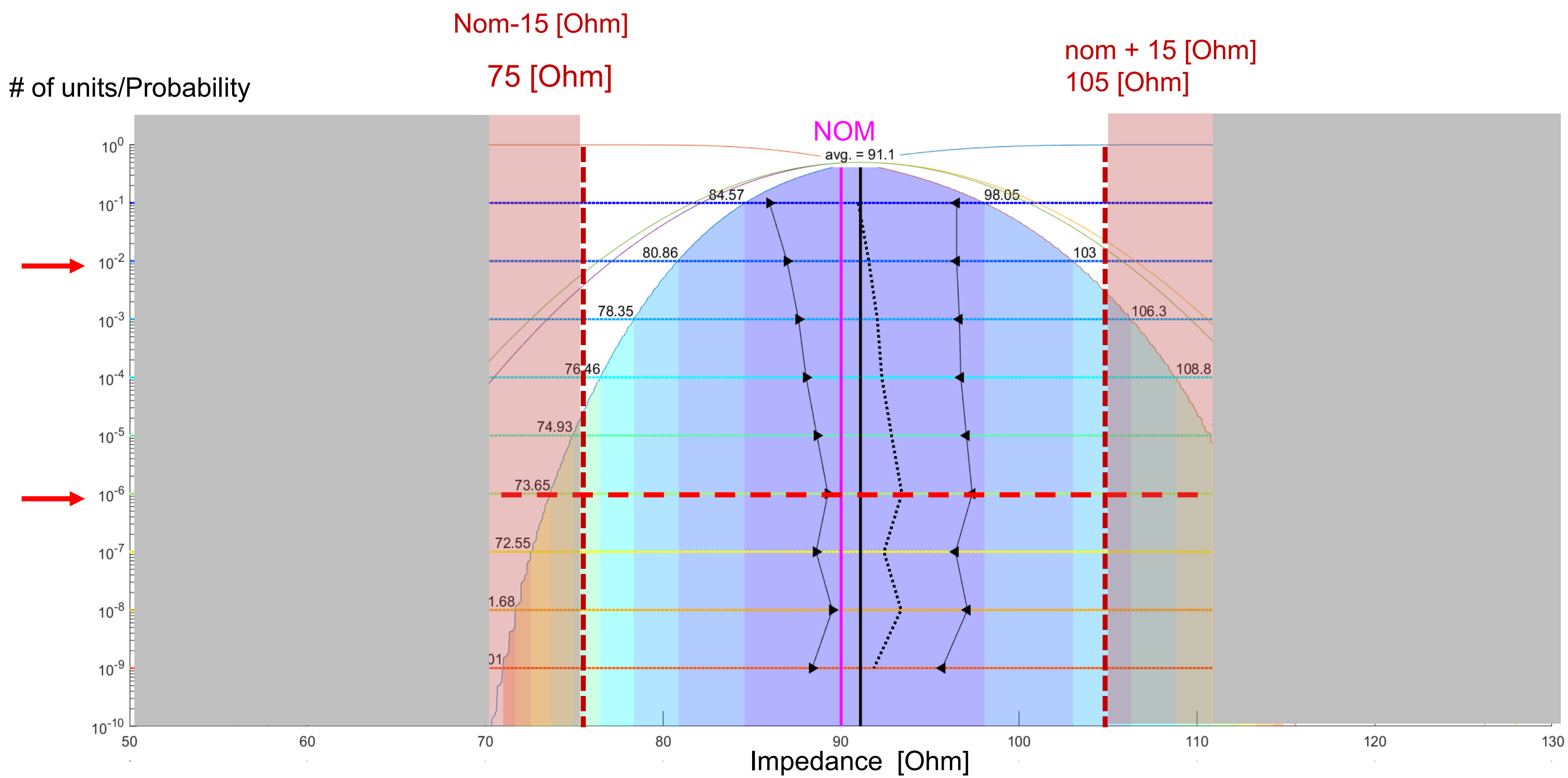
Impedance probability –Why do we care



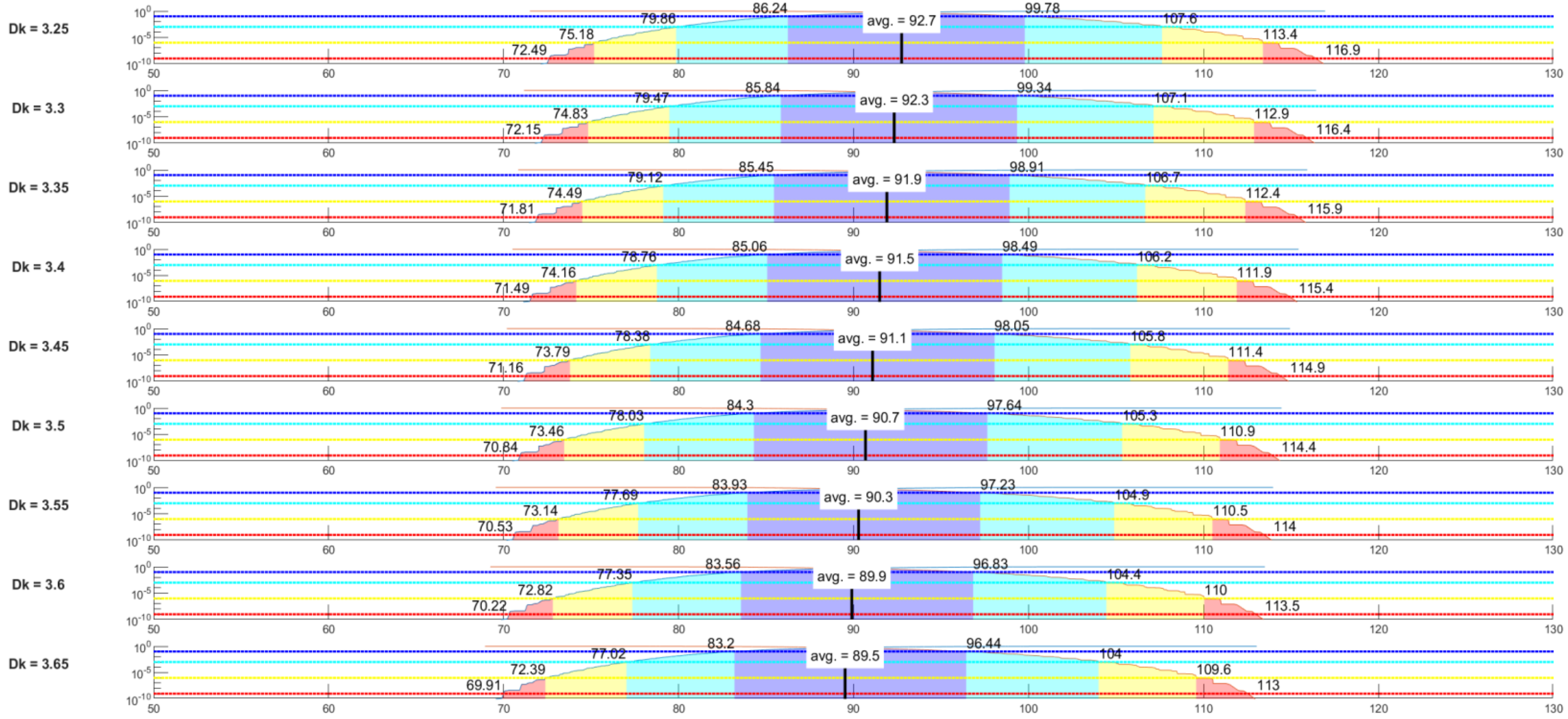
Impedance probability –Vendor screening



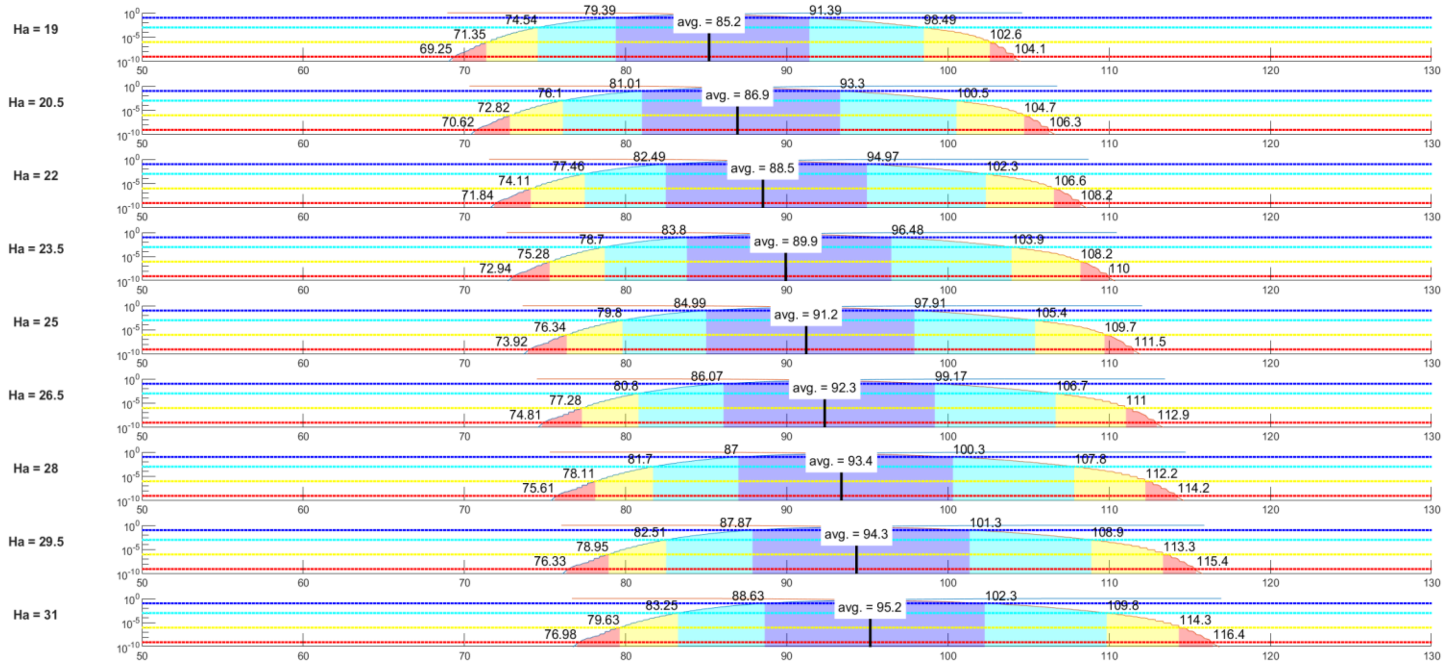
Vendor screening – Variation within same unit



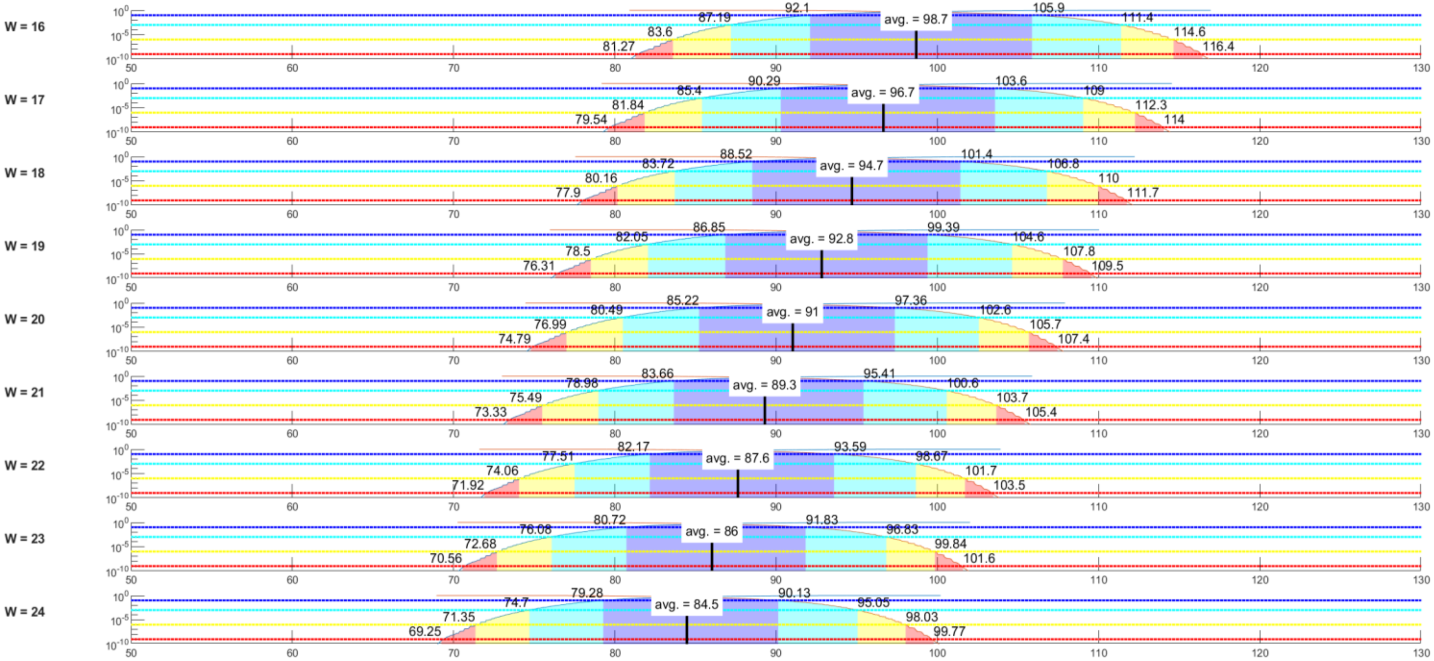
Dk Impact on Impedance Variation



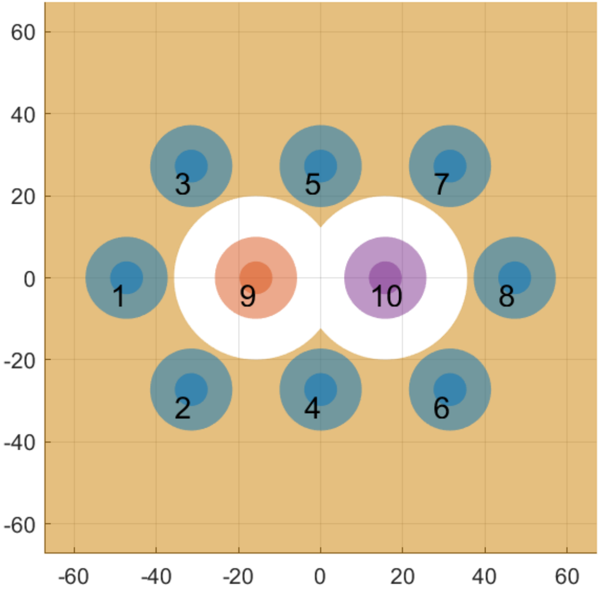
Dielectric Hieght Impact on Impedance Variation

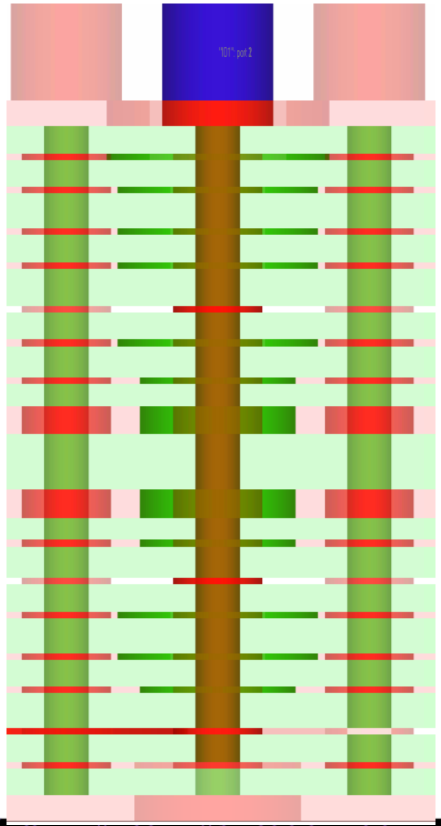


Trace widt Impact on Impedance Variation

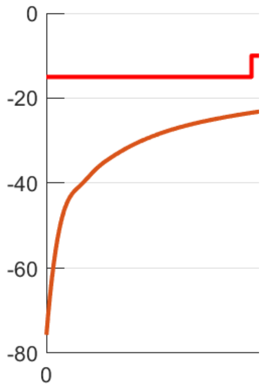


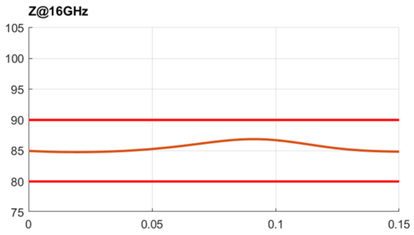
Via Design for 448 Gbs

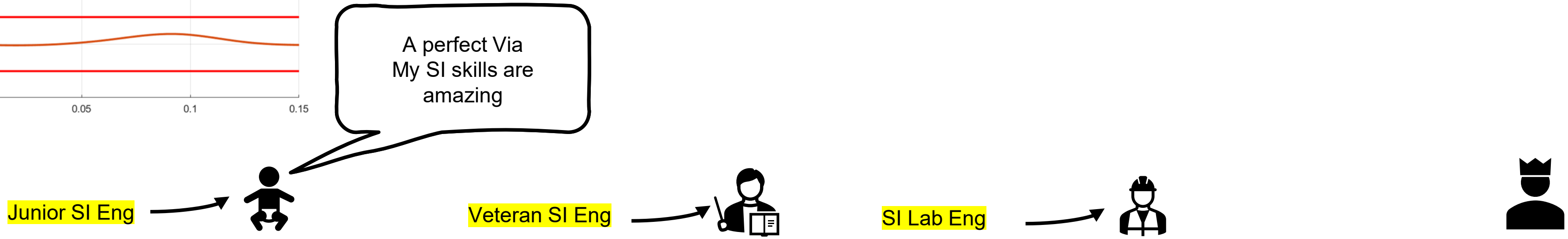




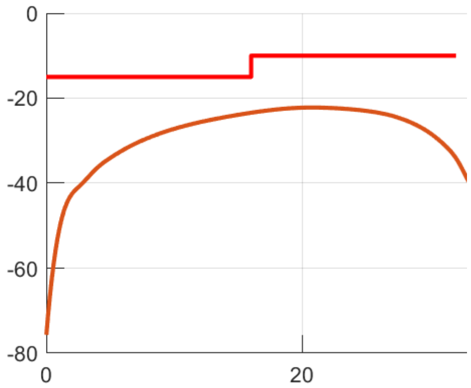
Frequency BW and Via optimization

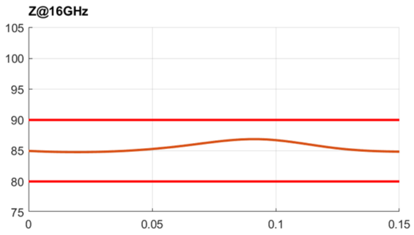


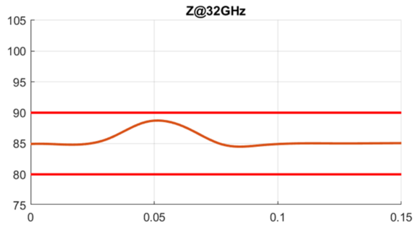




Frequency BW and Via optimization





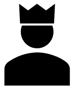


Not so perfect

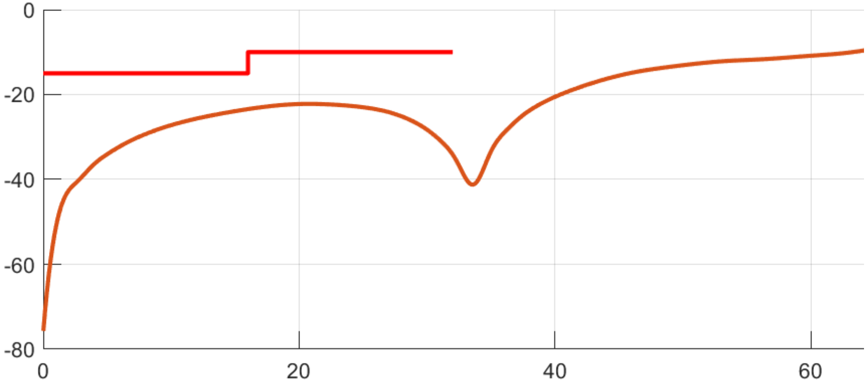
Junior SI Eng

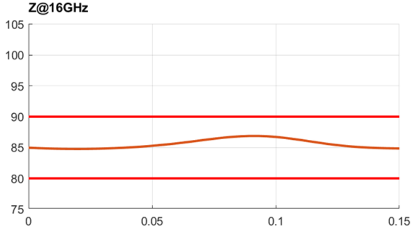
Veteran SI Eng

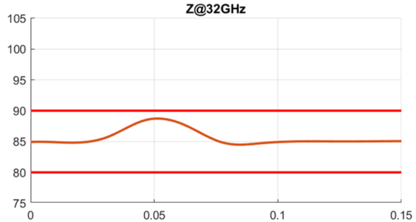
SI Lab Eng

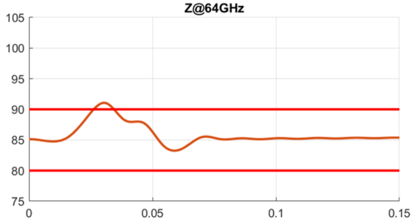


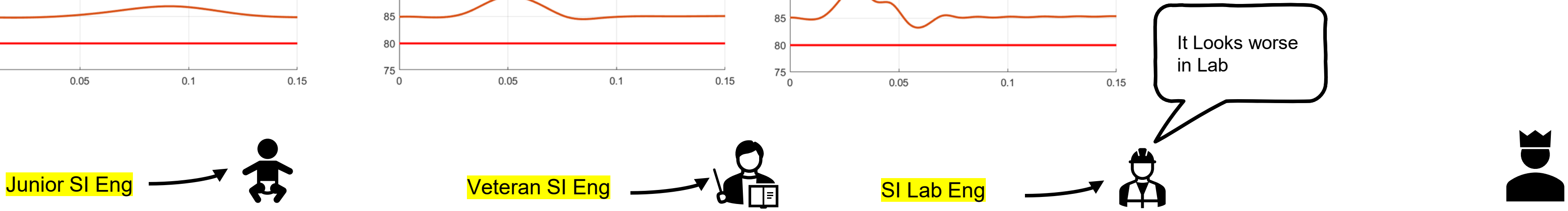
Frequency BW and Via optimization



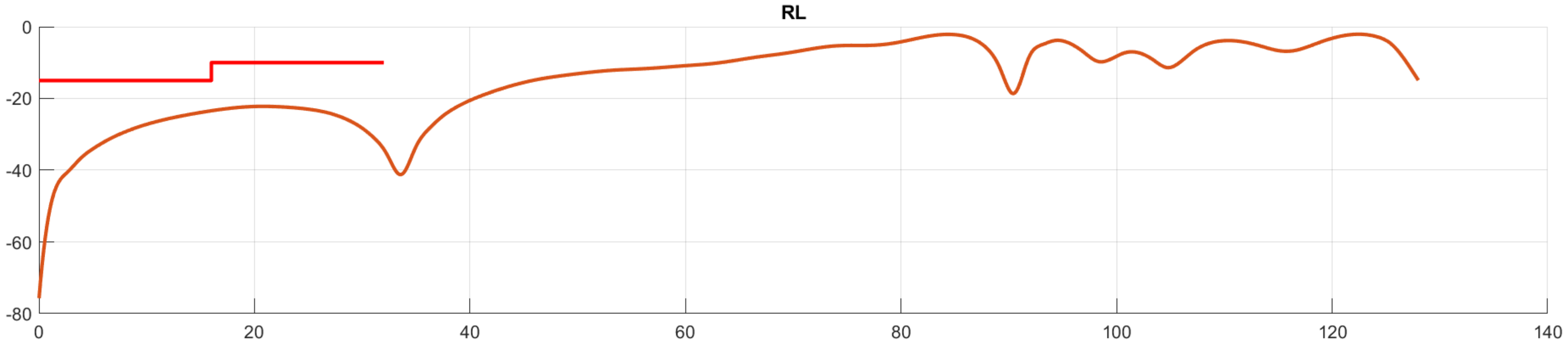


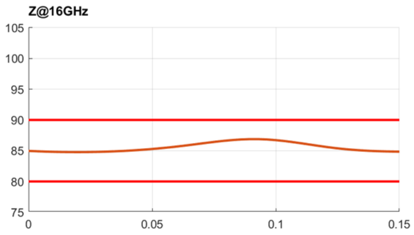


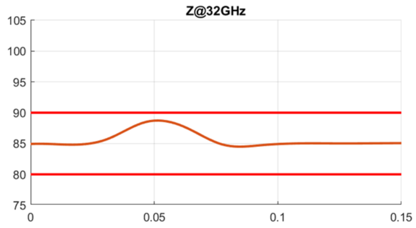


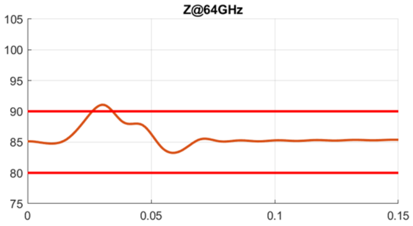


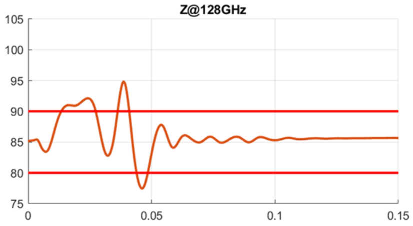
Frequency BW and Via optimization











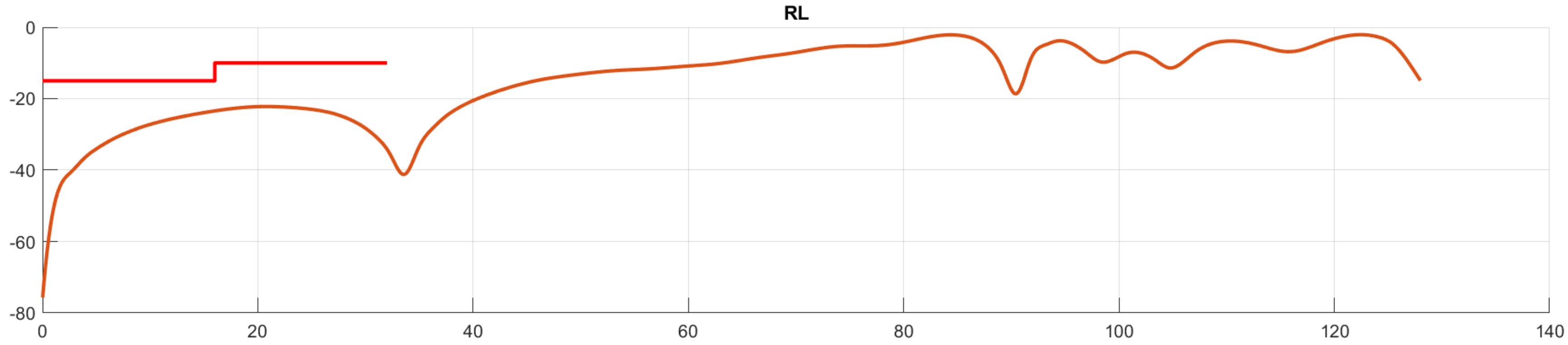
Junior SI Eng

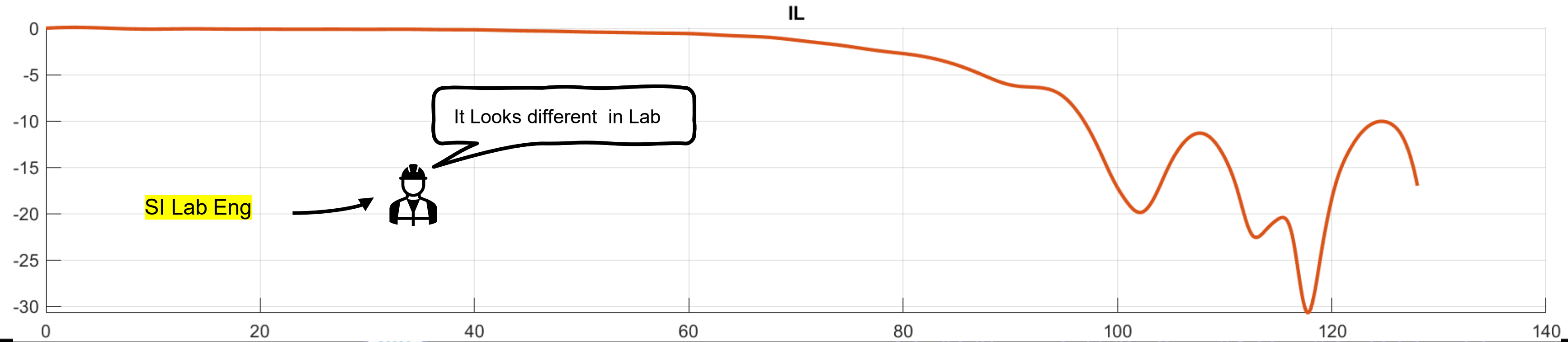
Veteran SI Eng

SI Lab Eng

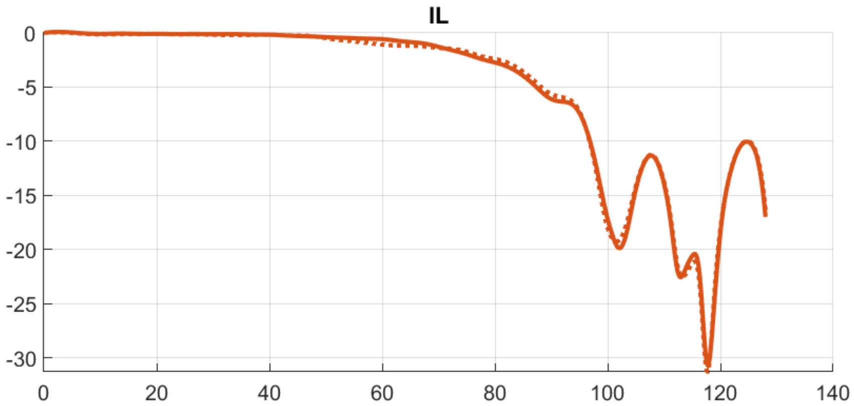
It Is a Disaster

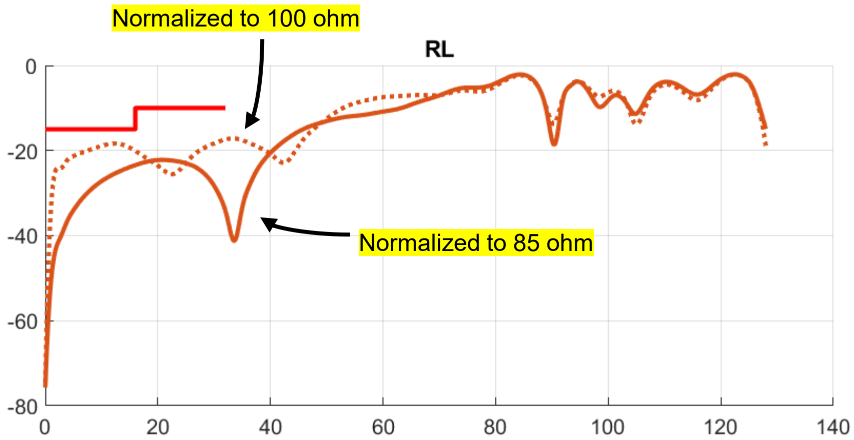
Nominal Case



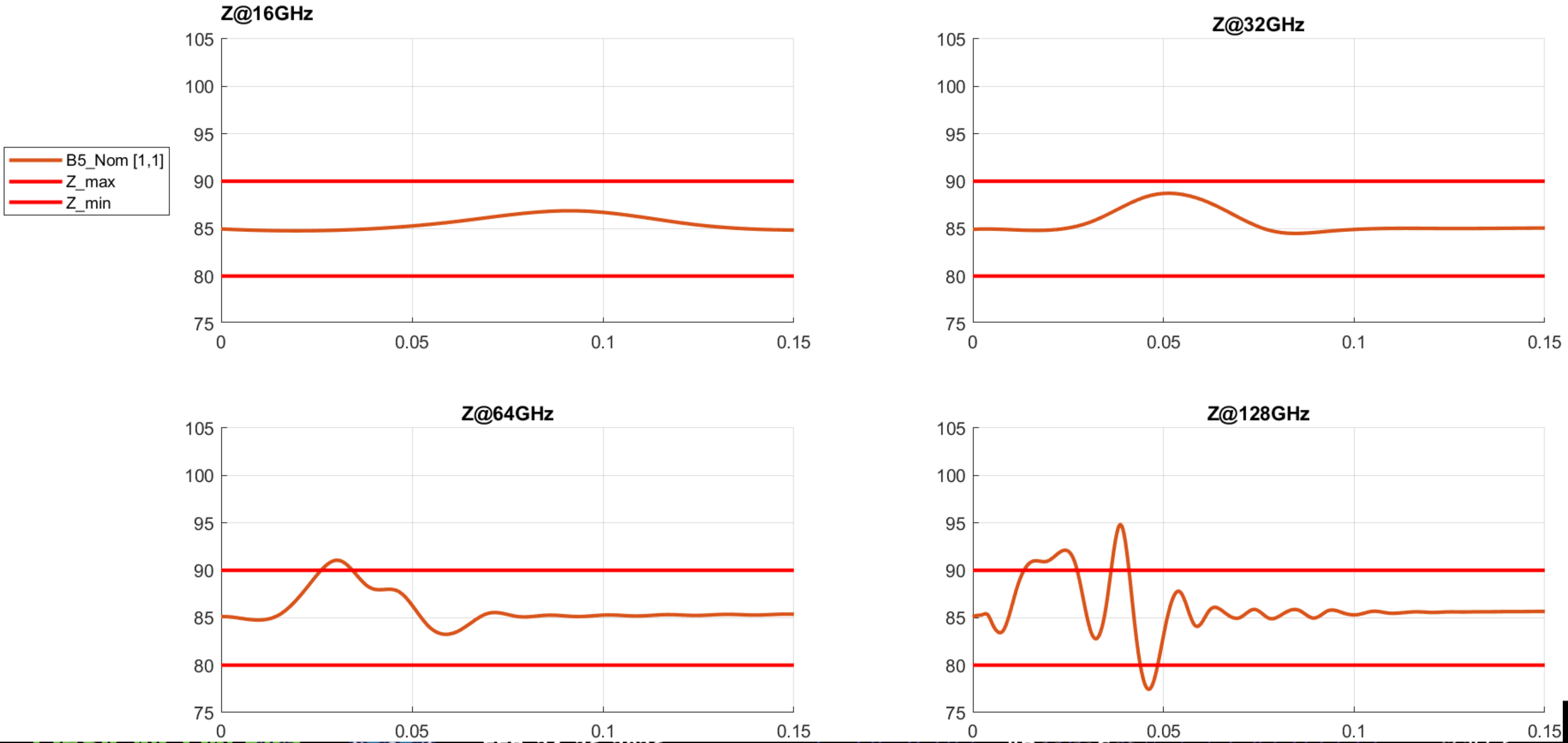


Is reference impedance Important ?

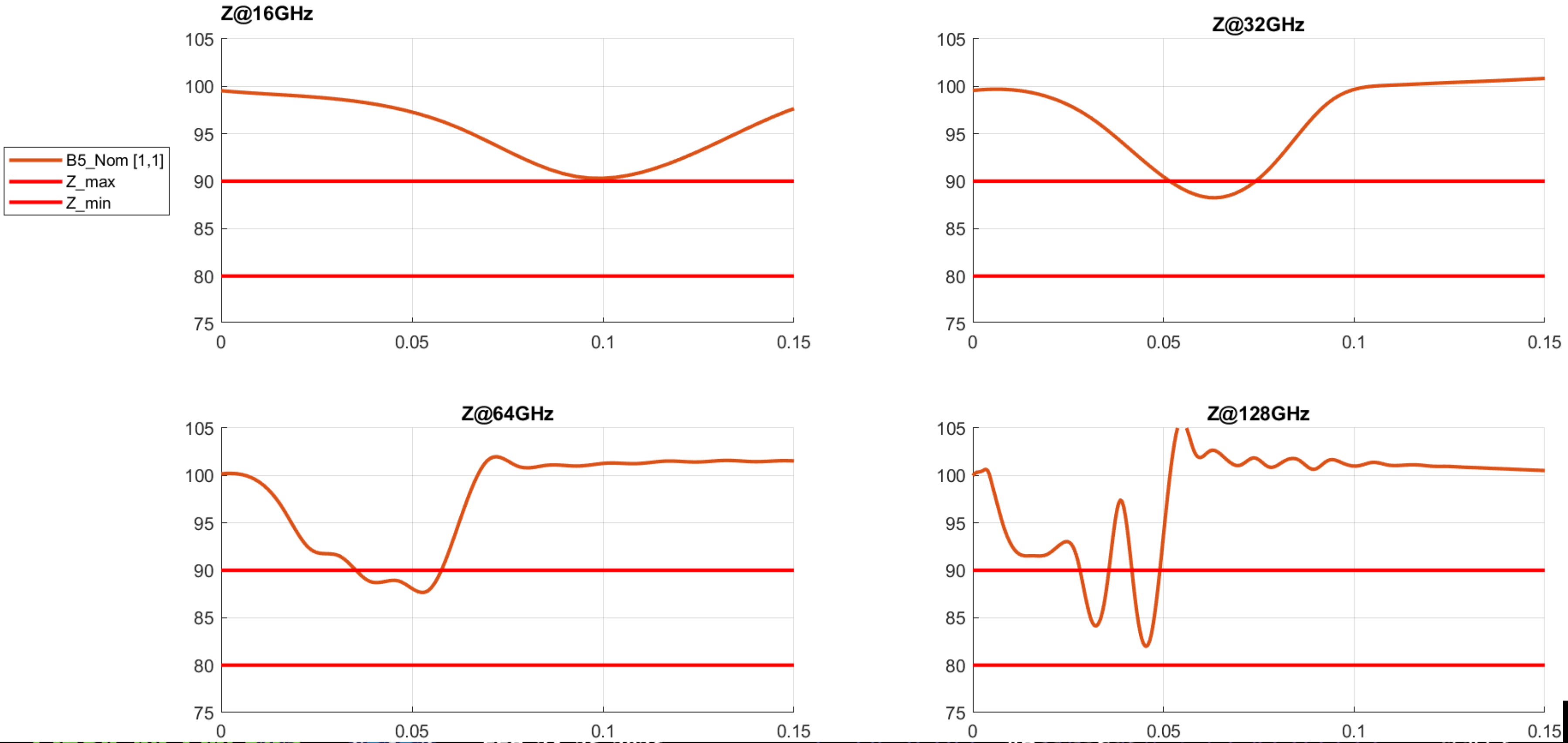




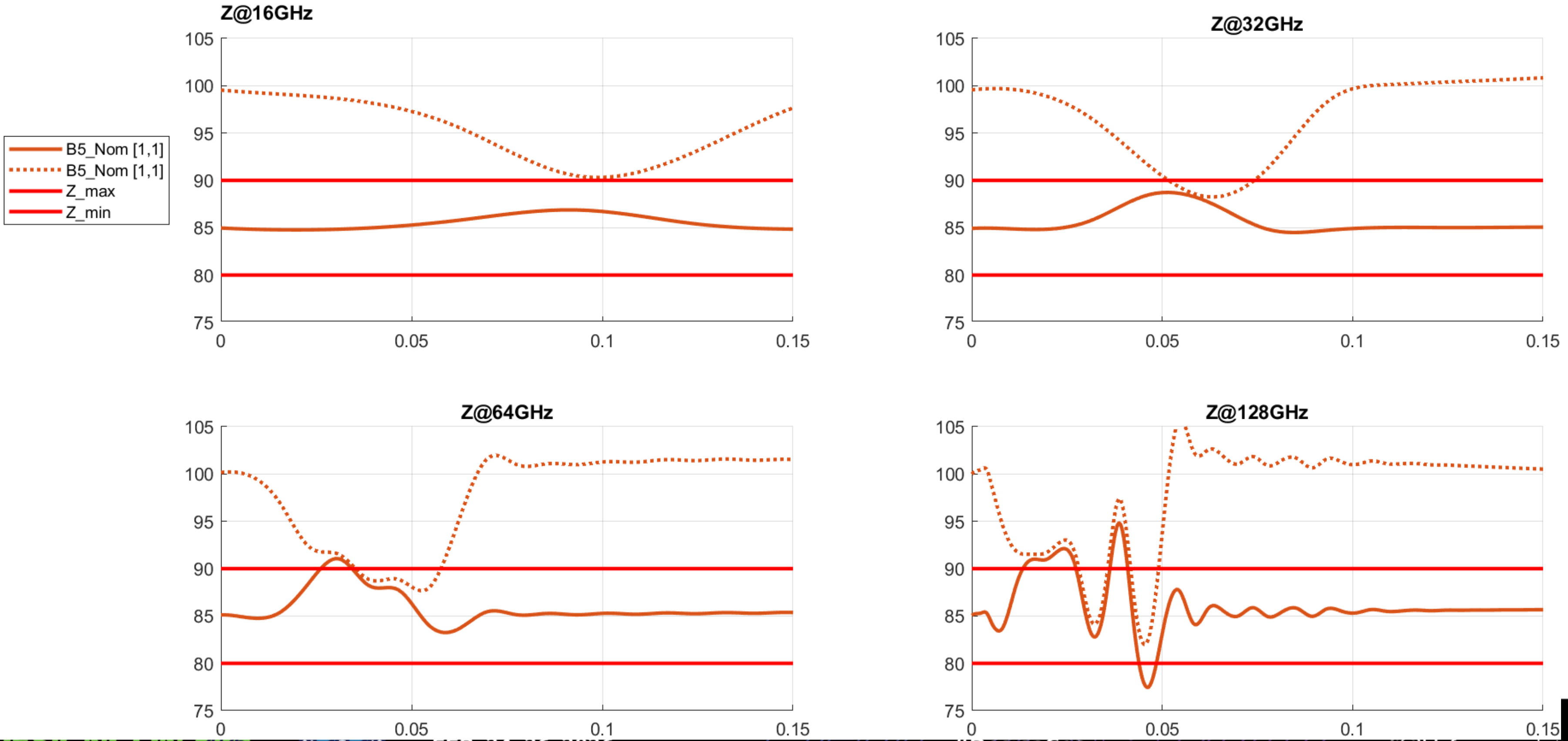
TDR reference impedance 85 Ohms



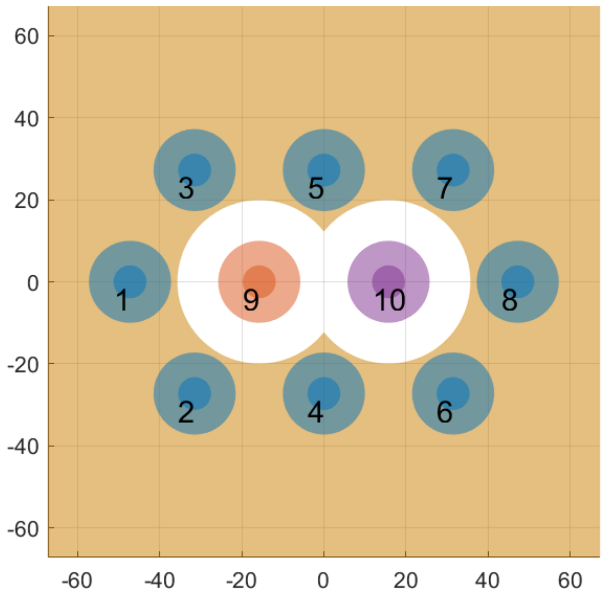
TDR reference impedance 100 Ohms

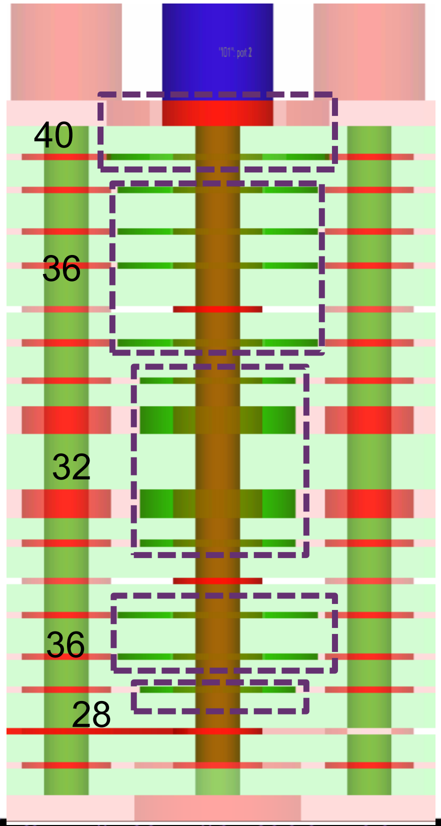


TDR reference impedance 85 and 100 Ohm

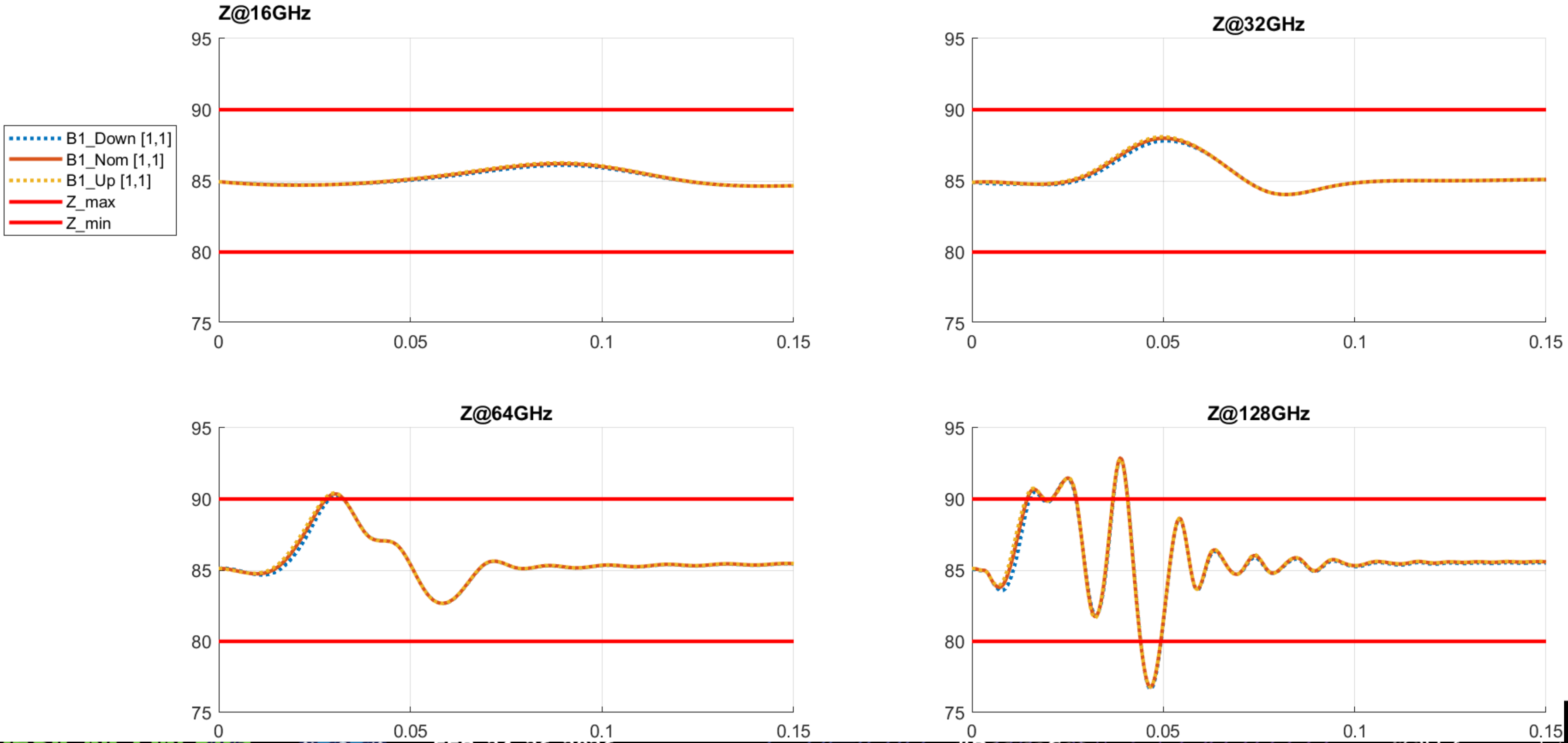


BGA Via Sensitivity Check

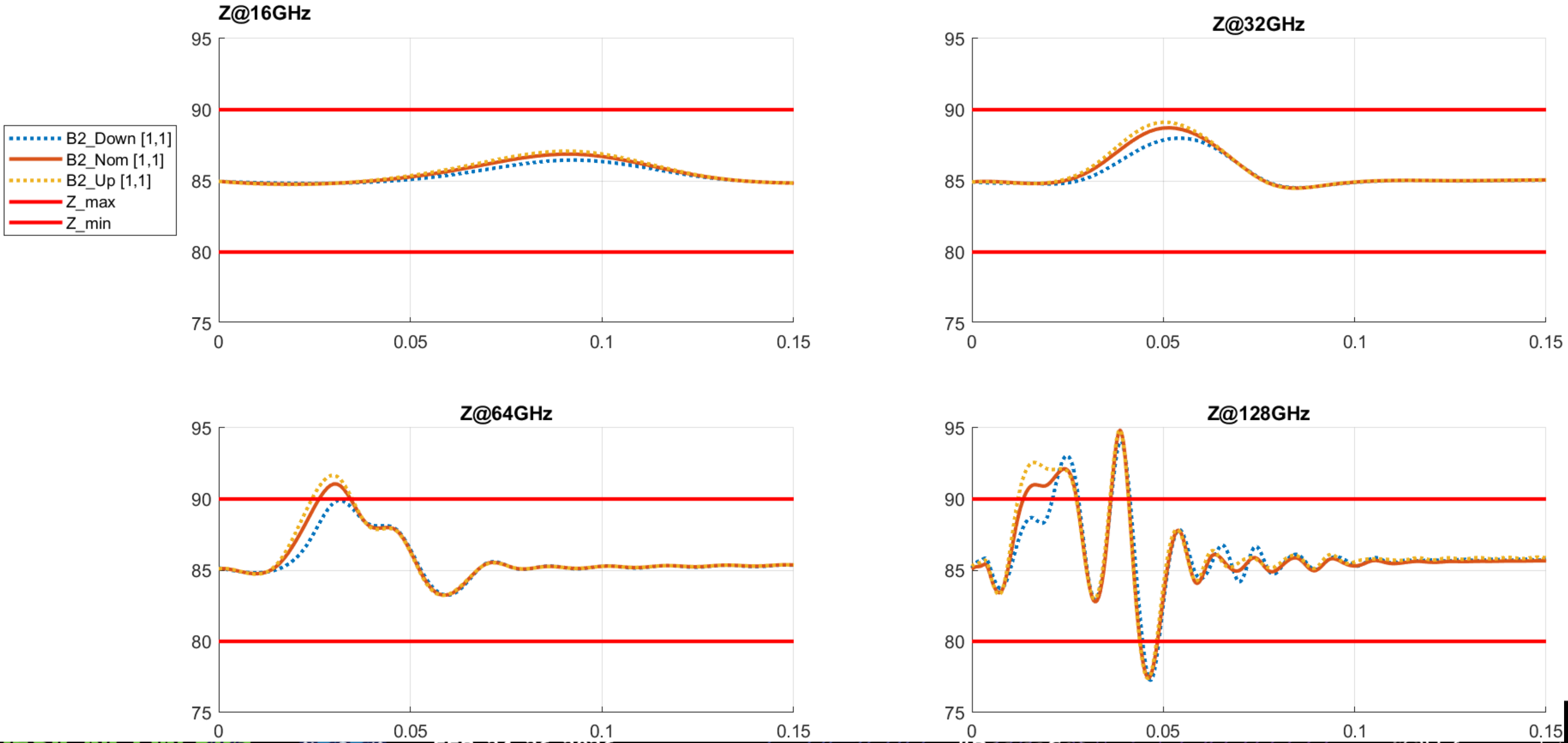




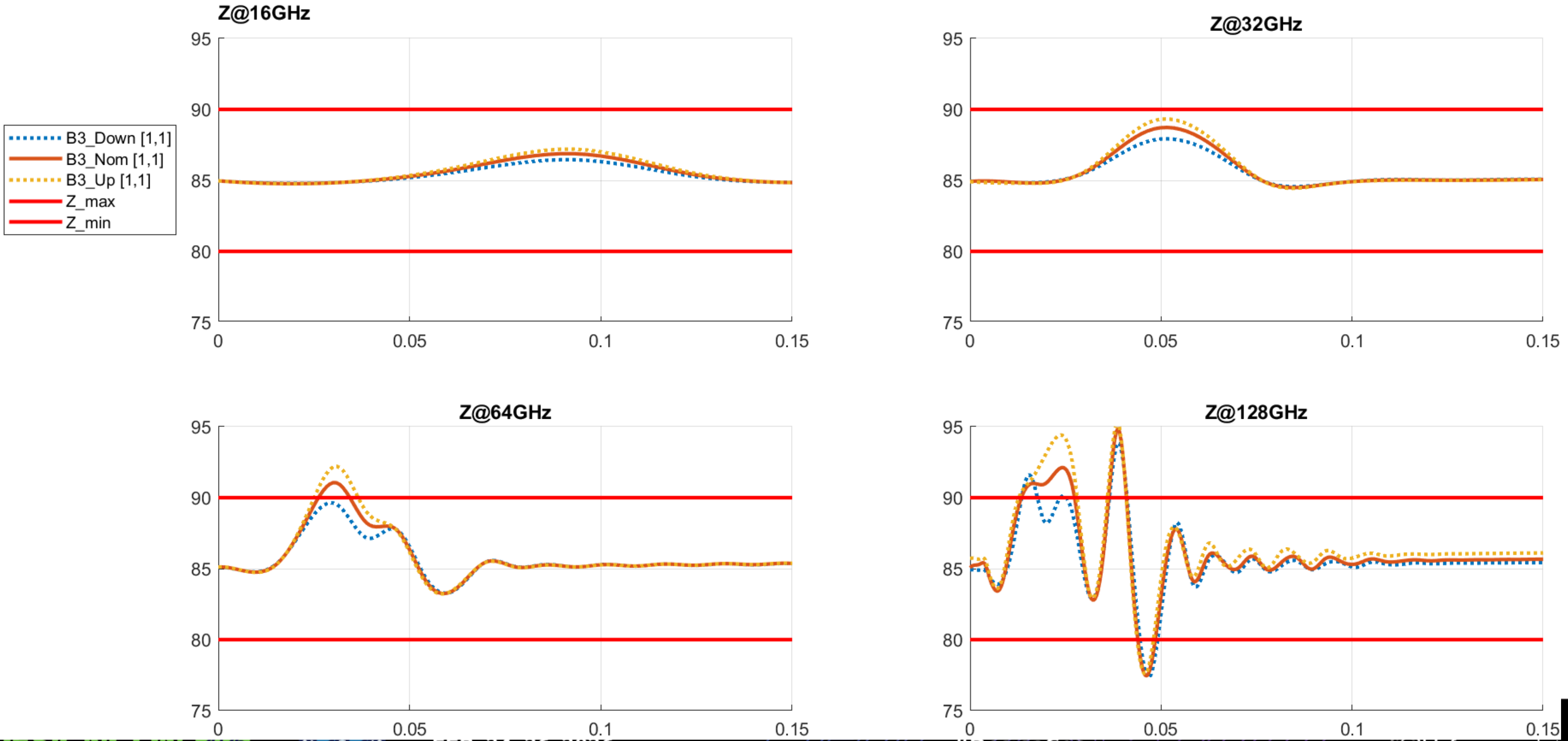
Block 1 (L1,L2) = 32



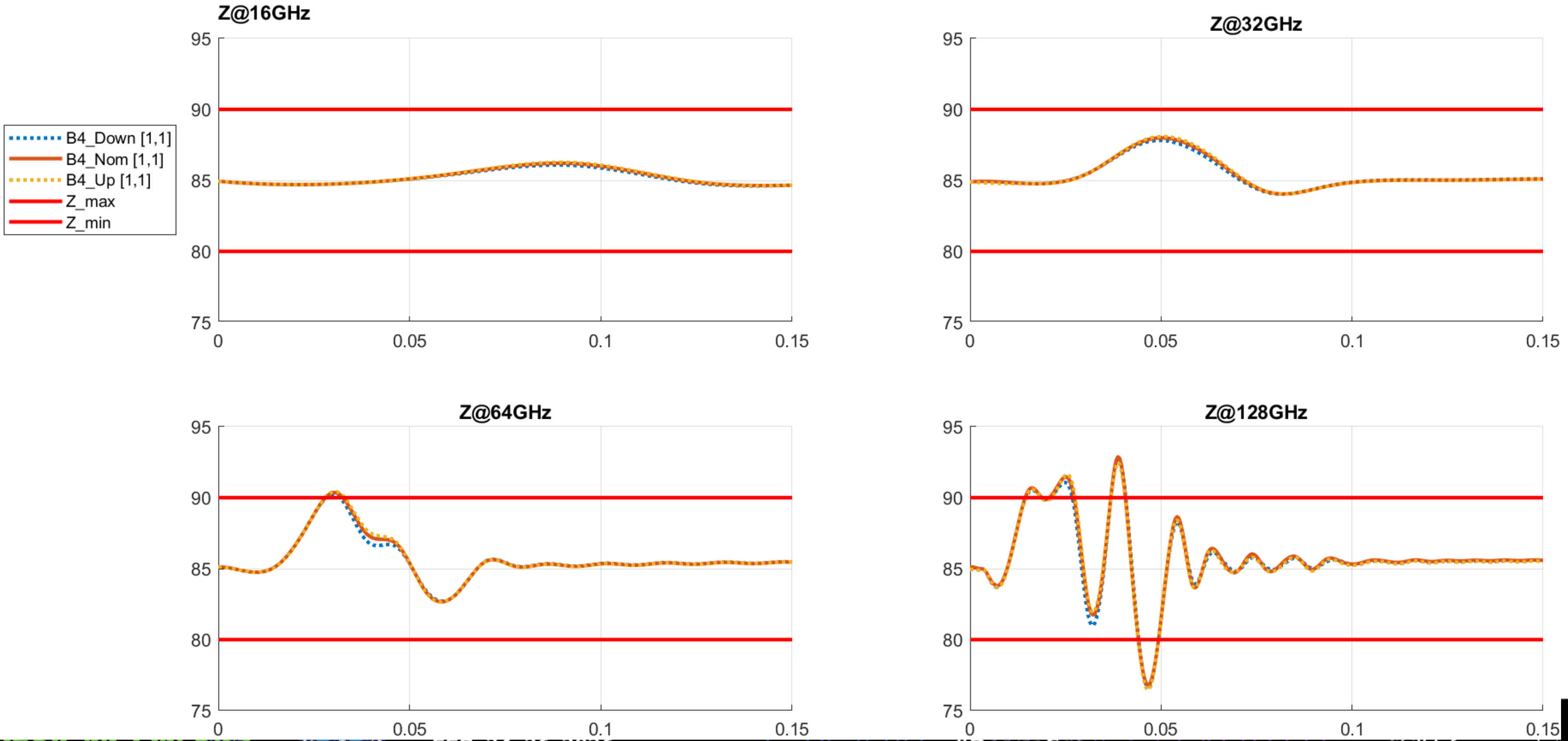
Block 2 (L3,L4,L5,L6,L7) = 28



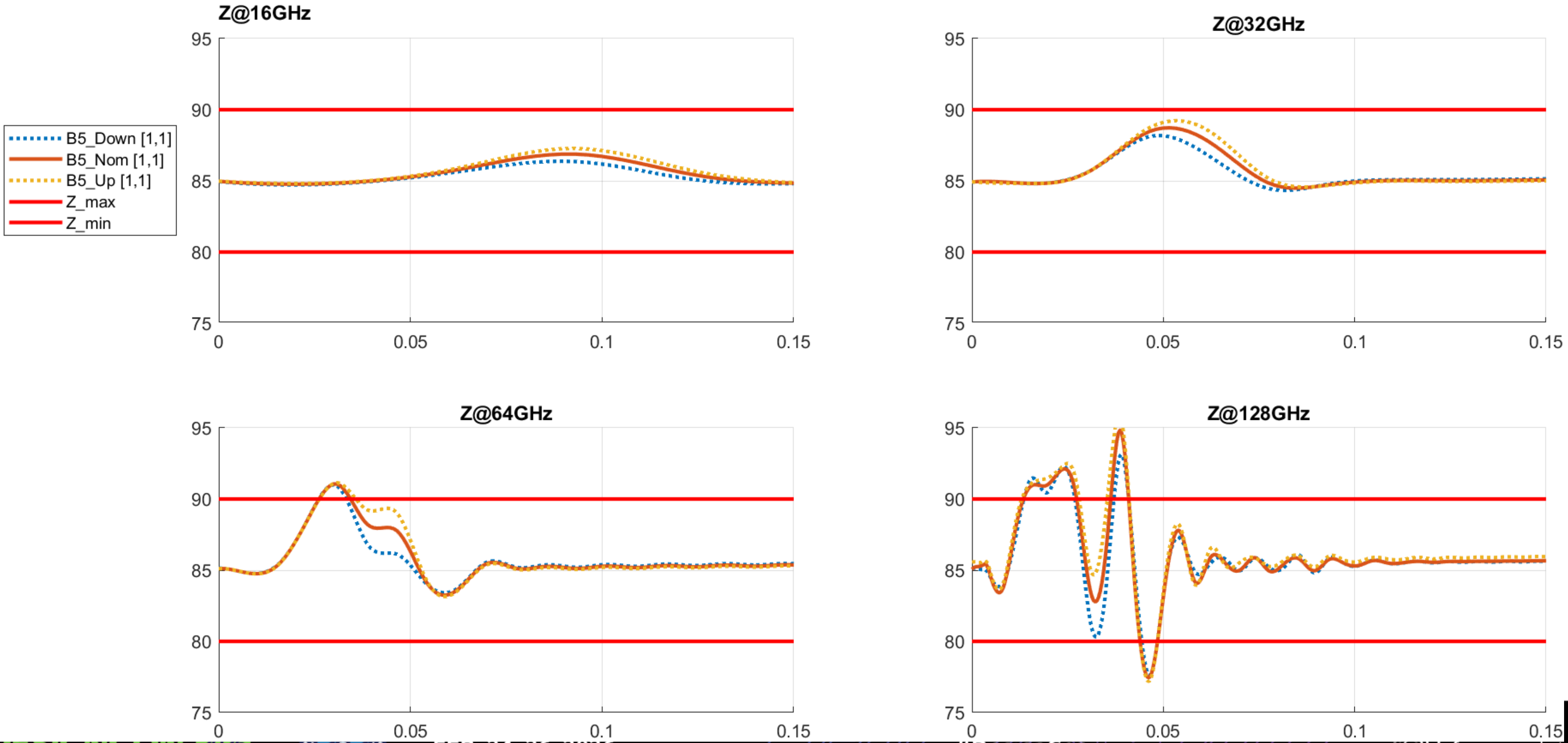
Block 3 (L8,L9,L10,L11) = 24



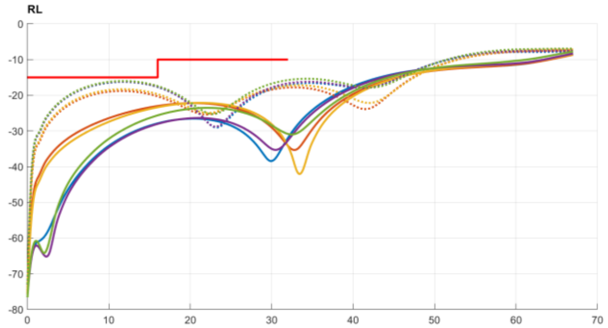
Block 4 (L12,L13,L14) = 28

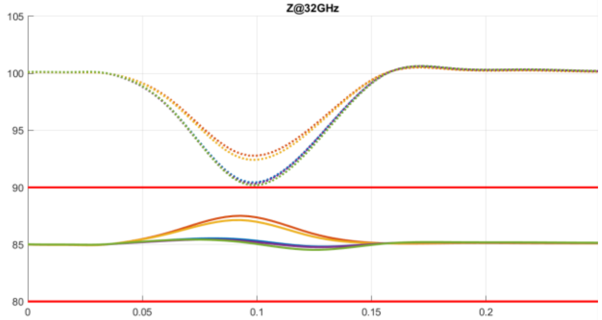


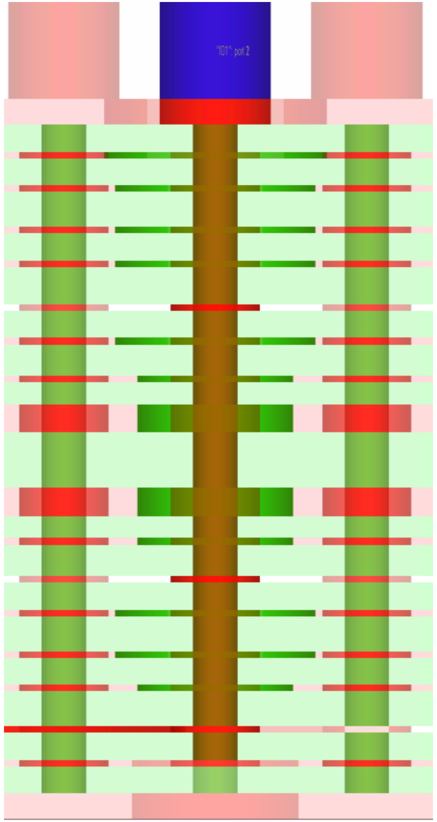
Block 5 (L15) = 20

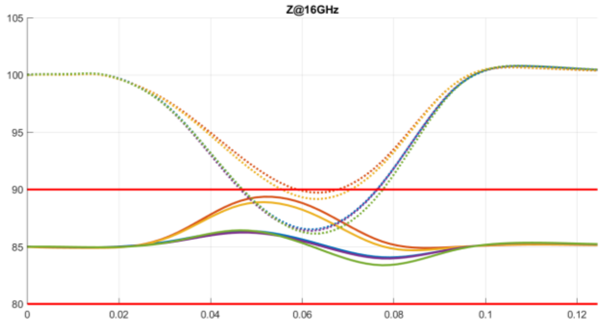


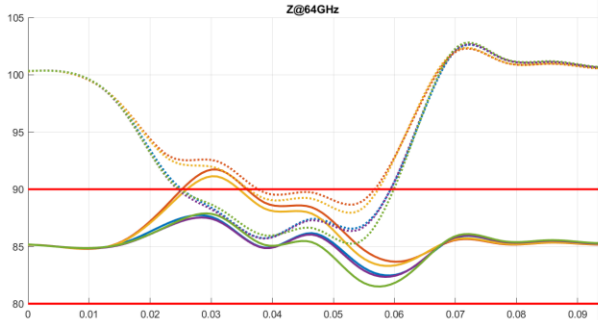
Single design Multiple PCB Fab Vendors





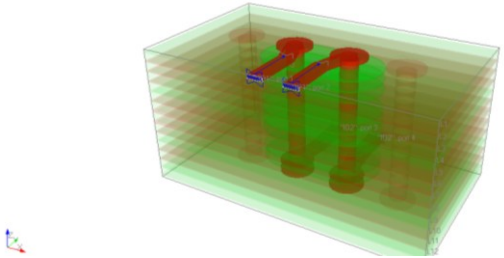


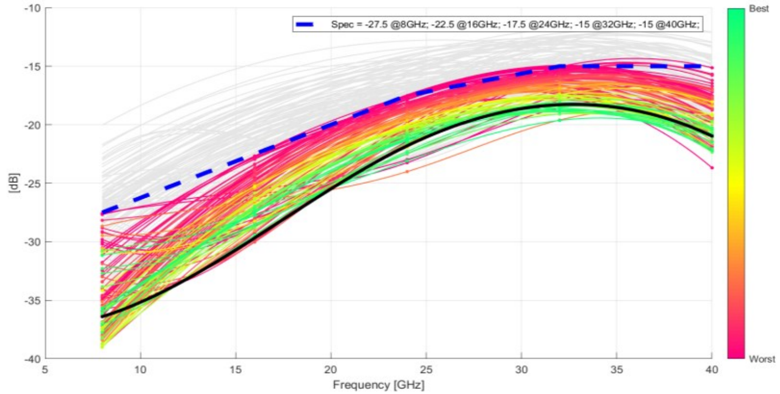


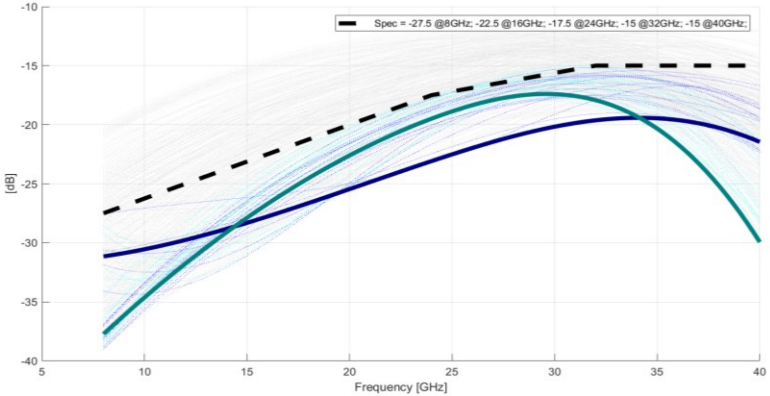


Multi Vendor-Via Optimization

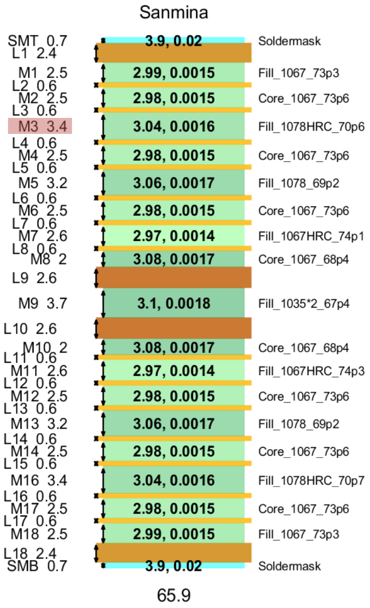
- The optimization algorithm seeks RL values that remain well below the specification maximum across all frequency points.
- A line with consistently lower average values receives a higher score than one that is very low at certain points but exceeds limits at others.
- Any line that exceeds the specification at any frequency point is considered a failure.
- Vias are evaluated both within their individual stackups and across all stackups collectively.
- The optimal via choice for the entire set of stackups may not necessarily be the best option within a single stackup.

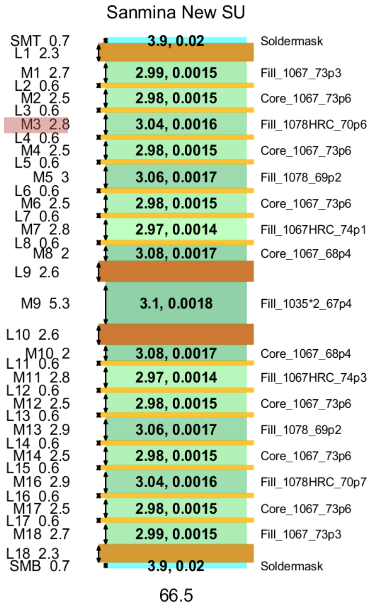




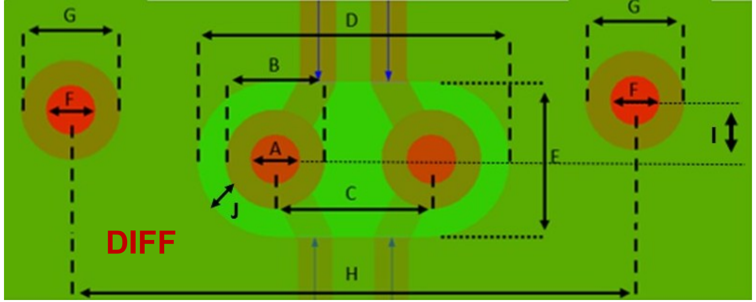


Copper Balance Impact on Via Design





Via_Top_to _L3_PCIe_85_ohm

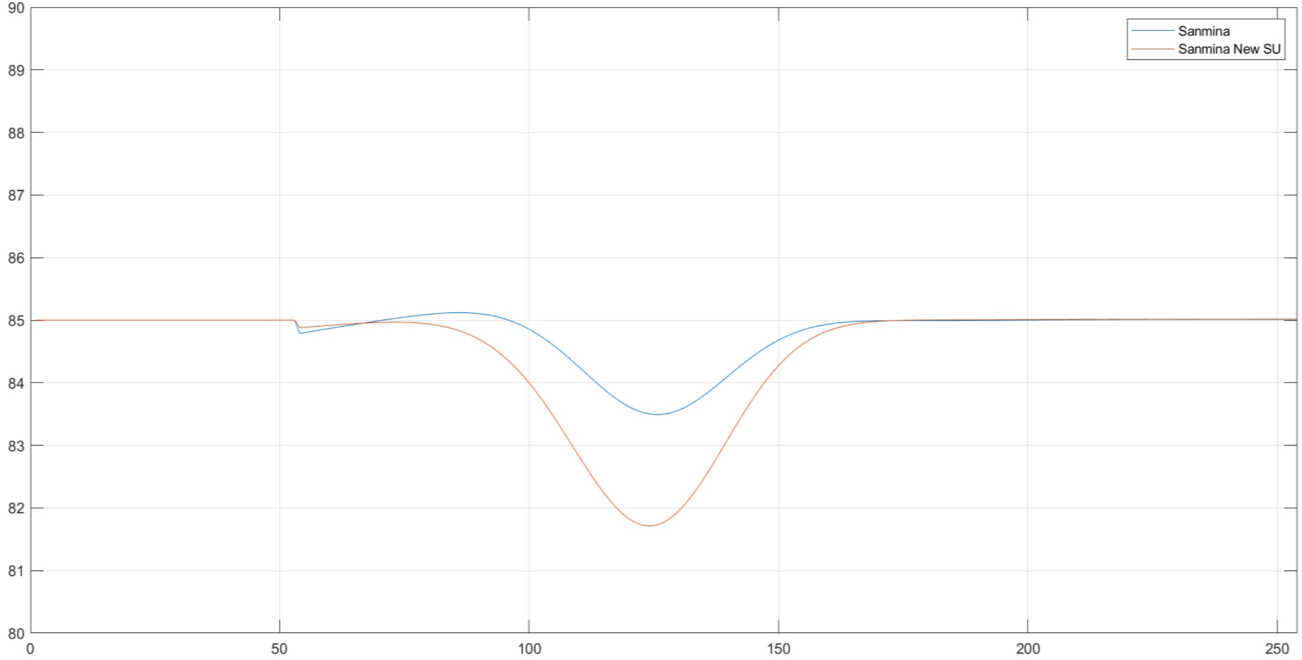


Via Target Impedance	SIG Start Layer	SIG End Layer	GND Start Layer	GND End Layer	Inverted Layers
85	L1	L3	L1	L18	,

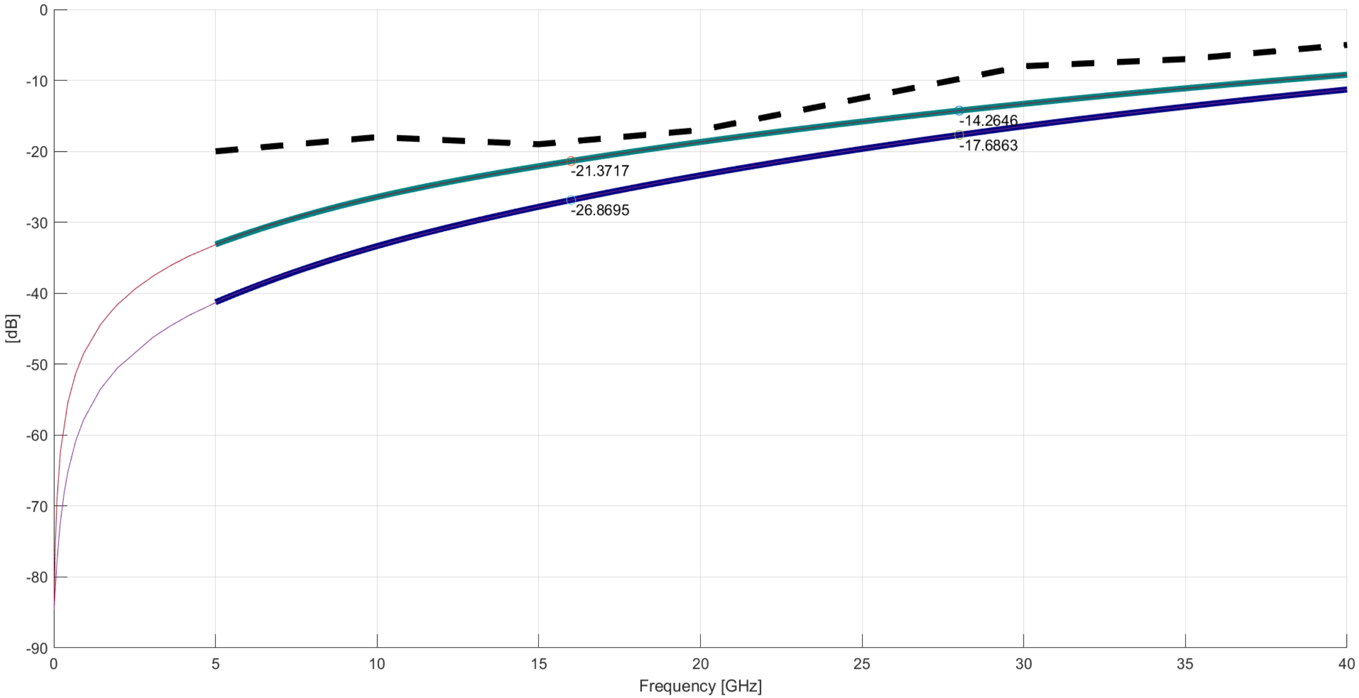
A	B	C	D	E	F	G	H	I
SIG Via Drill	SIG Via Pad	SIG Via Spacing	Apad Width	Apad Height	GND Via Drill	GND Via Pad	GND Via Spacing	GND Via Offset
9	17	28	61	33	8	20	86	0

Layer	Type	B	D	E	Apad Shape
L1	SIG	17	N/A	N/A	N/A
L2	GND	N/A	61	33	Diff Oblong
L3	SIG	17	N/A	N/A	N/A
L4	GND	N/A	N/A	N/A	N/A
L5	SIG	N/A	N/A	N/A	N/A
L6	GND	N/A	N/A	N/A	N/A
L7	SIG	N/A	N/A	N/A	N/A
L8	GND	N/A	N/A	N/A	N/A
L9	GND	N/A	N/A	N/A	N/A
L10	GND	N/A	N/A	N/A	N/A
L11	GND	N/A	N/A	N/A	N/A
L12	SIG	N/A	N/A	N/A	N/A
L13	GND	N/A	N/A	N/A	N/A
L14	SIG	N/A	N/A	N/A	N/A
L15	GND	N/A	N/A	N/A	N/A
L16	SIG	N/A	N/A	N/A	N/A
L17	GND	N/A	N/A	N/A	N/A
L18	SIG	N/A	N/A	N/A	N/A

TDR Via_Top_to _L3_PCIe_85_ohm



Return Loss


0
-10
-20
-30
-40
-50
-60
-70
-80
-90
[dB]
0
5
10
15
20
25
30
35
40
Frequency [GHz]
-14.2646
-17.6863
-21.3717
-26.8695

The Challenges of Predictability for 448Gbps

To repeat the simulations, we provide free Simbeor Complete license (valid for one week after DesignCon) and free API key for Open Router (AI) : Download "**AI4SI Getting Started Kit**" from www.simberian.com -> Knowledge Base -> Simbeor Examples https://kb.simberian.com/SimbeorExample.php?id=233

Either follow instructions provided at how_to_activate_simbeor_ai4si_trial.txt (activation with AI)

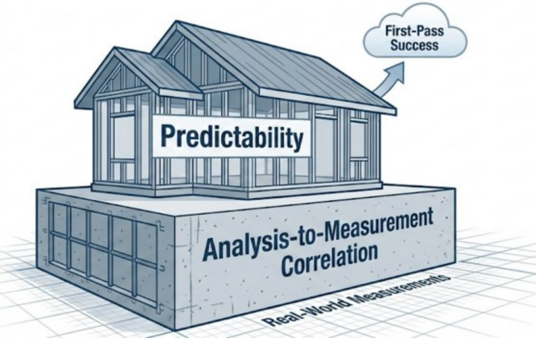
Or use license file directly: simbeor_dc2026.lic – here is how to use it https://kb.simberian.com/browse_item.php?id=837

OUTLINE

- The Challenges of Predictability for 448Gbps
- The Investigation: Establishing the Foundation for Predictability
- The Hurdles and Possible Solutions
    - Unpredictability in Traces and Probabilistic Models
    - Unpredictability of Vias and The Waveguiding Approach
- Conclusion

The Goal: Predictability at 448 Gbps

- **The Objective:**
  - Design interconnects that work at 448 Gbps on the first pass (Pragmatic Approach).
- **The Challenge:**
  - What does it take to achieve this for 112-448 Gbps?
  - Is it even possible to *predict* behavior at these datarates?
- **The Reality:**
  - We are entering uncharted territory where standard design approaches fail.
- **The Solution:**
  - We cannot guess. We must build on a solid foundation:
  - **Analysis-to-Measurement Correlation!**



(image by Nano Banana)

Three Brickwalls to 448 Gbps Predictability

1. The Bandwidth Brickwall

Measurement Gap: Equipment >110 GHz is scarce and costly.

Validation Gap: Solvers unproven in “mm-wave-territory."

Result: Flying blind at high frequencies.

2. The Manufacturing Brickwall

Tolerance Sensitivity: Tiny variations act as massive defects.

The Reality: "As-Designed" virtually never matches "As-Built."

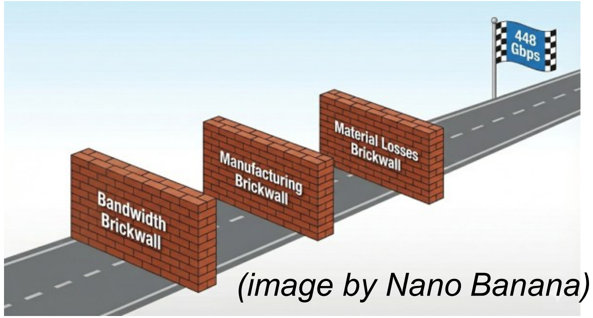
3. The Material Models Brickwall

Roughness Dominance: Conductor roughness overtakes dielectric loss.

Modeling Limits: Vendor-specific dielectric and roughness models are required.

+The Via Pitfall – conventional approach to viahole design creates unpredictable vias.

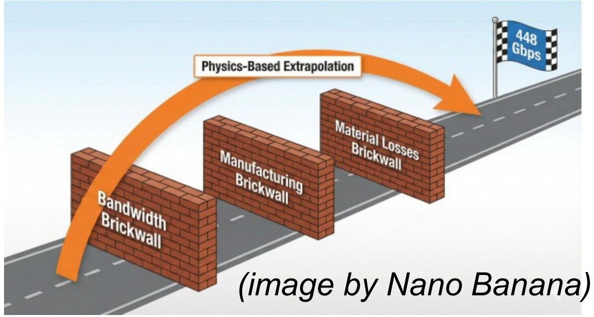
+EDA Tools Trap – unreasonable trust in un-validated 3D EM solvers.



(image by Nano Banana)

The Path Forward

- Measure: Validate analysis up to the maximal frequency you can measure – 70-110 GHz for instance.
- Extrapolate: Identify and use physics-based material models.
- Bound: Build and apply statistical manufacturing models.
- Localize: Abandon conventional via design approach – micro-vias or Waveguiding Vias (SICW, SIBW) are the alternative.



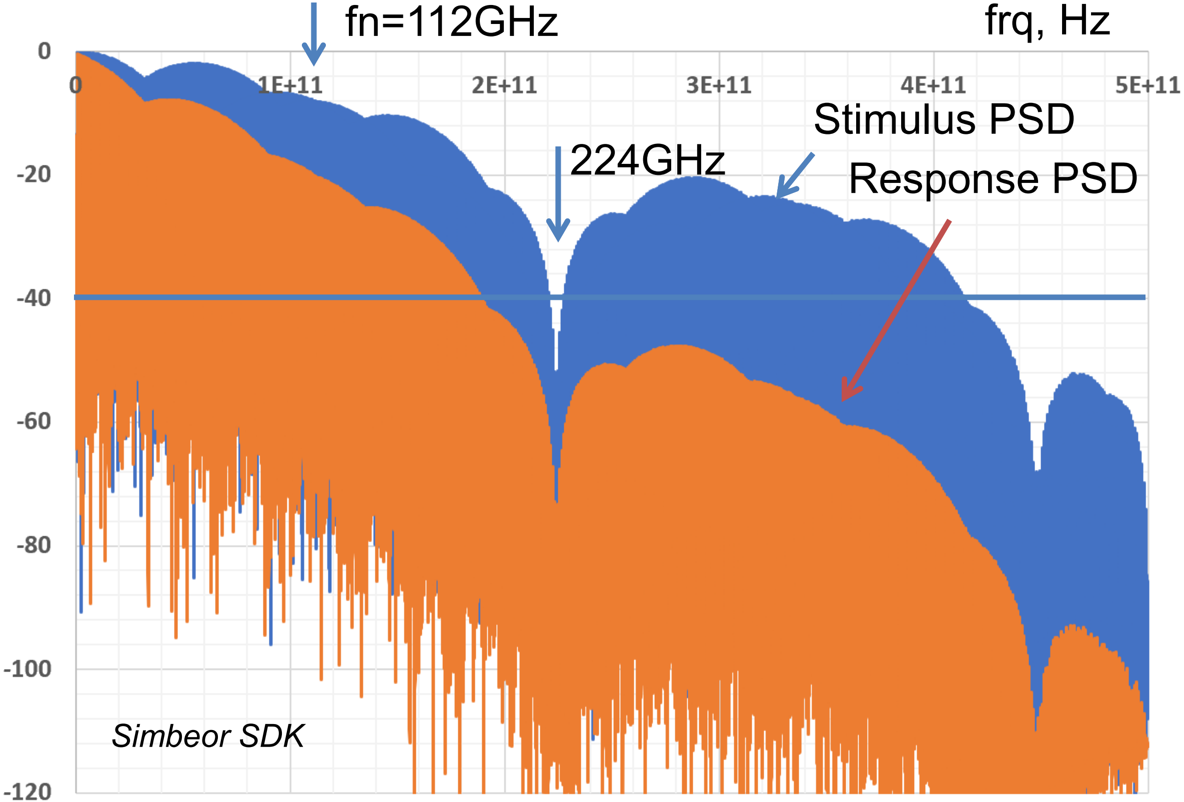
(image by Nano Banana)

Bandwidth Brickwall: PSD of Realistic Link

448Gbps PAM4, 2ps rise time, PRBS9
5-inch strip line, W=12mil, H=20mil
Meg7 – Wideband Debye: Dk=3.17, LT=0.001 @ 1 GHz
Copper: RR=1.4, Roughness – Huray-Bracken Model: SR=0.14 um, RF=8.7

1.5-2 x Nyquist may be required for accurate analysis
Formal pulse analysis can be used for better estimate (*)

Bandwidth for NEXT (crosstalk in vias) is practically the same as the stimulus ☹ - **maximal possible bandwidth must be used**



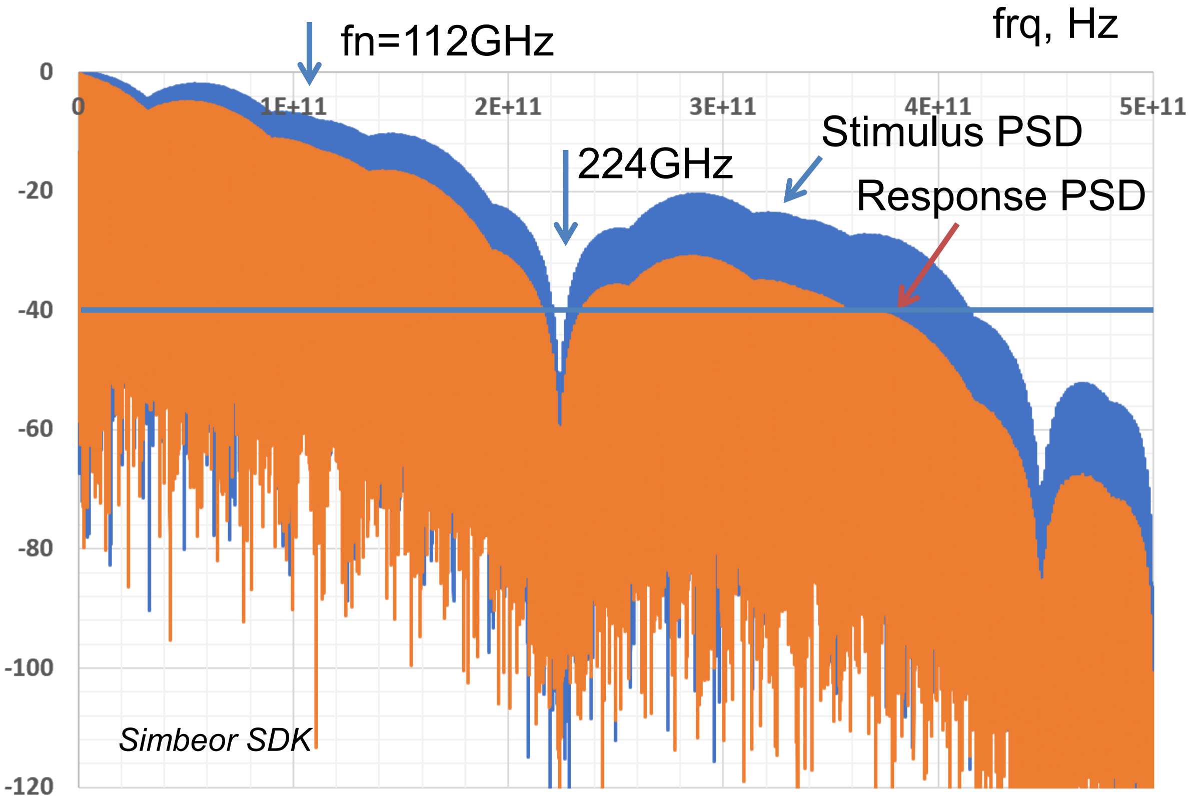
Bandwidth Brickwall: PSD of Low-Loss Link

448Gbps PAM4, 2ps rise time, PRBS9
5-inch strip line, W=12mil, H=20mil
Meg7 – Wideband Debye: Dk=3.17, LT=0.001 @ 1 GHz
Copper: RR=1.1, Roughness – Huray- Bracken Model: SR=0.01 um, RF=8.7

2-4 x Nyquist may be required for accurate analysis
Formal pulse analysis can be used for better estimate (*)

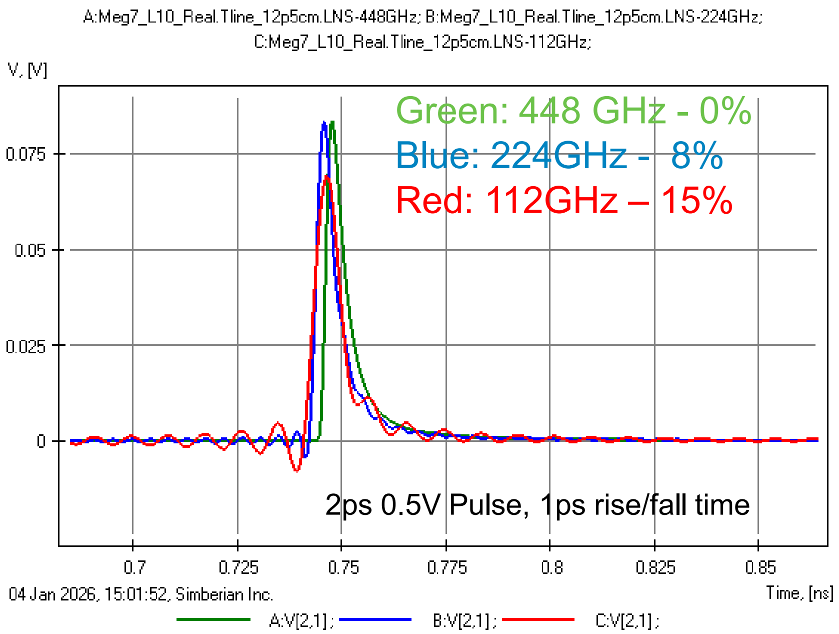
Bandwidth for NEXT (crosstalk in vias) is practically the same as the stimulus ☹ - **maximal possible bandwidth must be used**

*More on achievable losses in Presentation #2020_03 at Y. Shlepnev, **In search of fundamental limits for electrical interconnects**, January 2020.*

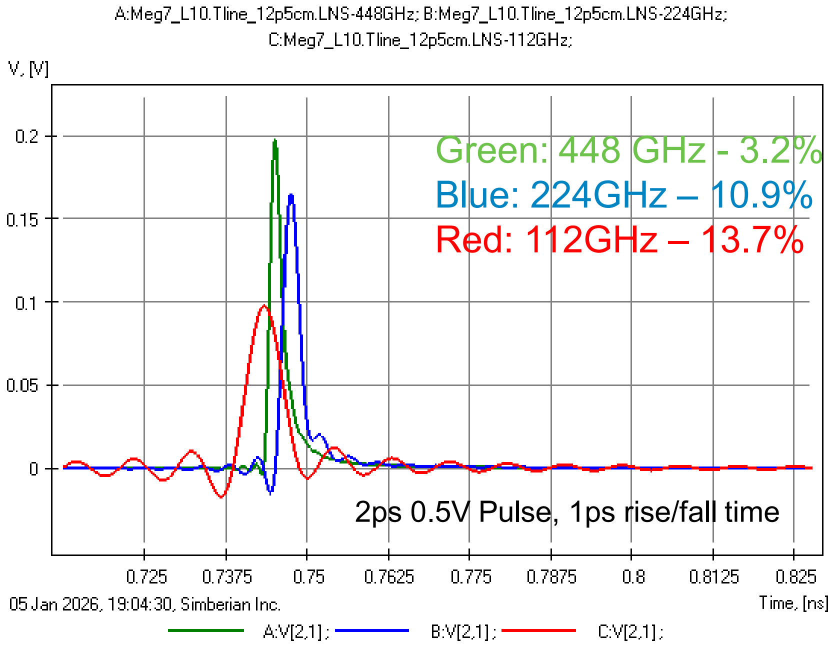


Bandwidth Identification with Pulse Analysis

Real 5-inch strip line, W=12mil, H=20mil
Meg7 – Wideband Debye: Dk=3.17, LT=0.001 @ 1 GHz
Copper: 0.5Oz, RR=1.4, Huray-Bracken: SR=0.14 um, RF=8.7



Low-Loss 5-inch strip line, W=12mil, H=20mil
Meg7 – Wideband Debye: Dk=3.17, LT=0.001 @ 1 GHz
Copper: 1Oz, RR=1.1, Huray-Bracken: SR=0.01 um, RF=8.7



*(*) Y. Shlepnev, How Interconnects Work: **Bandwidth for Modeling and Measurements**, Signal Integrity Journal, April 12, 2022*

Tolerance Sensitivity: The Electrical Size Matter

Package (~40 WL @112 GHz)

PCB (~200*WL @ 112 GHz)

14 GHz

28 GHz

56 GHz

84 GHz

112 GHz

1 mm = 39.37008 mil
1 mil = 0.0254 mm

Dk=4

Frequency [GHz]	WL [mm], Air	WL [mm]	WL/2 [mm]	WL/4 [mm]	WL/8 [mm]
14	21.414	10.707	5.353	2.677	1.338
28	10.707	5.353	2.677	1.338	0.669
56	5.353	2.677	1.338	0.669	0.335
84	3.569	1.784	0.892	0.446	0.223
112	2.677	1.338	0.669	0.335	0.167

Dk=2

Frequency [GHz]	WL [mm], Air	WL [mm]	WL/2 [mm]	WL/4 [mm]	WL/8 [mm]
14	21.414	15.142	7.571	3.785	1.893
28	10.707	7.571	3.785	1.893	0.946
56	5.353	3.785	1.893	0.946	0.473
84	3.569	2.524	1.262	0.631	0.315
112	2.677	1.893	0.946	0.473	0.237

WL is wavelength in dielectric

$$\lambda = \frac{c}{f \cdot \sqrt{\varepsilon_r}}$$

Design Limits:
WL/2 - cutoff for SIW formed by via fences;
WL/4 - resonances, via localization (pass/fail), via fence localization (WL/8);
About 10mil makes difference between pass and fail!

We are deep into microwave and mm wave territory
It is the Waveguide Domain ruled by the Electromagnetic Analysis!

The Investigation: Establishing the Predictability Foundation

Measurements quality
Material identification
Quantifying success

Validation Platforms to Investigate Predictability

XTALK-70 Validation Platform from Wild River Technology
https://wildrivertech.com/

All solutions are available in Simbeor Kit for CMP-70: CMP-70_Simbeor_Kit_2025/Dec2025

https://drive.google.com/open?id=1JqE62aMjKA0CG4c-wYS2-H1wCevwNjQ_&usp=drive_fs

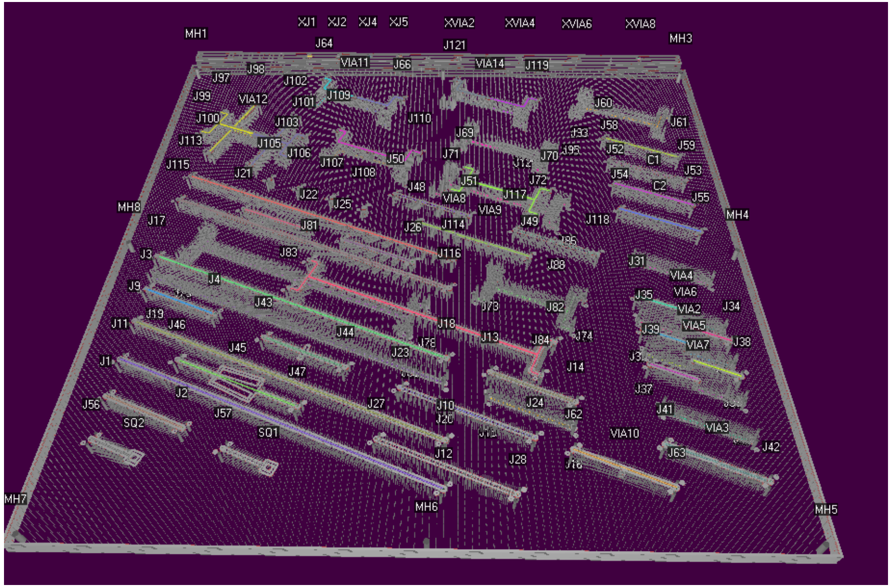
Detailed description: *A. P. Neves, K. Skytte, J. Phillips, F. Zavosh, E. Bogatin, Free signal integrity? How understanding anisotropic materials and tolerances could increase performance at 112/224Gbps and beyond, DesignCon 2025*

Prototypes of this platform (CMP-28/32) was used in the extensive analysis to measurement validation project:
Y. Shlepnev, **Sink or swim at 28 Gbps**, The PCB Design Magazine, October 2014, p. 12-23.
(Simberian App Note #2014_05)

Analysis Steps in Simbeor 2025.01

- *Board analysis with materials and stackup data from manufacturer:*
  create solution CMP-70-TTM and import stackup from CMP-70-TTM.pdf,
  export materials and stackup to CMP-TTM.json

- *For post-layout analysis with the data from manufacturer*
  create solution CMP-70-TTM for 112Gbps PAM4, 14ps rise time, import CMP-70.brd and merge it with stackup from CMP-70-TTM.json (use presets SL.preset or MSL.preset for the analysis)



Stackup & Materials from Manufacturer

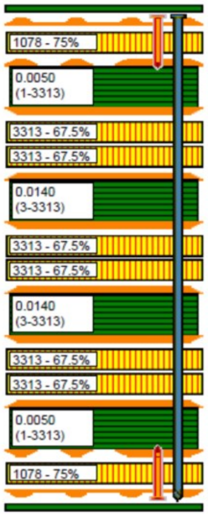
TTM Technologies

Viasystems Technologies Corp. LLC
8150 Sheppard Ave E
Toronto, ON, M1B 5K2

Job Name : CMP-70-A
Customer : WILD RIVER TECHNOLOGY LLC
Part Num : CMP-70
Part Rev : 1
Engineer : Saminder Jhawar

Layer	Calc Thickness	Description	Dk / Df
	0.0005	Taiyo 4000-HFX	3.80 / 0.0210
Layer - 1	0.0020	1/4oz Sig (Std Plt) HTE6P	
	0.0038	Tachyon100G	2.94 / 0.0018
Layer - 2	0.0006	1/2oz Mix VLP-2	
	0.0050	Tachyon100G	3.11 / 0.0018
Layer - 3	0.0006	1/2oz P/G VLP-2	
	0.0109	Tachyon100G	3.09 / 0.0018
Layer - 4	0.0006	1/2oz P/G VLP-2	
	0.0140	Tachyon100G	3.15 / 0.0020
Layer - 5	0.0006	1/2oz P/G VLP-2	
	0.0109	Tachyon100G	3.09 / 0.0018
Layer - 6	0.0006	1/2oz P/G VLP-2	
	0.0140	Tachyon100G	3.15 / 0.0020
Layer - 7	0.0006	1/2oz P/G VLP-2	
	0.0109	Tachyon100G	3.09 / 0.0018
Layer - 8	0.0006	1/2oz P/G VLP-2	
	0.0050	Tachyon100G	3.11 / 0.0018
Layer - 9	0.0006	1/2oz Mix VLP-2	
	0.0038	Tachyon100G	2.94 / 0.0018
Layer - 10	0.0020	1/4oz Sig (Std Plt) HTE6P	
	0.0005	Taiyo 4000-HFX	3.80 / 0.0210

Primary Stack



Solution CMP-70-TTM

CMP-70-TTM: "C:\Users\shlep\Documents\Simbeor THz Solutions\CMP-70-TTM\"
CMP-70
Materials: T=20[°C],...
"0.25oz_copper", RR=1
"0.5oz_copper", RR=1
"Taiyo_4000-HFX", Dk=3.8, LT=0.021 @ 1 GHz, PLM=WD, Dk(0)=4.74, Dk(inf)=3.33
"Tachyon100G_1078_75pct", Dk=2.94, LT=0.0018 @ 1 GHz, PLM=WD, Dk(0)=3, Dk(inf)=2.91
"Tachyon100G_1x3313", Dk=3.11, LT=0.0018 @ 1 GHz, PLM=WD, Dk(0)=3.18, Dk(inf)=3.08
"Tachyon100G_2x3313", Dk=3.09, LT=0.0018 @ 1 GHz, PLM=WD, Dk(0)=3.16, Dk(inf)=3.06
"Tachyon100G_3x3313", Dk=3.15, LT=0.002 @ 1 GHz, PLM=WD, Dk(0)=3.22, Dk(inf)=3.11
"air"
StackUp: LU=[inch], NL=10, T=0.0871[inch], TOP/BOT CSM=("Taiyo_4000-HFX", 0.0005/0.0005[inch]);
1| Signal: "L1", T=0.002, Fl="air", Cond="0.25oz_copper"
2| Medium: T=0.0038, Fl="Tachyon100G_1078_75pct"
3| Signal: "L2", T=0.0006, Fl="Tachyon100G_1078_75pct", Cond="0.5oz_copper"
4| Medium: T=0.005, Fl="Tachyon100G_1x3313"
5| Plane: "L3", Cond="0.5oz_copper", T=0.0006, Fl="Tachyon100G_2x3313"
6| Medium: T=0.0109, Fl="Tachyon100G_2x3313"
7| Plane: "L4", Cond="0.5oz_copper", T=0.0006, Fl="Tachyon100G_2x3313"
8| Medium: T=0.014, Fl="Tachyon100G_3x3313"
9| Plane: "L5", Cond="0.5oz_copper", T=0.0006, Fl="Tachyon100G_2x3313"
10| Medium: T=0.0109, Fl="Tachyon100G_2x3313"
11| Plane: "L6", Cond="0.5oz_copper", T=0.0006, Fl="Tachyon100G_2x3313"
12| Medium: T=0.014, Fl="Tachyon100G_3x3313"
13| Plane: "L7", Cond="0.5oz_copper", T=0.0006, Fl="Tachyon100G_2x3313"
14| Medium: T=0.0109, Fl="Tachyon100G_2x3313"
15| Plane: "L8", Cond="0.5oz_copper", T=0.0006, Fl="Tachyon100G_2x3313"
16| Medium: T=0.005, Fl="Tachyon100G_1x3313"
17| Signal: "L9", T=0.0006, Fl="Tachyon100G_1078_75pct", Cond="0.5oz_copper"
18| Medium: T=0.0038, Fl="Tachyon100G_1078_75pct"
19| Signal: "L10", T=0.002, Fl="air", Cond="0.25oz_copper"

CMP-70 Structures (1)

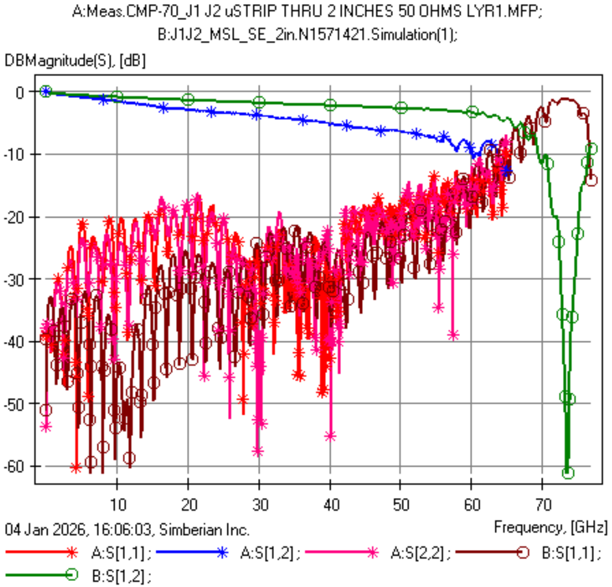
Pins	Net	Description	Purpose	Files
J1/J2	N1571421	MSL SE 50 Ohm SE, 2 inches, L1	Identification	"CMP-70_J1 J2 uSTRIP THRU 2 INCHES 50 OHMS LYR1.S2P"
J3/J4	N2564054	SL SE 50 Ohm SE, 2 inches, L2	Identification	"CMP-70_J3 J4 STRIPLINE THRU 2 INCHES 50 OHMS LYR2.S2P"
J5/J6	N2564082	SL SE 50 Ohm SE, 2 inches, L9	Verification	"CMP-70_J5 J6 STRIPLINE THRU 2 INCHES 50 OHMS LYR9.S2P"
J7/J8	N2584712	MSL SE 50 Ohm SE, 2 inches, L10	Verification	"CMP-70_J7 J8 uSTRIP THRU 2 INCHES 50 OHMS LYR10.S2P"
J9/J10	N2564058	SL SE 50 Ohm SE, 8 inches, L2	Identification	"CMP-70_J9 J10 STRIPLINE THRU 8 INCHES 50 OHMS LYR2.S2P"
J11/J12	N1569517	MSL SE 50 Ohm SE, 8 inches, L1	Identification	"CMP-70_J11 J12 uSTRIP THRU 8 INCHES 50 OHMS LYR1.S2P"
J13/J14	N2565349	SL SE 60 Ohm SE, 2 inches, L2	Verification	"CMP-70_J13 J14 STRIPLINE THRU 2 INCHES 60 OHMS LYR2.S2P"
J15/J16	N2565325	SL SE 40 Ohm SE, 2 inches, L9	Verification	no measurements
J17/J18	N2565329	SL SE 60 Ohm SE, 8 inches, L2	Verification	"CMP-70_J17 J18 STRIPLINE THRU 8 INCHES 60 OHMS LYR2.S2P"
J19/J20	N2565373	SL SE 40 Ohm SE, 8 inches, L9	Verification	"CMP-70_J19 J20 STRIPLINE THRU 8 INCHES 40 OHMS LYR9.S2P"
J21/J22	N2563196	SL SE Capacitive Connector Launch	Pathology	"CMP-70_J21 J22 STRIPLINE THRU 2 INCHES 50 OHMS LYR2 CAP LAUNCHES.S2P"
J23/J24	N2563250	SL SE 25 Ohm Beatty Standard (Resonant)	Verification	"CMP-70_J23 J24 STRIPLINE BEATTY 50-25-50 OHMS.S2P"
J25/J26	N2563204	SL SE Inductive Connector Launch	Pathology	"CMP-70_J25 J26 STRIPLINE THRU 2 INCHES 50 OHMS LYR2 IND LAUNCHES.S2P"
J27/J28	N2563200	SL SE 60 Ohm SE Beatty Standard (Resonant)	Verification	"CMP-70_J27 J28 STRIPLINE BEATTY 50-60-50 OHMS.S2P"
J31/J32	N2446200	MSL SE Transition Via (too inductive)	Validation	"CMP-70_J31 J32 uSTRIP SE VIA HIGHLY INDUCTIVE.S2P"
J33/J34	N2446996	MSL SE Transition Via (inductive)	Validation	"CMP-70_J33 J34 uSTRIP SE VIA INDUCTIVE.S2P"
J35/J36	N1673088	MSL SE Transition Via (about matched)	Validation	"CMP-70_J35 J36 uSTRIP SE VIA NOMINAL.S2P"
J37/J38	N2440004	MSL SE Transition Via (capacitive)	Validation	"CMP-70_J37J38 uSTRIP SE VIA MODERATELY CAPACITIVE.S2P"
J39/J40	N2440222	MSL SE Transition Via (too capacitive)	Validation	"CMP-70_J39 J40 uSTRIP SE VIA HIGHLY CAPACITIVE.S2P"
J41/J42	N2101295	SL SE Transition Via	Validation	"CMP-70_J41 J42 STRIPLINE SE VIA.S2P"
J43/J44	N2561070	SL SE Balanced Resonator - two long stubs (Resonant)	Verification	"CMP-70_J43 J44 STRIPLINE BALANCED RESONATOR.S2P"
J46/J47	N2561066	MSL SE Gradual Coplanar	Validation	"CMP-70_J46 J47 STRIPLINE GRADUATED COPLANAR COUPLED.S2P"
J48/J49	N1001839	MSL/SL SE Via Field Pathology	Pathology	"CMP-70_J48 J49 STRIPLINE VIA FIELD PATHOLOGY.S2P"
J50/J51	N2560407	SL SE Thru with Whisker Stubs (50 mil pitch, Resonant)	Calibration	"CMP-70_J50 J51 STRIPLINE WHISKER STUBS 50 MIL PITCH.S2P"

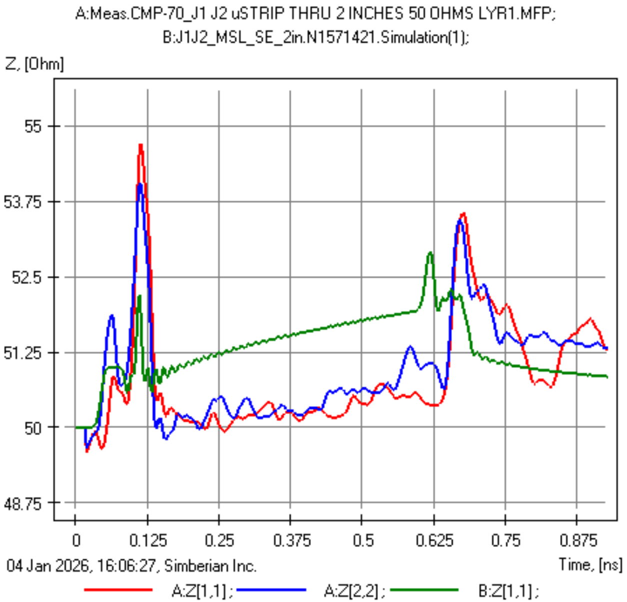
CMP-70 Structures (2)

J52	N2560387	MSL SE with 0201 Series Capacitor (with cutout)	Validation	"CMP-70_J52 J53 uSTRIP SERIES CAP WITH REF VOID.S2P"
J53	N1456130	part of previous		same
J54	N2539003	MSL SE with 0201 Series Capacitor (without cutout)	Validation	"CMP-70_J54 J55 uSTRIP SERIES CAP WITHOUT REF VOID.S2P"
J55	N2539007	part of previous		same
J58/J59	N2564791	SL SE Offset Radial Stub Resonator - 50mil pitch (Resonant)	Validation	"CMP-70_J58 J59 STRIPLINE OFFSET RADIAL STUB RESONATOR 50 MIL SEP.S2P"
J60/J61	N2466269	SL SE Offset Radial Stub Resonator - 84mil pitch (Resonant)	Validation	"CMP-70_J60 J61 STRIPLINE OFFSET RADIAL STUB RESONATOR 84 MIL SEP.S2P"
J62/J63	N2405894	MSL Via Resonator (Resonant)	Anisotropy Test	"CMP-70_J62 J63 MICROSTRIP ANISOTROPIC RESONATOR.S2P"
J64/J65	N2772938	MSL SE Via Crosstalk - Link1	Crosstalk	"CMP-70_J64J65J66J67_uSTRIP_SE_VIA_CROSSTALK_ANTENNA_NOM-NOM.s4p"
J66/J67	N2773298	MSL SE Via Crosstalk - Link2	Crosstalk	same
J69/J70	DP1+	MSL 100 Ohm DIFF, 2 inches, L1	Identification	"CMP-70_J69J70J71J72_uSTRIP_DIFFERENTIAL_THRU_LYR_1_2_INCHES.s4p"
J71/J72	DP1-	MSL 100 Ohm DIFF, 2 inches, L1		same
J73/J74	DP3+	SL 100 Ohm DIFF, 2 inches, L9	Identification	"CMP-70_J73J74J75J76_STRIPLINE_DIFFERENTIAL_THRU_LYR_9_2_INCHES.s4p"
J75/J76	DP3-	SL 100 Ohm DIFF, 2 inches, L9		same
J77/J78	DP2+	MSL 100 Ohm DIFF, 6 inches, L10	Identification	"CMP-70_J77J78J79J80_uSTRIP_DIFFERENTIAL_THRU_LYR_10_6_INCHES.s4p"
J79/J80	DP2-	MSL 100 Ohm DIFF, 6 inches, L10		same
J81/J82	DP4+	SL 100 Ohm DIFF, 6 inches, L2	Identification	"CMP-70_J81J82J83J84_STRIPLINE_DIFFERENTIAL_THRU_LYR2_6_INCHES.s4p"
J83/J84	DP4-	SL 100 Ohm DIFF, 6 inches, L2		same
J85/J86	DP9+	MSL DIFF Beatty standard (Resonant)	Verification	"CMP-70_J85J86J87J88_uSTRIP_DIFFERENTIAL_PAIR_BEATTY.s4p"
J87/J88	DP9-	MSL DIFF Beatty standard (Resonant)	Verification	"CMP-70_J85J86J87J88_uSTRIP_DIFFERENTIAL_PAIR_BEATTY.s4p"
J89/J90	DP10+	MSL DIFF Pair with Ground Plane Cutout	Pathology	"CMP-70_J89J90J91J92_uSTRIP_DIFFERENTIAL_PAIR,_WITH_PLANE_CUTOUT.s4p"
J91/J92	DP10-	MSL DIFF Pair with Ground Plane Cutout		same
J93/J94	DP11+	DIFF MSL to SL Via Transition	Validation	no measurements
J95/J96	DP11-	DIFF MSL to SL Via Transition	Validation	no measurements
J97/J98	DP44+	DIFF MSL to SL Via Transition	Crosstalk	"CMP-70_J97J98J99J100J101J102J103J104_STRIPLINE_DIFFERENTIAL_COUPLED_uV
J99/J100	DP44-	DIFF MSL to SL Via Transition		same
J101/J102	DP45+	DIFF MSL to SL Via Transition		same
J103/J104	DP45-	DIFF MSL to SL Via Transition		same
J109/J110	N2727243	MSL-SL SE Z-axis crosstalk Link1	Crosstalk	"CMP-70_J109J110J111J112_uSTRIP_STRIPLINE_Z-AXIS_CROSSTALK.s4p"
J111/J112	N2727483	MSL-SL SE Z-axis crosstalk Link2		same
J113/J114	N2854334	SL SE Capacitive Connector Launch	Pathology	"CMP-70_J113 J114 STRIPLINE THRU 8 INCHES 50 OHMS LYR2 CAP LAUNCHES.S2P"
J115/J116	N2855260	SL SE Inductive Connector Launch	Pathology	"CMP-70_J115 J116 STRIPLINE THRU 8 INCHES 50 OHMS LYR2 IND LAUNCHES.S2P"
J117/J118	N2862910	SL SE Through Wiskers, 84 mil pitch	Calibration	"CMP-70_J117 J118 STRIPLINE WHISKER STUBS 84 MIL PITCH.S2P"
J119/J120	N2978364	MSL SE Via Crosstalk - Link1	Crosstalk	"CMP-70_J119J120J121J122_uSTRIP_SE_VIA_CROSSTALK_ANTENNA_CAP-IND.s4p"
J121/J122	N2978724	MSL SE Via Crosstalk - Link2		same

Analysis-To-Meas As Is: J1J2 – MSL SE 2in

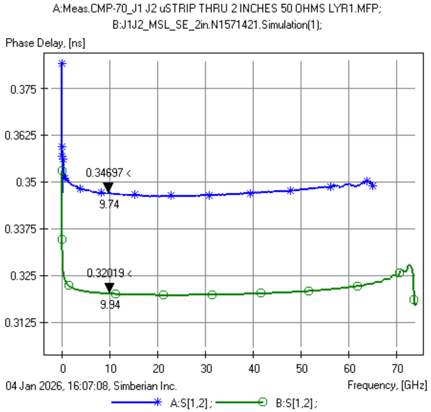
J1/J2	N1571421	MSL SE 50 Ohm SE, 2 inches, L1	Identification	"CMP-70_J1 J2 uSTRIP THRU 2 INCHES 50 OHMS LYR1.S2P"





Observations: Impedance is OK
IL is OFF; Phase Delay is OFF;
SPS: BAD;

Solution CMP-70-PreQualify

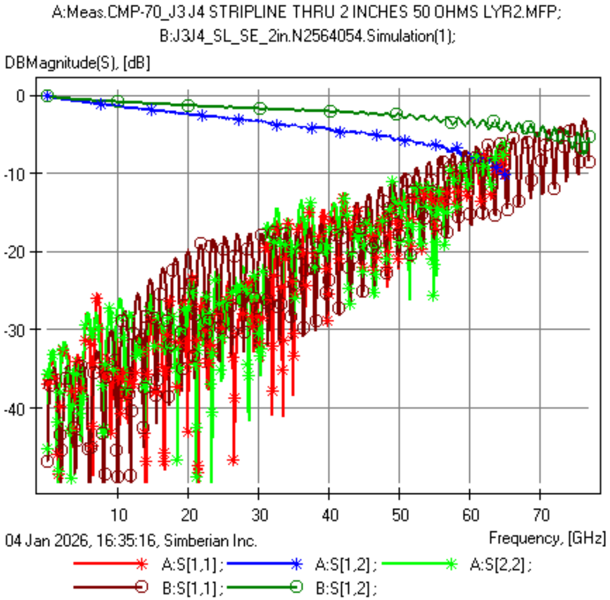


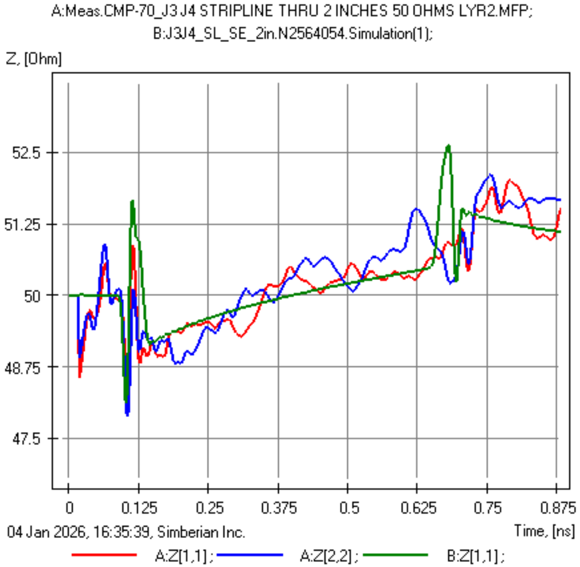
* **Overall SPS Score (100% BW):** 39.08 → **Bad**
* **Overall SPS Score (80% BW):** 50.39 → **Bad**

S-Par.	SPS (100% BW)	Rating (100% BW)	SPS (80% BW)	Rating (80% BW)
S11	94.30	Good	95.58	Good
S21	39.08	Bad	50.39	Bad
S12	39.10	Bad	50.43	Bad
S22	94.18	Good	95.57	Good

Analysis-To-Meas As Is: J3J4 – SL SE 2in

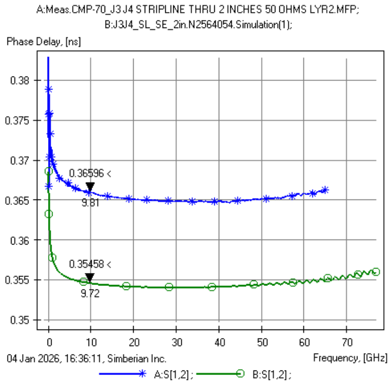
J3/J4	N2564054	SL SE 50 Ohm SE, 2 inches, L2	Identification	"CMP-70_J3 J4 STRIPLINE THRU 2 INCHES 50 OHMS LYR2.S2P"





Observations: Impedance is Perfect; IL is OFF; Phase Delay is OFF; SPS: BAD;

Solution CMP-70-PreQualify



* **Overall SPS Score (100% BW):** 38.02 → **Bad**
* **Overall SPS Score (80% BW):** 49.46 → **Bad**

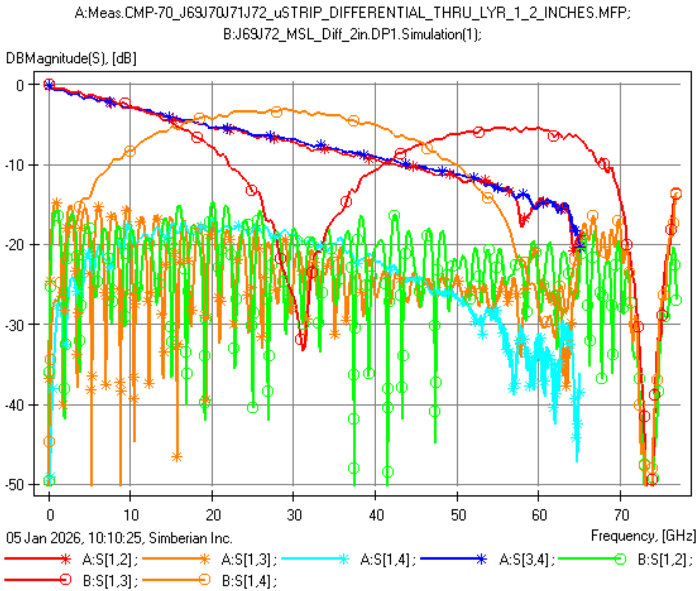
S-Par.	SPS (100% BW)	Rating (100% BW)	SPS (80% BW)	Rating (80% BW)
S11	94.13	Good	95.98	Good
S21	38.02	Bad	49.46	Bad
S12	38.11	Bad	49.59	Bad
S22	93.85	Good	95.74	Good

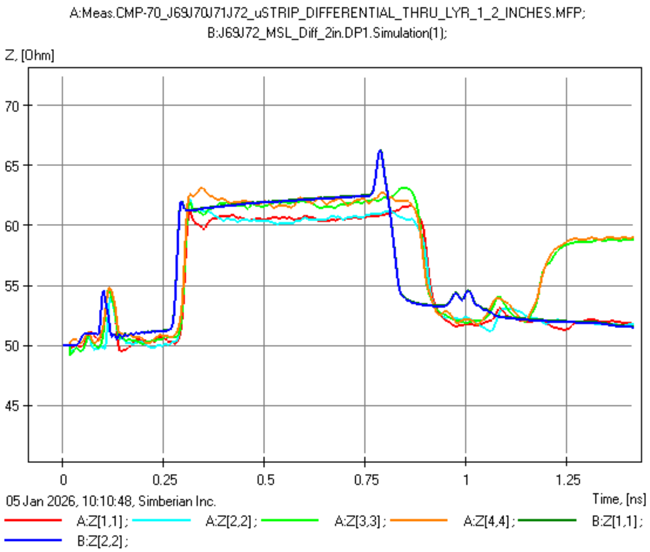
Analysis-To-Meas As Is: J69J72 – MSL DIFF 2in

J69/J70	DP1+	MSL 100 Ohm DIFF, 2 inches, L1	Identification	"CMP-70_J69J70J71J72_uSTRIP_DIFFERENTIAL_THRU_LYR_1_2_INCHES.s4p"
J71/J72	DP1-	MSL 100 Ohm DIFF, 2 inches, L1		same

Observations:
Impedance is Perfect;
IL is OFF;
FEXT is OFF;
TDR Delay is OFF;
SPS: BAD;

Solution CMP-70-PreQualify





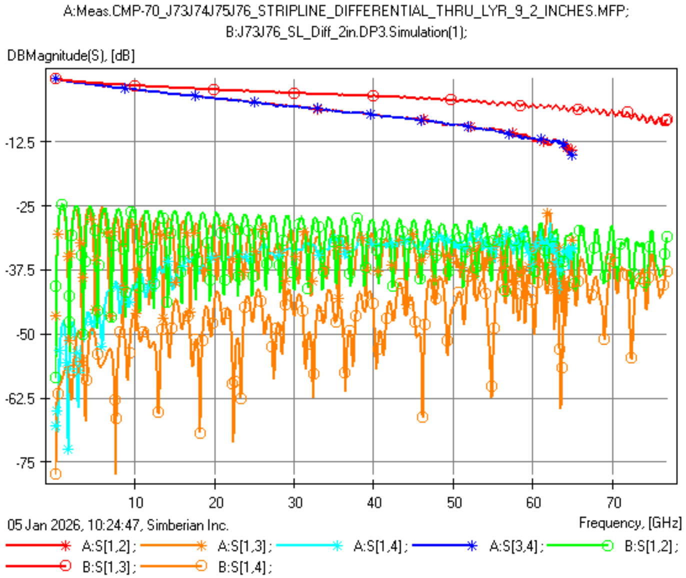
* **Overall SPS Score (100% BW):** 60.02 → **Bad**
* **Overall SPS Score (80% BW):** 67.18 → **Bad**

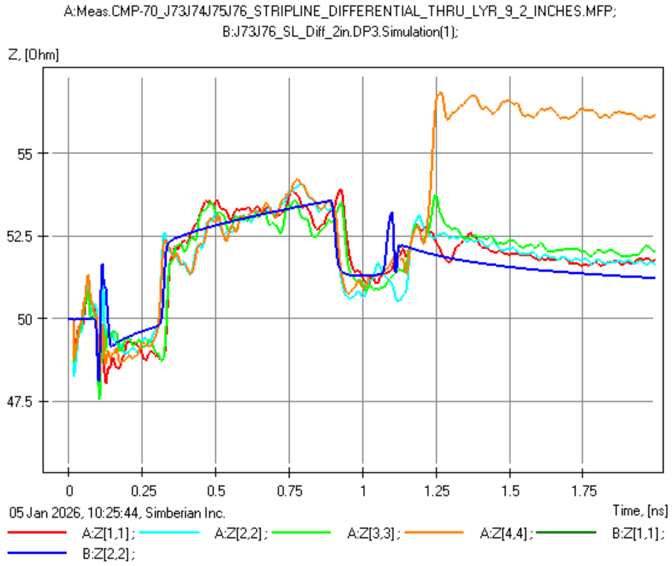
Analysis-To-Meas As Is: J73J76 – SL DIFF 2in

J73/J74	DP3+	SL 100 Ohm DIFF, 2 inches, L9	Identification	"CMP-70_J73J74J75J76_STRIPLINE_DIFFERENTIAL_THRU_LYR_9_2_INCHES.s4p"
J75/J76	DP3-	SL 100 Ohm DIFF, 2 inches, L9		same

Observations:
Impedance is Perfect;
TDR Delay is OFF;
IL is OFF;
FEXT: OFF;
SPS: BAD;

Solution CMP-70-PreQualify





* **Overall SPS Score (100% BW):** 36.31 → **Bad**
* **Overall SPS Score (80% BW):** 43.27 → **Bad**

The "Disaster": Why No Correlation?

- The Usual Suspects:
  - Bad Measurements? (VNA calibration, operator error)
  - Not Accurate Analysis? (not validated solvers)
  - Launch Issues? (Poor localization, calibration or de-embedding artifacts)
  - Wrong Material Models? (Datasheet Dk/Df vs. reality, roughness)
  - Manufacturing Variations? ("As-Designed" != "As-Built")

- The realization: If we do nothing or try to tune everything simultaneously, we are just guessing (*the "sink" approach*).
- The Path Forward: We need a systematic approach to isolate and eliminate uncertainties one by one (*the "swim" approach*).

The "Swim" Approach: A Systematic Workflow

1. Prequalify measurements with formal quality metrics
2. Identify dielectric and conductor roughness models
   a. Select structures for material model identification and pre-qualify them
   b. Identify manufacturing adjustments – cross-section geometry
   c. Identify models for dielectrics and conductor roughness
3. Run analysis for all 41 validation structures and compare with measurements (no further adjustments)
   a. Analyze: Separate Swimmers (Pass) from Sinkers (Fail)
   b. Investigate the sinkers and figure out what is predictable and what is not

Y. Shlepnev, Sink or Swim at 28 Gbps - The PCB Design Magazine, October 2014, p. 12-23.
M. Marin, Y. Shlepnev, 40 GHz PCB Interconnect Validation: Expectations vs. Reality, DesignCon 2018
M. Marin, Y. Shlepnev, Systematic approach to PCB interconnects analysis to measurement validation, EMC 2018

1a. Prequalify with Formal Quality Measures

First introduced at IBIS forum at DesignCon 2010
Now part of IEEE Standard P370

- Passivity Quality Measure: should be >99%

$$PQM = \max\left[\frac{100}{N}\left(N - \sum_{n=1}^{N} PW_n\right), 0\right]\%$$

$$PW_n = 0 \text{ if } PM_n < A; \text{ otherwise } PW_n = \frac{PM_n - A}{B}$$

$$PM_n = \sqrt{\max\left[eigenvals\left(S^*(f_n)\cdot S(f_n)\right)\right]}$$

Simbeor:

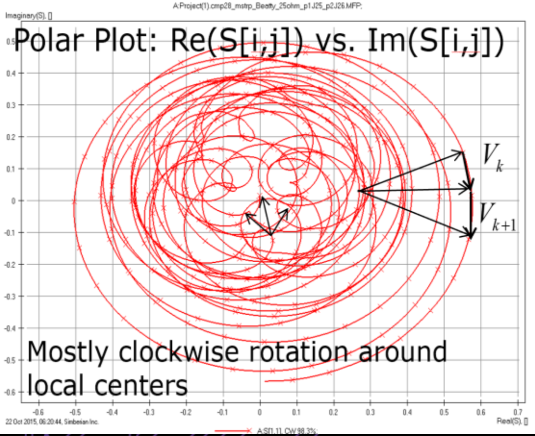
$$A = 1.00001$$
$$B = 0.1$$
$$C = 10^{-6}$$

- Reciprocity Quality Measure: should be >99%

$$RQM = \max\left[\frac{100}{N}\left(N - \sum_{n=1}^{N} RW_n\right), 0\right]\%$$

$$RM_n = \frac{1}{N_s}\sum_{i,j}\left|S_{i,j}(f_n) - S_{j,i}(f_n)\right|$$

$$RW_n = 0 \text{ if } RM_n < C; \text{ otherwise } RW_n = \frac{RM_n - C}{B}$$



- Causality (Rotational?) Quality Measure: Minimal ratio of clockwise rotation measure to total rotation measure in %
should be > 80%

1b. Prequalify with Final Quality Measure

- Accuracy of discrete S-parameters approximation with frequency-continuous macro-model, passive from DC to infinity and RMSE is uses as the quality measure

Rational Compact Model (RCM)

$$RMSE = \max_{i,j}\left[\sqrt{\frac{1}{N}\sum_{n=1}^{N}\left|S_{ij}(n) - S_{ij}(\omega_n)\right|^2}\right]$$

$$S_{i,j}(i\omega) = \left[d_{ij} + \sum_{n=1}^{N_{ij}}\left(\frac{r_{ij,n}}{i\omega - p_{ij,n}} + \frac{r_{ij,n}^*}{i\omega - p_{ij,n}^*}\right)\right]\cdot e^{-s\cdot T_{ij}}$$

original tabulated data

$$Q = 100\cdot\max\left(1 - RMSE, 0\right)\%$$

Introduced in “Reflections on S-parameter Quality”
IBIS Summit at DesignCon 2011

Final metric (includes passivity and causality)

Model Icon/Quality	Quality Metric	RMSE
- good	[99, 100]	[0, 0.01]
- acceptable	[90, 99)	(0.01, 0.1]
- inconclusive	[50, 90)	(0.1, 0.5]
- bad	[0, 50)	> 0.5
- uncertain	[0,100], not passive or not reciprocal	

Preliminary metrics

Column color code	Passivity (PQM)	Reciprocity (RQM)	Causality (CQM)
Green – good	PQM >= 99.9	PQM >= 99.9	CQM >= 80
Blue – acceptable	99.9 > PQM >= 99	99.9 > RQM >= 99	80 > CQM >= 50
Yellow – inconclusive	99 > PQM >= 80	99 > RQM >= 80	50 > CQM >= 20
Red - bad	PQM < 80	RQM < 80	CQM < 20

Implemented in Simbeor Touchstone Analyzer…

Step 1: Prequalified Measured Data

Acceptable Final Quality Measures for 47 files (Simbeor Touchstone Analyzer)

C:\Repository\Simbeor\CMP-70_Simbeor_Kit_2025\CMP-70_s-parameters_20240401

File name	Quality	Passivity	Reciprocity
CMP-70_J1 J2 uSTRIP THRU 2 INCHES 50 OHMS LYR1.S2P	96.6	100	92.7
CMP-70_J105 SHORT TO GND LYR1.S2P	95.9	95.7	98.5
CMP-70_J106 SHORT TO GND LYR2.S2P	95.4	95.9	98.5
CMP-70_J107 SHORT TO GND LYR5.S2P	95.5	94.2	98.5
CMP-70_J108 SHORT TO GND LYR10.S2P	95.6	95.9	98.5
CMP-70_J109J110J111J112_uSTRIP_STRIPLINE_Z-AXIS_CROSSTALK.s4p	96.5	99.8	96.8
CMP-70_J11 J12 uSTRIP THRU 8 INCHES 50 OHMS LYR1.S2P	96.4	100	96.4
CMP-70_J113 J114 STRIPLINE THRU 8 INCHES 50 OHMS LYR2 CAP LAUNCHES.S2P	96.5	100	96.2
CMP-70_J115 J116 STRIPLINE THRU 8 INCHES 50 OHMS LYR2 IND LAUNCHES.S2P	96.7	100	96.2
CMP-70_J117 J118 STRIPLINE WHISKER STUBS 84 MIL PITCH.S2P	95.4	100	90.6
CMP-70_J119J120J121J122_uSTRIP_SE_VIA_CROSSTALK_ANTENNA_CAP-IND.s4p	94.7	99.9	97
CMP-70_J13 J14 STRIPLINE THRU 2 INCHES 60 OHMS LYR2.S2P	96.4	100	91.4
CMP-70_J17 J18 STRIPLINE THRU 8 INCHES 60 OHMS LYR2.S2P	95.2	100	96.5
CMP-70_J19 J20 STRIPLINE THRU 8 INCHES 40 OHMS LYR9.S2P	96.2	100	96
CMP-70_J21 J22 STRIPLINE THRU 2 INCHES 50 OHMS LYR2 CAP LAUNCHES.S2P	95.9	100	90.8
CMP-70_J23 J24 STRIPLINE BEATTY 50-25-50 OHMS.S2P	96.7	100	91.1
CMP-70_J25 J26 STRIPLINE THRU 2 INCHES 50 OHMS LYR2 IND LAUNCHES.S2P	95.7	100	91.1
CMP-70_J27 J28 STRIPLINE BEATTY 50-60-50 OHMS.S2P	96.5	100	87.3
CMP-70_J3 J4 STRIPLINE THRU 2 INCHES 50 OHMS LYR2.S2P	95.9	100	91.5
CMP-70_J31 J32 uSTRIP SE VIA HIGHLY INDUCTIVE.S2P	96.8	100	92.5
CMP-70_J33 J34 uSTRIP SE VIA INDUCTIVE.S2P	96.9	100	92.3
CMP-70_J35 J36 uSTRIP SE VIA NOMINAL.S2P	97.2	100	92.5
CMP-70_J37J38 uSTRIP SE VIA MODERATELY CAPACITIVE.S2P	96.8	100	92.1
CMP-70_J39 J40 uSTRIP SE VIA HIGHLY CAPACITIVE.S2P	97.3	100	91.8

File name	Quality	Passivity	Reciprocity
CMP-70_J39 J40 uSTRIP SE VIA HIGHLY CAPACITIVE.S2P	97.3	100	91.8
CMP-70_J41 J42 STRIPLINE SE VIA.S2P	96	100	92.1
CMP-70_J43 J44 STRIPLINE BALANCED RESONATOR.S2P	95.8	100	91.9
CMP-70_J46 J47 STRIPLINE GRADUATED COPLANAR COUPLED.S2P	95.5	100	93.2
CMP-70_J48 J49 STRIPLINE VIA FIELD PATHOLOGY.S2P	96.2	100	93.4
CMP-70_J5 J6 STRIPLINE THRU 2 INCHES 50 OHMS LYR9.S2P	95.9	100	91.5
CMP-70_J50 J51 STRIPLINE WHISKER STUBS 50 MIL PITCH.S2P	95.8	100	91.5
CMP-70_J52 J53 uSTRIP SERIES CAP WITH REF VOID.S2P	95.9	100	97
CMP-70_J54 J55 uSTRIP SERIES CAP WITHOUT REF VOID.S2P	95.8	100	98.4
CMP-70_J56 uSTRIP SHORT TO GND 1 INCH.S2P	95.6	95.9	98.5
CMP-70_J57 STRIPLINE SHORT TO GND 1 INCH.S2P	95.7	95.8	98.5
CMP-70_J58 J59 STRIPLINE OFFSET RADIAL STUB RESONATOR 50 MIL SEP.S2P	95.9	100	91.9
CMP-70_J60 J61 STRIPLINE OFFSET RADIAL STUB RESONATOR 84 MIL SEP.S2P	96	100	90.6
CMP-70_J62 J63 MICROSTRIP ANISOTROPIC RESONATOR.S2P	96.2	100	91.9
CMP-70_J64J65J66J67_uSTRIP_SE_VIA_CROSSTALK_ANTENNA_NOM-NOM.s4p	95.1	99.4	96.9
CMP-70_J69J70J71J72_uSTRIP_DIFFERENTIAL_THRU_LYR_1_2_INCHES.s4p	94.8	99.7	96.8
CMP-70_J7 J8 uSTRIP THRU 2 INCHES 50 OHMS LYR10.S2P	95.9	100	92.8
CMP-70_J73J74J75J76_STRIPLINE_DIFFERENTIAL_THRU_LYR_9_2_INCHES.s4p	95.5	99.9	96.7
CMP-70_J77J78J79J80_uSTRIP_DIFFERENTIAL_THRU_LYR_10_6_INCHES.s4p	95.6	100	97.2
CMP-70_J81J82J83J84_STRIPLINE_DIFFERENTIAL_THRU_LYR2_6_INCHES.s4p	95.9	100	97.6
CMP-70_J85J86J87J88_uSTRIP_DIFFERENTIAL_PAIR_BEATTY.s4p	95.6	100	96.7
CMP-70_J89J90J91J92_uSTRIP_DIFFERENTIAL_PAIR._WITH_PLANE_CUTOUT.s4p	95.1	99.7	96.6
CMP-70_J9 J10 STRIPLINE THRU 8 INCHES 50 OHMS LYR2.S2P	95.8	100	96.4
CMP-70_J97J98J99J100J101J102J103J104_STRIPLINE_DIFFERENTIAL_COUPLED_uVIA...	85.4	98.6	97.7

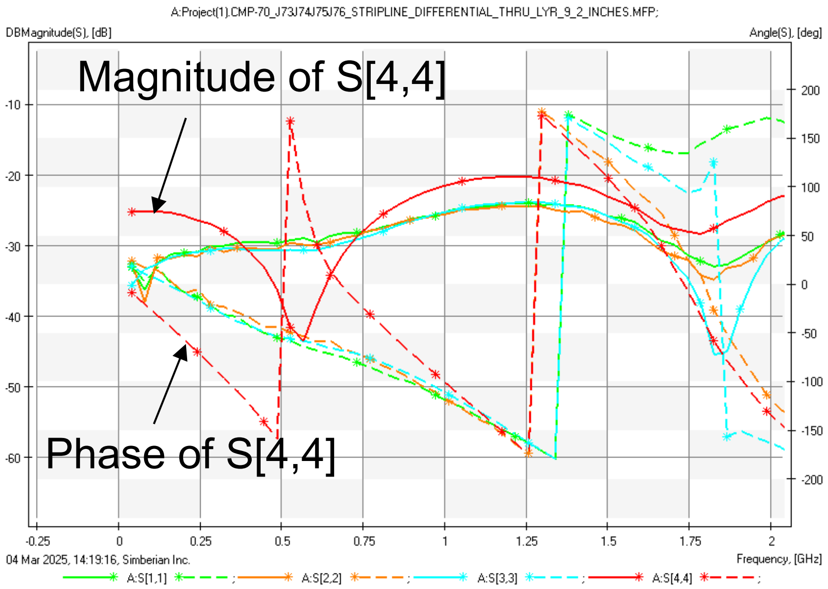
Very noisy elements

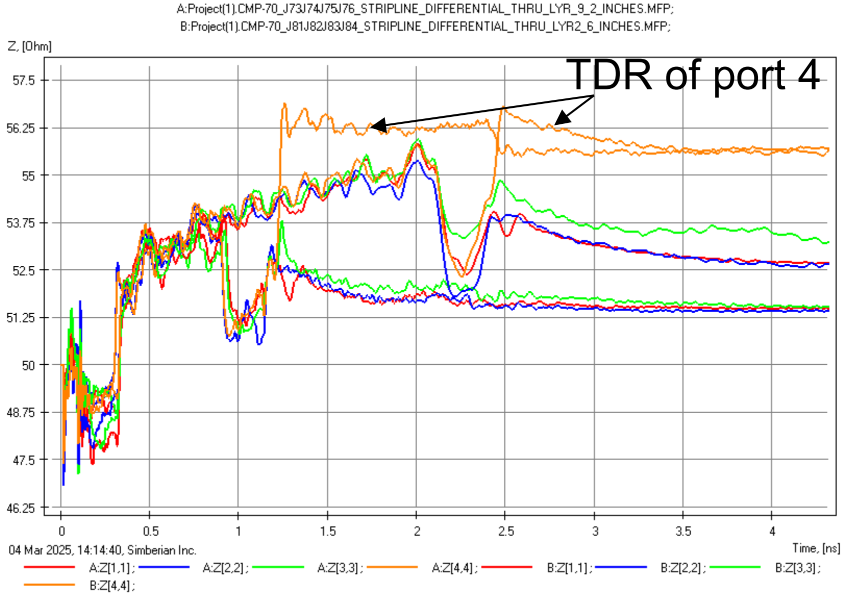
Let's take a close look at structures for material model identification and validation…

SL DIFF : Low-Frequency Problem

DP3 (J73-76) and DP4 (J81-84) Severe symmetry violation – symmetric structure, but S[4,4] is difference, that shows up on TDR

Relatively large variation of impedance along the segments



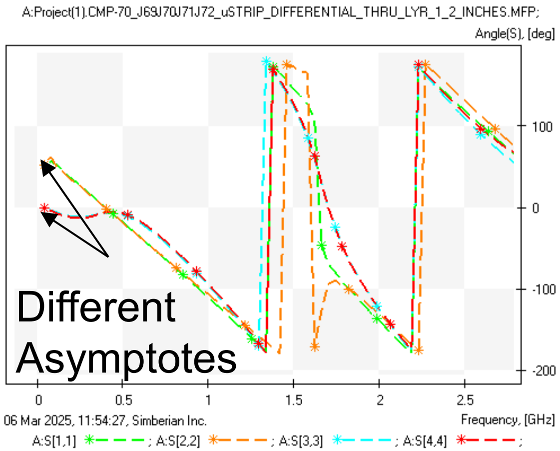


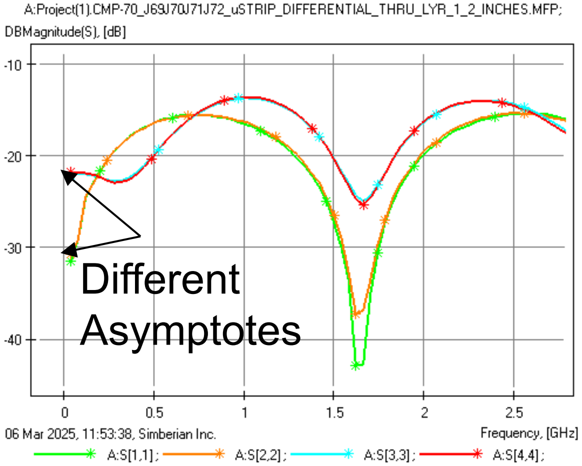
Cannot be used to identify copper resistivity

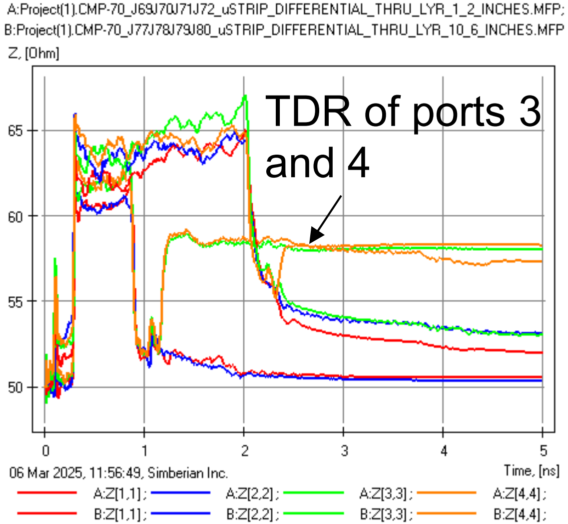
MSL DIFF: Low-Frequency Problem

Severe symmetry violation – symmetric structure, but S[3,3] and S[4,4] are different from S[1,1] and S[2,2] at lower frequencies, that shows up on TDR as well

Relatively large variation of impedance along the segments and between the segments



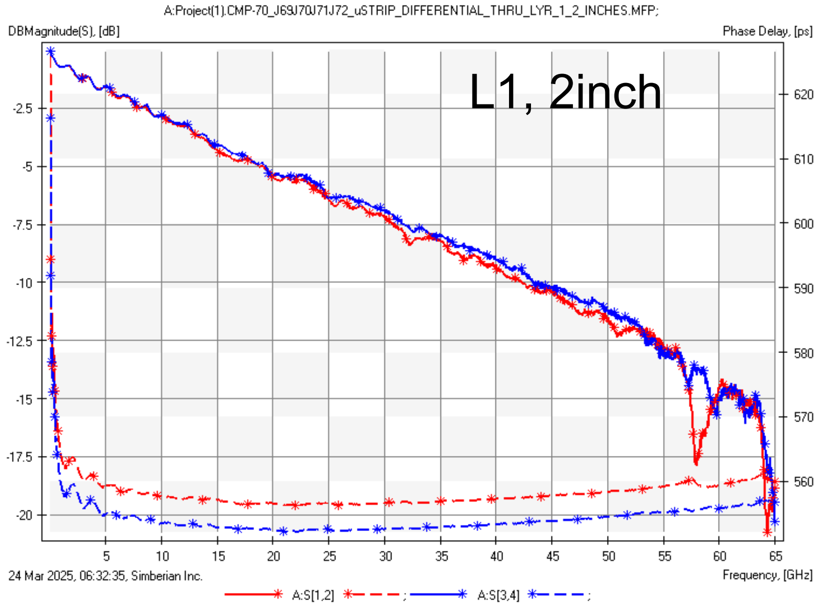


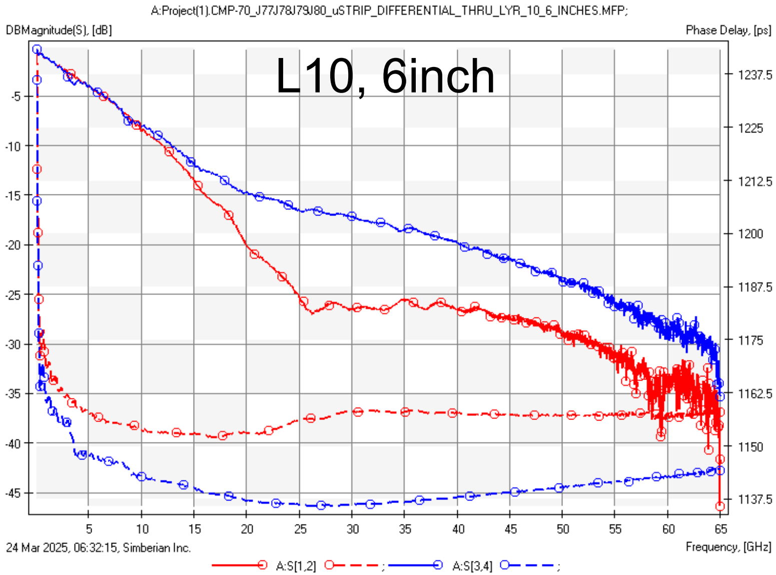


Cannot expect ideal results on MSL differential segments

MSL DIFF Sever Asymmetry

Structures for material model identification: IL and PD should be identical

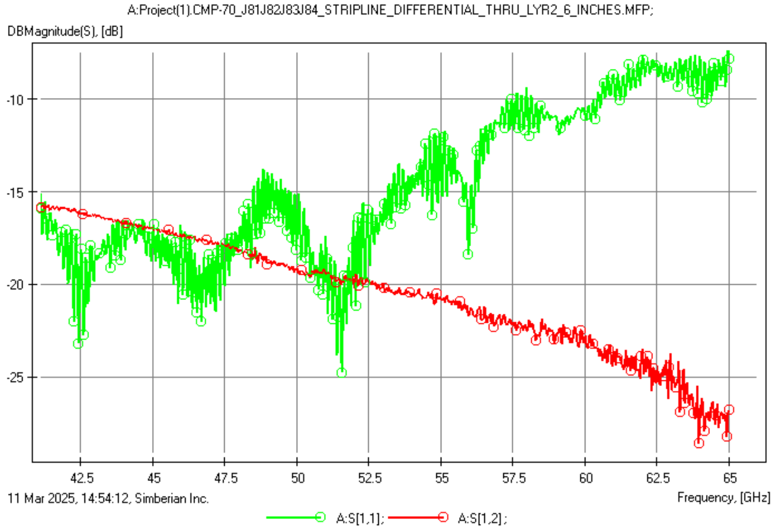


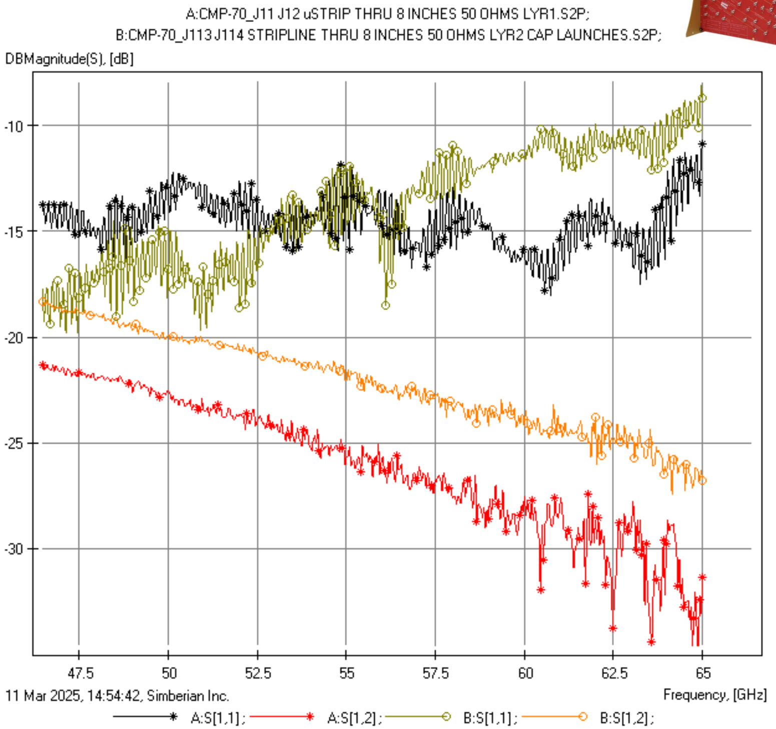


Cannot expect accurate identification and ideal correlation on microstrip differential segments – source of unpredictability

High-Frequency Oscillations

On almost all measurements – do not correlate with the electrical length of the structures - something longer may cause that
Difficult to build RCM – lower Quality





Expect noisy GMS-parameters at higher frequencies – that further reduces the material model identification bandwidth (in addition to the impedance variations)

Landscape of Material Identification Methods

1. **The "Loss Only" Approach**: Delta-L2 - extracts propagation constant (Gamma) from S-parameters.

   Limitation: Evaluates loss only; no material models generated.

2. **The "Overkill" Approach**: Complete De-embedding (TRL, AFR, ISD): Removes fixture effects.

   Limitation: Unnecessarily complicated. Output has reflections and coupling artifacts.

3. **The Time-Domain Approach (SPP):** Standard SPP (IPC-TM-650): The official standard.

   Limitation: Low-frequency defects prevent separation of conductor vs. dielectric loss.

4. **SPP-Light or Gamma-T**: Use Gamma or combine it with T-resonator (EPEPS’16, DesignCon’17).

   Limitation: Accurate, but resource-heavy (requires 3 separate structures).

5. **The Best Option:** Generalized Modal S-parameters or GMS-parameters (EPEPS’15).

   Advantage: Similar physics to SPP but uses S-parameters. Similar to Delta-L2, but allows material model identification (uses accurate t-line models).

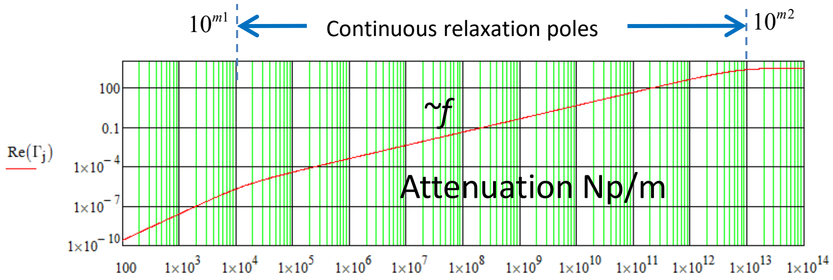
Revelation: We never measure material properties directly. We ***infer*** *them by fitting a model to measurements – so, let’s discuss the models first…*

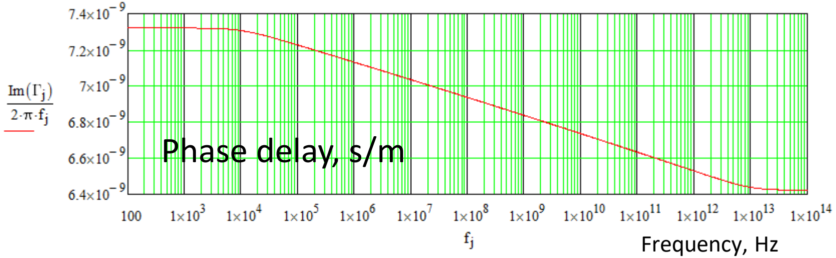
Dielectric Model: Wideband Debye

More in Material World… tutorial (DesignCon'16

Aka Djordjevic-Sarkar or Swensson-Dermer

$$\varepsilon_r(f) = \varepsilon_\infty + \sum_{k=1}^{K} \frac{\Delta\varepsilon_k}{1 + i\, f / f_{rk}} \Rightarrow \varepsilon_r(f) = \varepsilon_\infty + \frac{\Delta\varepsilon}{(m_2 - m_1)\cdot \ln(10)} \cdot \ln\left[\frac{10^{m2} + if}{10^{m1} + if}\right]$$

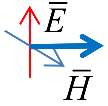




Example:

Plane wave propagation constant

$$\Gamma(f) = i 2\pi f \sqrt{\varepsilon_r(f)\cdot \varepsilon_0 \cdot \mu_0}$$

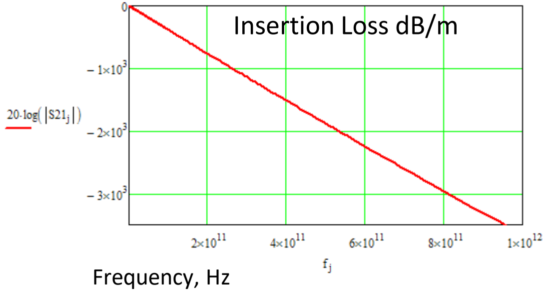


$$\varepsilon_\infty = 3.707;\ \Delta\varepsilon = 1.108;\ m1 = 4;\ m2 = 13;$$

$$\mathrm{Re}\left(\varepsilon(10^9)\right) = 4.2;\ \tan\delta\left(10^9\right) = 0.02$$

Generalized transmission parameter for distance *l:*

$$S21(\omega) = e^{-\Gamma \cdot l}$$



This model can be defined with Dk and LT measured at 1 frequency point!

Other wideband model options: Havriliak-Negami

Conductor Roughness Model: Huray-Bracken

J. E. Bracken, A Causal Huray Model for Surface Roughness, DesignCon 2012

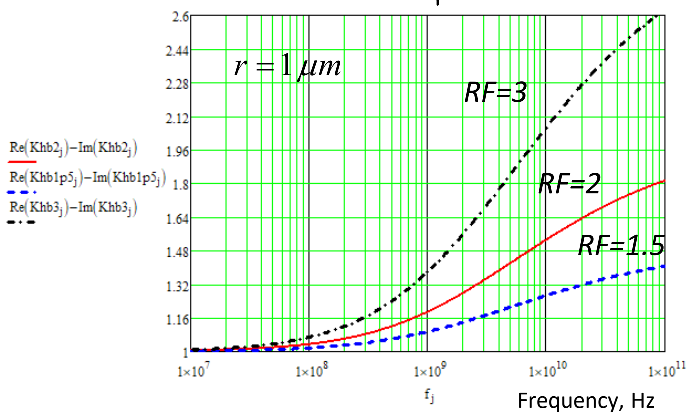
$$K_{sr} = 1 + \sum_k \left((RF_k - 1) \cdot \left(1 + (1-i)\frac{\delta_s}{2r_i} \right)^{-1} \right) \qquad \delta_s = (\pi \cdot f \cdot \mu \cdot \sigma)^{-1/2}$$

Makes SIBC causal! $Z_{rough} = \frac{K_{sr}}{\sigma \cdot \delta_s} \cdot (1+i)$

***RF**i - roughness factor, defines maximal growth of losses due to all balls with radius ri;*
*ri – ball radius (**SR**i parameter in Simbeor);*

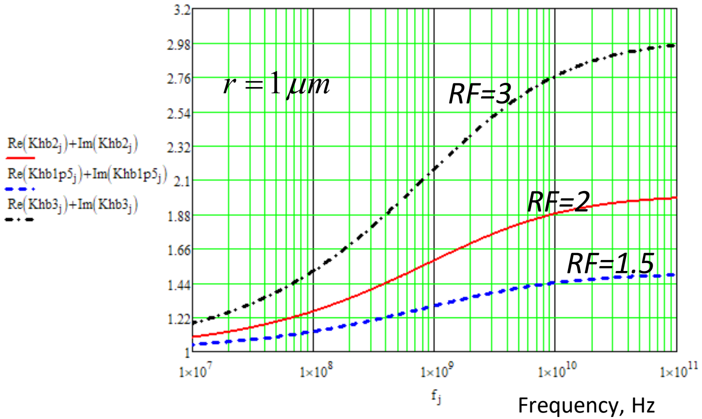
Conductor losses (same as in Huray model)

$$\mathrm{Re}(Z_{rough}) = [\mathrm{Re}(K_{sr}) - \mathrm{Im}(K_{sr})] \cdot \frac{1}{\sigma \cdot \delta_s}$$



Additional conductor inductance

$$\mathrm{Im}(Z_{rough}) = [\mathrm{Re}(K_{sr}) + \mathrm{Im}(K_{sr})] \cdot \frac{1}{\sigma \cdot \delta_s}$$



One-level model has 2 parameters: SR (metric) and RF

Causal Hammerstad is an alternative

The GMS Identification Algorithm (5 Steps)

1. Measure Two Lines: Measure S-parameters of two transmission lines with lengths L1 and L2 (where L2>L1).

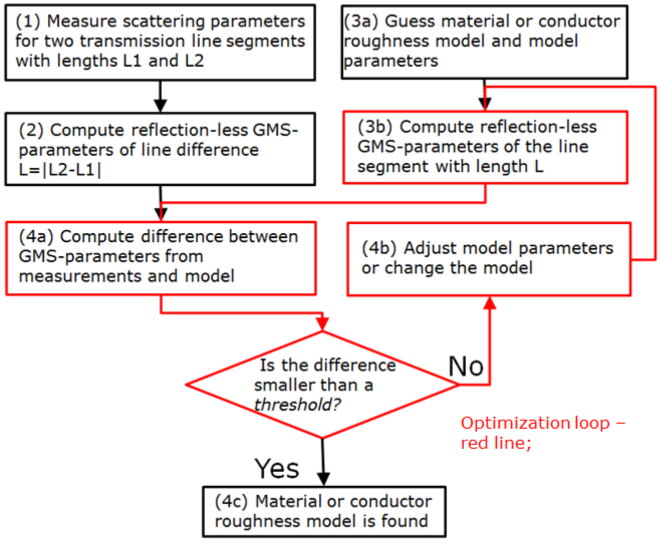
2. Extract "Measured" GMS-Parameters: Compute GMS-parameters for the **virtual line segment** (L2−L1).

Benefit: This mathematically de-embeds the launches/fixtures without physical calibration.

3. Initialize the Physics: Define the geometry (Cross-section) and Material Models (Wideband Debye, Huray-Bracken). Set **initial seed values** for the unknown parameters (e.g., Dk, Df, SR, RF).

4. Compute "Model" GMS-Parameters: Solve Maxwell’s equations (2D or 3D Field Solver) for the cross-section to generate the S-parameters of the model.

5. Optimize (The Inverse Problem): Run an optimizer to minimize the error between **Measured GMS** and **Model GMS** by adjusting the material parameters.



Introduced in Simbeor in 2009 and published in DesignCon 2010 paper

Generalized Modal S-parameters (GMS-parameters)

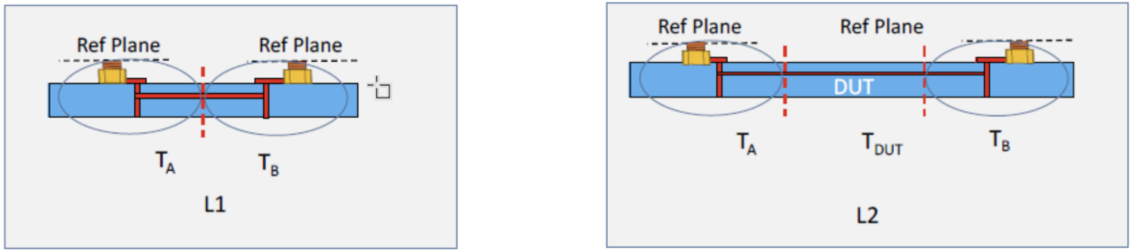


Figure 3. Two-line structure for Eigenvalue based method

From IPC-TM-650 Method 2.5.5.14
Also, EPEPS'16

$$T_{L1} = T_A \times T_B \qquad \text{(eq. 2)}$$

$$T_{L2} = T_A \times T_{DUT} \times T_B \qquad \text{(eq. 3)}$$

where DUT is the transmission line with length of L2-L1. From (1) and (2) we can easily get

$$T_{L2} \times T_{L1}^{-1} = T_A \times T_{DUT} \times T_B \times T_B^{-1} \times T_A^{-1} = T_A \times T_{DUT} \times T_A^{-1} \qquad \text{(eq. 4)}$$

Therefore, $T_{L2} \times T_{L1}^{-1}$ and T_{DUT} are similar matrices, and should have the same eigenvalue. Meanwhile, assuming the DUT is a uniform transmission line, we have:

Reflection-less GMS-Parameters

$$T_{DUT} = \begin{bmatrix} e^{\gamma(L2-L1)} & 0 \\ 0 & e^{-\gamma(L2-L1)} \end{bmatrix} \qquad \text{(eq. 5)}$$

$$S_{DUT} = \begin{bmatrix} 0 & e^{-\gamma L} \\ e^{-\gamma L} & 0 \end{bmatrix} \qquad \text{(eq. 1)}$$

N. R. Franzen, R. A. Speciale, "A New Procedure for System Calibration and Error Removal in Automated S-Parameter Measurements", Proceedings of the 5th European Microwave Conference, Hamburg, Germany, 1-4 September 1975, pp. 69-73.

Three Strategies for Loss Identification

1. Simultaneous Identification

Best for: **Low-Loss** dielectrics (where Df is relatively small).
Method: Optimize Df and RF, SR variables together over separate bandwidths.
Risk: Requires pristine test structures and low-noise measurements.

2. Bandwidth Separation (Divide & Conquer)

Best for: **Medium to High-Loss** dielectrics.

- **< 50 MHz:** Identify Bulk Resistivity (DC/Skin-effect onset).
- **< 1 GHz:** Identify Dielectric Loss (Roughness impact is negligible).
- **> 2 GHz:** Identify Roughness Model (Conductor loss dominates).

Refinement: Iterate to fine-tune.

3. The "Trusted Laminate Vendor" Approach

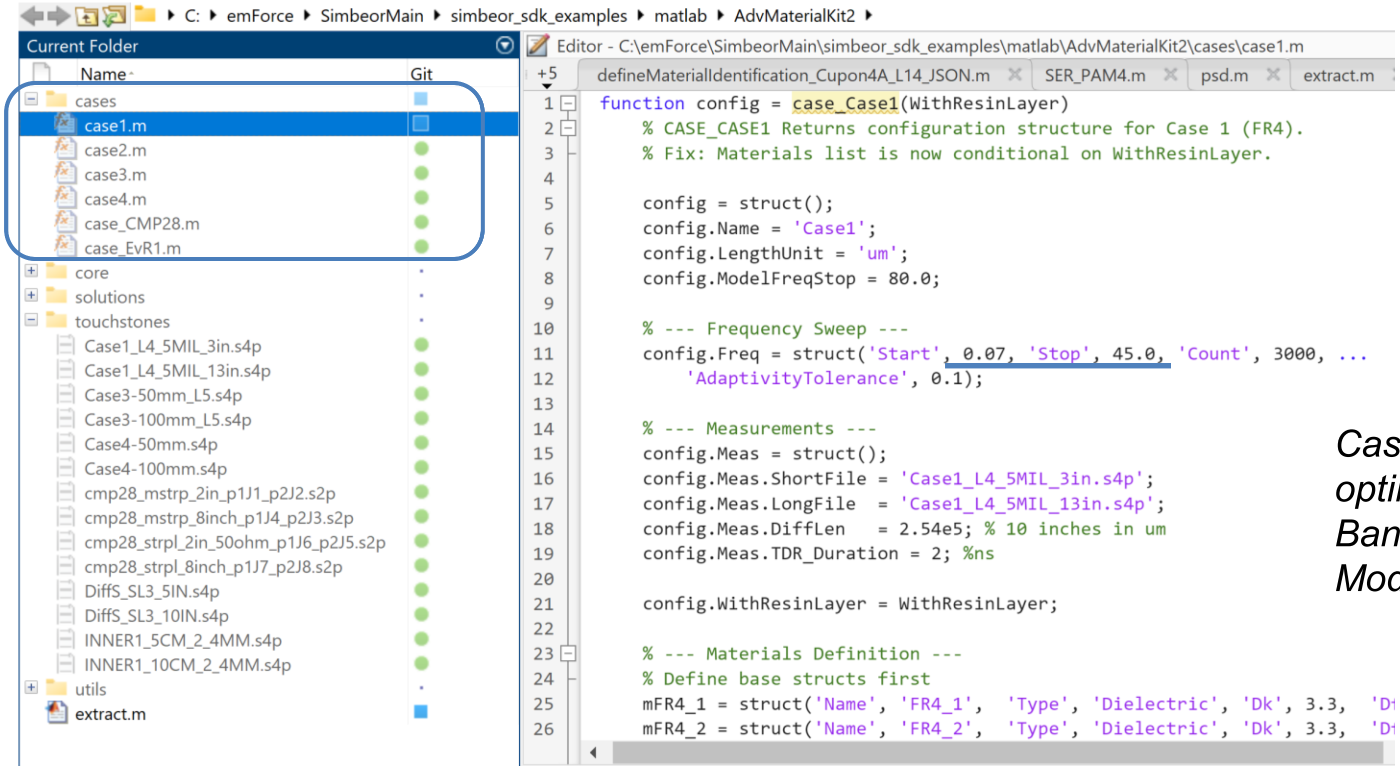
Best for: **Ultra-Low-Loss** and **Low-Loss** reliable laminate data sets.
Method: **Fix Df** to the manufacturer's spec. Identify **only SR and RF** parameters.
Result: Simplify the process without affecting the accuracy (roughness dominates).

← *Spoiler - Best for CMP-70 Isola's Tachyon*

Select strategy or quickly try each approach with AdvMaterialKit2 in Simbeor SDK

Material Identification Script Examples

AdvMaterialKit2 is available in Simbeor SDK 2025.01



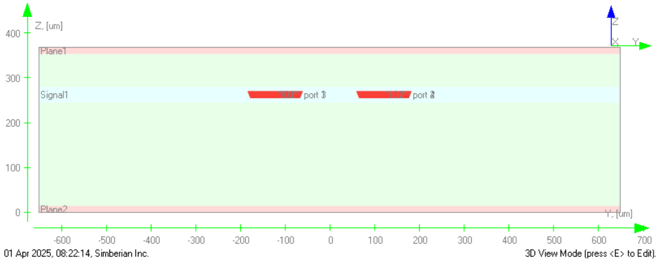
Case1 – simultaneous optimization of Df, SR and RF
Bandwidth 45GHz
Model up to 80GHz

Case1: Simultaneous Optimization Example Setup

Differential Stripline with resin layer (to have FEXT)

Describe cross-section with initial values for models to be identified

File case1.m




```
% --- Materials Definition ---
% Define base structs first
mFR4_1 = struct('Name', 'FR4_1',  'Type', 'Dielectric', 'Dk', 3.3,  'Df', 0.001, 'ID_Group', 1);
mFR4_2 = struct('Name', 'FR4_2',  'Type', 'Dielectric', 'Dk', 3.3,  'Df', 0.001, 'ID_Group', 1);
mResin = struct('Name', 'Resin',  'Type', 'Dielectric', 'Dk', 3.3,  'Df', 0.001, 'ID_Group', 2);
mCond  = struct('Name', 'Copper', 'Type', 'Conductor',  'Res', 1.05,'SR', 0.001, 'RF', 8.0, 'ID',
```

```
else
    % WITH Resin: Include it in list
    config.Materials = {mFR4_1, mFR4_2, mResin, mCond};

    config.Stackup = {
        struct('Type', 'Plane',  'Name', 'L1', 'Thick', 14.31, 'Mat', 'Copper', 'Fill', 'FR4_2'),
        struct('Type', 'Medium', 'Thick', 74,    'Fill', 'FR4_2'), ...
        struct('Type', 'Medium', 'Thick', 10,    'Fill', 'Resin'), ...
        struct('Type', 'Signal', 'Name', 'L2', 'Thick', 15.37, 'Fill', 'Resin', 'Cond', 'Copper'),
        struct('Type', 'Medium', 'Thick', 10,    'Fill', 'Resin'), ...
        struct('Type', 'Medium', 'Thick', 231,   'Fill', 'FR4_1'), ...
        struct('Type', 'Plane',  'Name', 'L3', 'Thick', 14.31, 'Mat', 'Copper', 'Fill', 'FR4_2')
    };
end

% --- Trace Geometry ---
config.Trace = struct();
config.Trace.Layer = 'L2';
config.Trace.Width = 117;
config.Trace.Spacing = 126;
config.Trace.Shape = 'Trapezoidal';
config.Trace.EtchFactor = 0.39;
```

Case1: Simultaneous Optimization Goals

Differential Stripline with resin layer (to have FEXT)

Define Goals and bandwidth for each goal
File case1.m

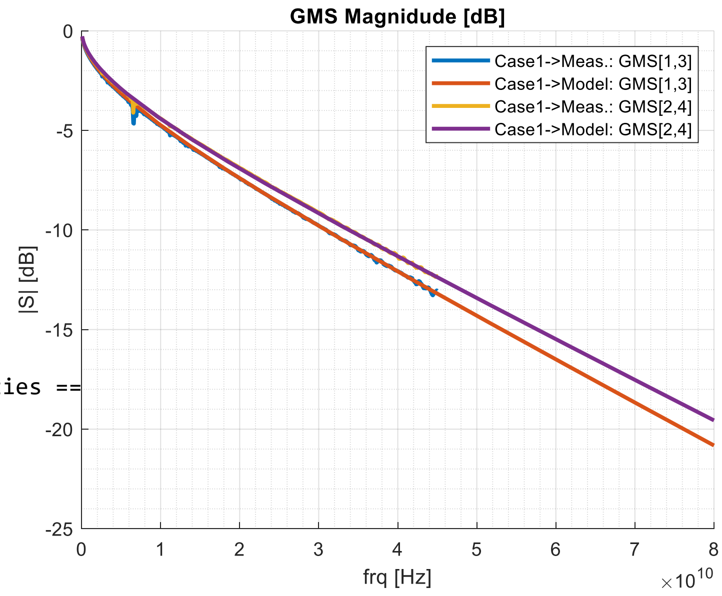

```
% --- Optimization Goals ---
config.Goals = struct();
config.Goals.RoughnessAndLT = true;
config.Goals.FineTuneLosses = true;
config.Goals.FineTuneRoughness = true;

config.Goals.Dk = struct('Optimize', true, 'Min', 1.0, 'Max', 5.0, ...
    'FrqMin', 1.0e9, 'FrqMax', 45e9);
config.Goals.Df = struct('Optimize', true, 'Min', 0.001, 'Max', 0.01, ...
    'FrqMin', 0.07e9, 'FrqMax', 1.0e9);
config.Goals.Resistivity = struct('Optimize', true, 'Min', 1.0, 'Max', 1.4, ...
    'FrqMin', 0.01e9, 'FrqMax', 0.02e9);

config.Goals.Roughness = struct();
config.Goals.Roughness.SR = struct('Optimize', true, 'Min', 0.0, 'Max', 0.1);
config.Goals.Roughness.RF = struct('Optimize', true, 'Min', 1.0, 'Max', 20.0);
config.Goals.Roughness.FrqMin = 10.0e9;
config.Goals.Roughness.FrqMax = 45e9;
```

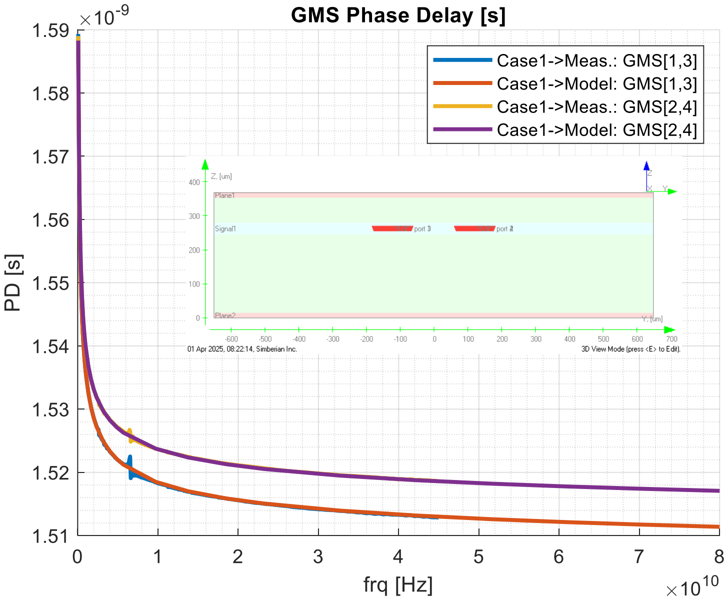
Optimize Df, SR and RF simultaneously

Case1: Simultaneous Identification Results

```
Final Dielectric Properties:
     Name: {'FR4_1'}
    Model: 'WidebandDebye'
       Dk: 3.2442
       LT: 0.0013
      Frq: 1.0000e+09

     Name: {'FR4_2'}
    Model: 'WidebandDebye'
       Dk: 3.2442
       LT: 0.0013
      Frq: 1.0000e+09

     Name: {'Resin'}
    Model: 'WidebandDebye'
       Dk: 2.9237
       LT: 0.0013
      Frq: 1.0000e+09

=== Final Conductor Properties ==
         Name: 'Copper'
           RR: 1.0500
    Roughness: [1×1 struct]

--- Conductor Roughness ---
    Model: 'HurayBracken'
       SR: 0.0335
       RF: 17.1718
```

Identification With Resin Layer: difference in Odd and Even modes cause FEXT
Measured vs. Modeled GMS-parameters



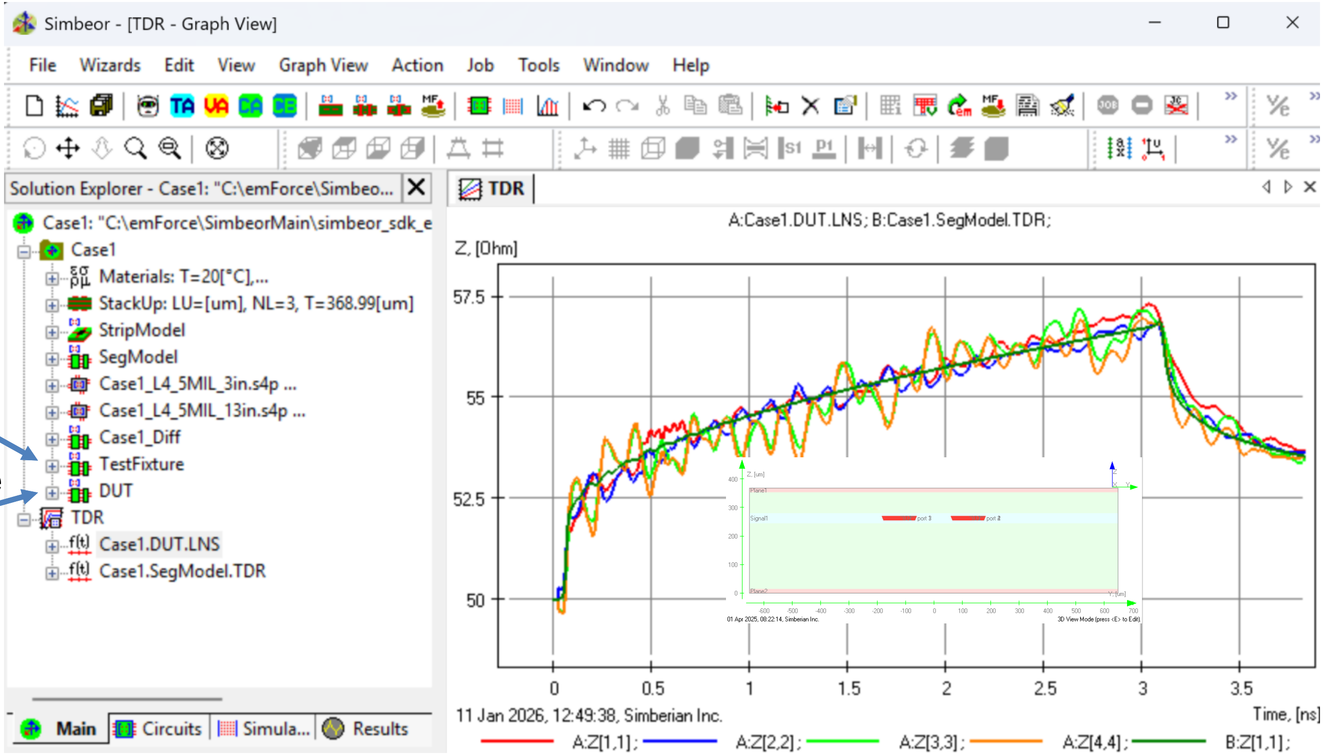


Case1: DUT, TDR & Solution

Solution with identified material models is written into **solutions** folder of the Kit

Optionally, test fixture is extracted for de-embedding,

And L2-L1 segment of t-line is de-embedded (DUT) to compare analysis to measured TDR

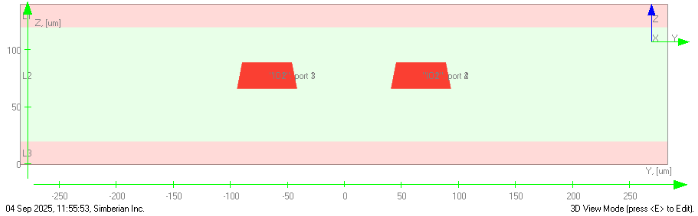


See More on deembedding steps: https://kb.simberian.com/browse_item.php?id=849

Case3: Bandwidth Separation Example Geometry

Describe cross-section with initial values for models to be identified

File case3.m



extract.m | case3.m

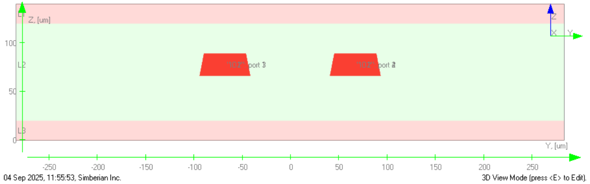
```
function config = case3(WithResinLayer)
    % CASE3 Returns configuration structure for Cupon1 L5.
    % Converted from defineMaterialIdentification_Cupon1_L5_JSON.m

    config = struct();
    config.Name = 'Cupon1_L5';
    config.LengthUnit = 'um';
    config.ModelFreqStop = 40.0;
      % --- Identification Frequency Sweep ---
    % fgmax = 25.0
    config.Freq = struct('Start', 0.01, 'Stop', 25.0, 'Count', 3000, ...
        'AdaptivityTolerance', 0.01);

    % --- Geometry Parameters (um) ---
    % Averaging calculations from original script
    w_top = (43.46 + 43.71) / 2;
    w_bot = (52.48 + 52.59) / 2;
    Hb    = (45.14 + 47.24) / 2; % avg_dist_to_bottom_plane
    T     = (23.20 + 22.67) / 2; % avg_thickness
    Ht    = (31.18 + 30.76) / 2; % avg_dist_to_top_plane

    % Pitch definition from original
    Pitch = 82.4 + w_bot;
```

```
% --- Materials Definition ---
mFR4_1 = struct('Name', 'FR4_1',  'Type', 'Dielectric', 'Dk', 3.3,  'Df', 0.001, 'ID_Group', 1);
mFR4_2 = struct('Name', 'FR4_2',  'Type', 'Dielectric', 'Dk', 3.3,  'Df', 0.001, 'ID_Group', 1);
mResin = struct('Name', 'Resin',  'Type', 'Dielectric', 'Dk', 3.3,  'Df', 0.001, 'ID_Group', 2);

% Conductor: Copper, Res=1.05, RF=8.0
mCond  = struct('Name', 'Copper', 'Type', 'Conductor',  'Res', 1.05,'SR', 0.001, 'RF', 8.0, 'ID'

config.WithResinLayer = WithResinLayer;

% --- Stackup & Material Selection ---
if ~WithResinLayer
    % NO Resin
    config.Materials = {mFR4_1, mFR4_2, mCond};

    config.Stackup = {
        struct('Type', 'Plane',  'Name', 'L1', 'Thick', 20, 'Mat', 'Copper', 'Fill', 'FR4_2'), .
        struct('Type', 'Medium', 'Thick', Ht, 'Fill', 'FR4_2'), ...
        struct('Type', 'Signal', 'Name', 'L2', 'Thick', T,  'Fill', 'FR4_2', 'Cond', 'Copper'),
        struct('Type', 'Medium', 'Thick', Hb, 'Fill', 'FR4_1'), ...
        struct('Type', 'Plane',  'Name', 'L3', 'Thick', 20, 'Mat', 'Copper', 'Fill', 'FR4_2')
    };
else
```

Case3: Bandwidth Separation Example Goals

Define Goals and bandwidth for each goal – similar to simultaneous optimization

File case3.m



extract.m | case3.m

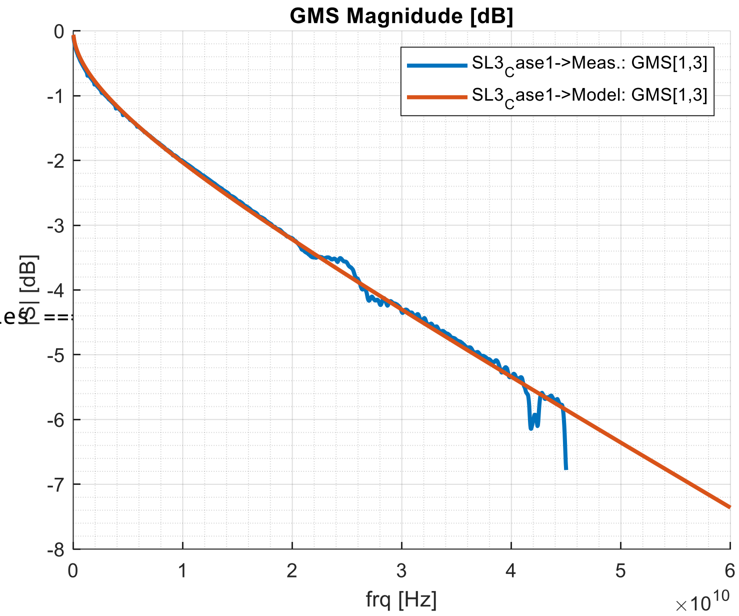
```
%   Optimization Goals
config.Goals = struct();
config.Goals.RoughnessAndLT = false;
config.Goals.FineTuneLosses = true;
config.Goals.FineTuneRoughness = true;

% Dk: 1.0 - 5.0 (1G - 25G)
config.Goals.Dk = struct('Optimize', true, 'Min', 1.0, 'Max', 5.0, ...
                         'FrqMin', 1.0e9, 'FrqMax', 25.0e9);

% Df: 0.001 - 0.02 (0.01G - 1G)
config.Goals.Df = struct('Optimize', true, 'Min', 0.001, 'Max', 0.02, ...
                         'FrqMin', 0.01e9, 'FrqMax', 1.0e9);

% Resistivity: 1.0 - 1.4 (0.01G - 0.02G)
config.Goals.Resistivity = struct('Optimize', true, 'Min', 1.0, 'Max', 1.4, ...
                                  'FrqMin', 0.01e9, 'FrqMax', 0.02e9);

% Roughness: SR(0-0.5), RF(1-20), Freq(10G-25G)
config.Goals.Roughness = struct();
config.Goals.Roughness.SR = struct('Optimize', true, 'Min', 0.0, 'Max', 0.5);
config.Goals.Roughness.RF = struct('Optimize', true, 'Min', 1.0, 'Max', 20.0);
config.Goals.Roughness.FrqMin = 10.0e9;
config.Goals.Roughness.FrqMax = 25.0e9;
```

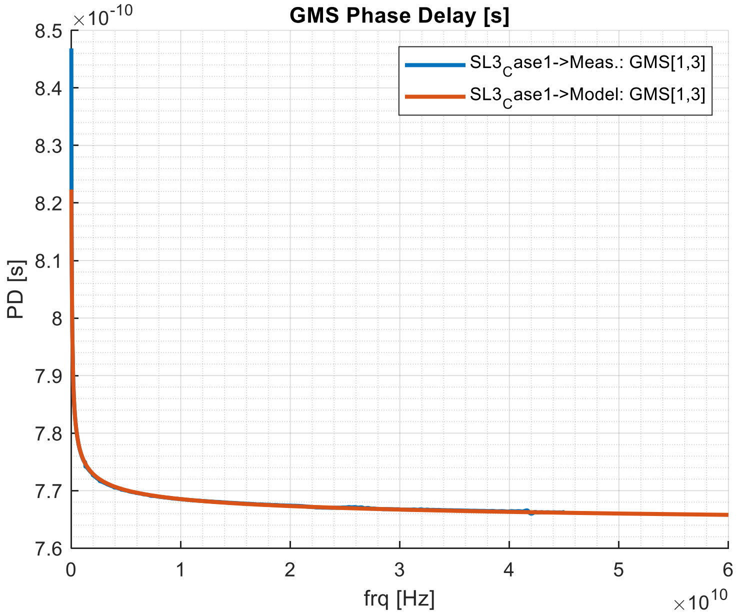
Optimize Df, SR and RF separately

Case3: Bandwidth Separation Example Results

```
Final Dielectric Properties:
      Name: {'FR4_1'}
     Model: 'WidebandDebye'
        Dk: 3.2318
        LT: 0.0015
       Frq: 1.0000e+09

      Name: {'FR4_2'}
     Model: 'WidebandDebye'
        Dk: 3.2318
        LT: 0.0015
       Frq: 1.0000e+09

=== Final Conductor Properties ===
           Name: 'Copper'
             RR: 1.1000
     Roughness: [1×1 struct]

--- Conductor Roughness ---
     Model: 'HurayBracken'
        SR: 0.0320
        RF: 20
```

Identification Without Resin Layer: identical Odd and Even mode PD, no FEXT
Measured vs. Modeled GMS-parameters





The "Swim" Approach: A Systematic Workflow

1. Prequalify measurements with formal quality metrics
2. Identify dielectric and conductor roughness models
   a. Select structures for material model identification and pre-qualify them
   b. Identify manufacturing adjustments – cross-section geometry
   c. Identify models for dielectrics and conductor roughness
3. Run analysis for all 41 validation structures and compare with measurements (no further adjustments)
   a. Analyze: Separate Swimmers (Pass) from Sinkers (Fail)
   b. Investigate the Sinkers

Step 2a: CMP-70 Material Identification Structures

Select structures for material model identification and pre-qualify them

6 single-ended SL and MSL and 4 differential SL and MSL structures;
SL – stripline; MSL – microstrip line; SE – single-ended; DIFF – differential;

Pins	Net	Description	Purpose	Files
J1/J2	N1571421	MSL 50 Ohm SE, 2 inches, L1	Identification	"CMP-70_J1 J2 uSTRIP THRU 2 INCHES 50 OHMS LYR1.S2P"
J3/J4	N2564054	SL 50 Ohm SE, 2 inches, L2	Identification	"CMP-70_J3 J4 STRIPLINE THRU 2 INCHES 50 OHMS LYR2.S2P"
J5/J6	N2564082	SL 50 Ohm SE, 2 inches, L9	Verification	"CMP-70_J5 J6 STRIPLINE THRU 2 INCHES 50 OHMS LYR9.S2P"
J7/J8	N2584712	MSL 50 Ohm SE, 2 inches, L10	Verification	"CMP-70_J7 J8 uSTRIP THRU 2 INCHES 50 OHMS LYR10.S2P"
J9/J10	N2564058	SL 50 Ohm SE, 8 inches, L2	Identification	"CMP-70_J9 J10 STRIPLINE THRU 8 INCHES 50 OHMS LYR2.S2P"
J11/J12	N1569517	MSL 50 Ohm SE, 8 inches, L1	Identification	"CMP-70_J11 J12 uSTRIP THRU 8 INCHES 50 OHMS LYR1.S2P"

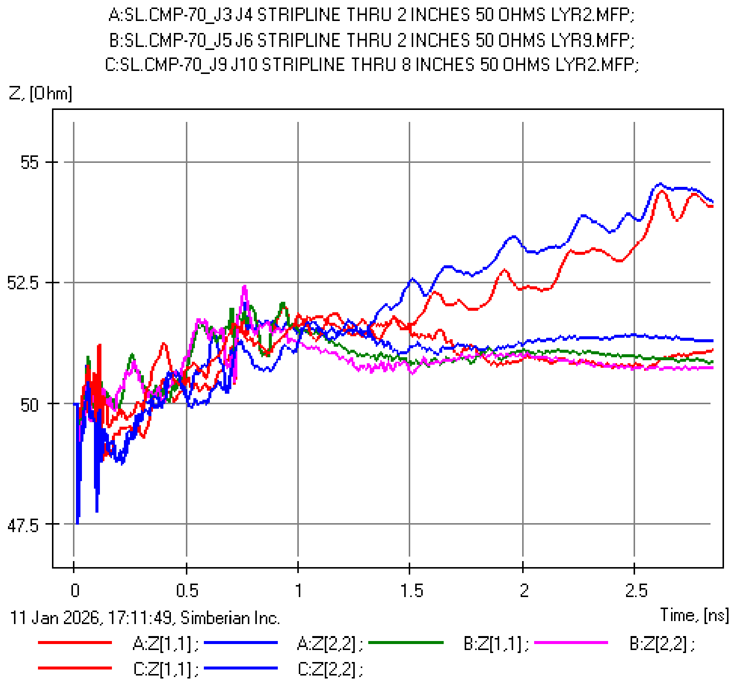
J69/J70	DP1+	MSL 100 Ohm DIFF, 2 inches, L1	Identification	"CMP-70_J69J70J71J72_uSTRIP_DIFFERENTIAL_THRU_LYR_1_2_INCHES.s4p"
J71/J72	DP1-	MSL 100 Ohm DIFF, 2 inches, L1		same
J73/J74	DP3+	SL 100 Ohm DIFF, 2 inches, L9	Identification	"CMP-70_J73J74J75J76_STRIPLINE_DIFFERENTIAL_THRU_LYR_9_2_INCHES.s4p"
J75/J76	DP3-	SL 100 Ohm DIFF, 2 inches, L9		same
J77/J78	DP2+	MSL 100 Ohm DIFF, 6 inches, L10	Identification	"CMP-70_J77J78J79J80_uSTRIP_DIFFERENTIAL_THRU_LYR_10_6_INCHES.s4p"
J79/J80	DP2-	MSL 100 Ohm DIFF, 6 inches, L10		same
J81/J82	DP4+	SL 100 Ohm DIFF, 6 inches, L2	Identification	"CMP-70_J81J82J83J84_STRIPLINE_DIFFERENTIAL_THRU_LYR2_6_INCHES.s4p"
J83/J84	DP4-	SL 100 Ohm DIFF, 6 inches, L2		same

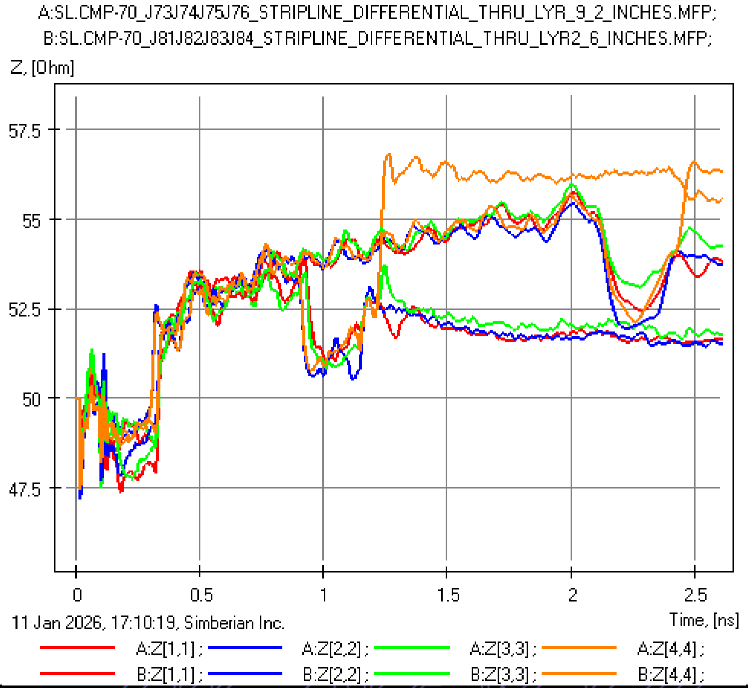
Stackup symmetry by design: L1 – L10 and L2 – L9;

Prequalify with TDR: SL

SL SE – differences within about 1.5 Ohm, traces in L2 and L9 are consistent - select two traces in L2;
SL DIFF: up to 2 Ohm differences, DC defect (discussed earlier);
Substantial variations of impedance along the traces in all cases.

Solution CMP-70-PreQualify

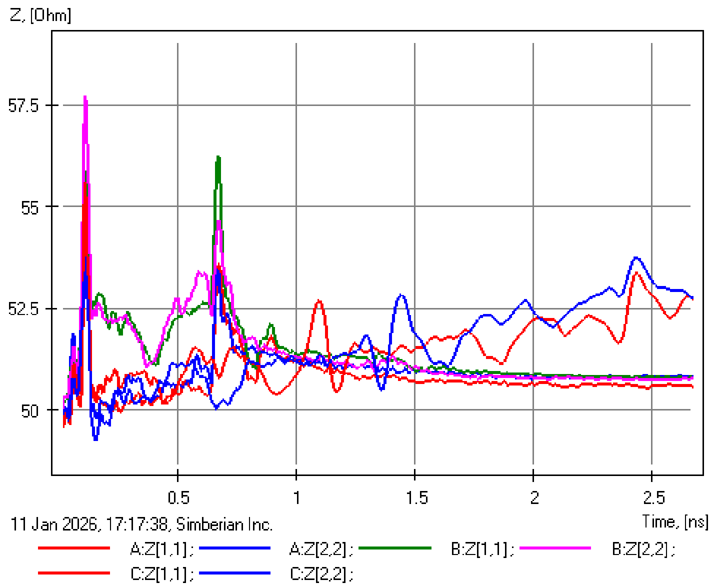


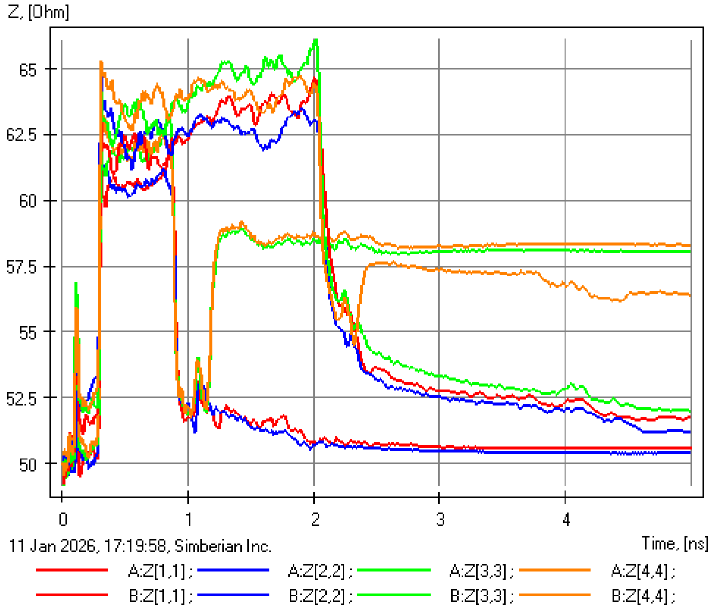


Prequalify with TDR: MSL

MSL SE – L1 is not consistent with L10 – big difference, over 2 Ohm variation, select two traces in L1;
MSL DIFF: over 3 Ohm difference in L1 and L10, DC defect;
Substantial variations of impedance along the traces in all cases.

Solution CMP-70-PreQualify

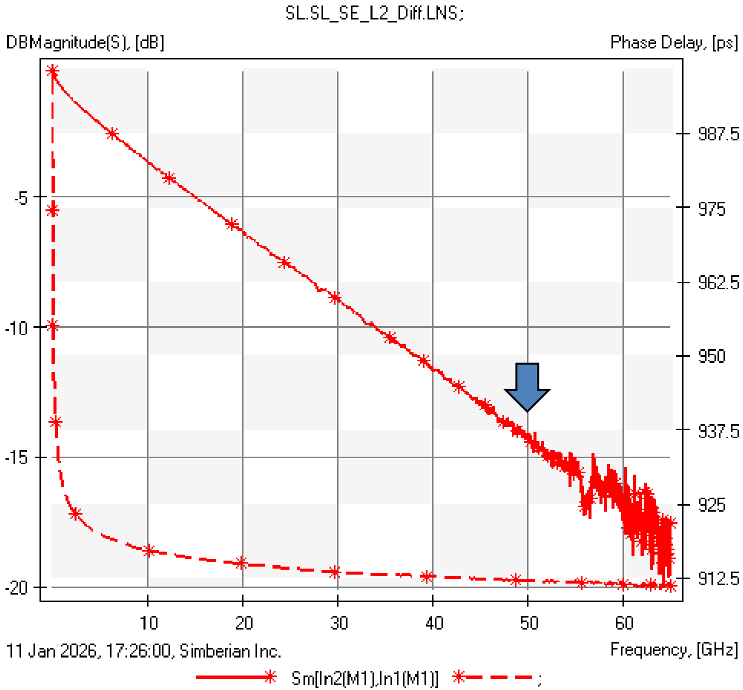


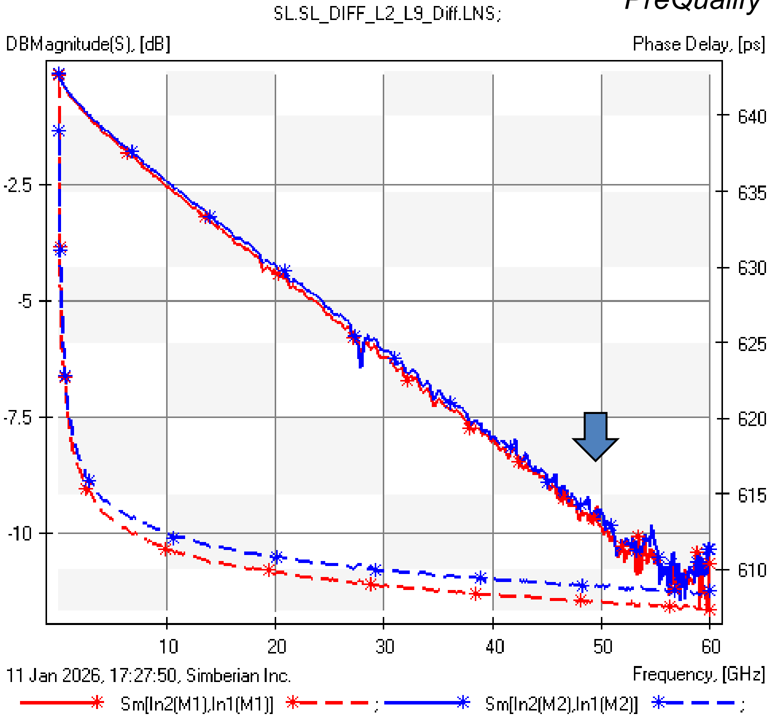


Prequalify with GMS-parameters: SL

Solution CMP-70-PreQualify

DIFF Extraction: Modes are sorted by phase; Longitudinal symmetry is enforced;
Observations: Magnitudes are noisy above about 50GHz – restrict the identification to 50GHz;

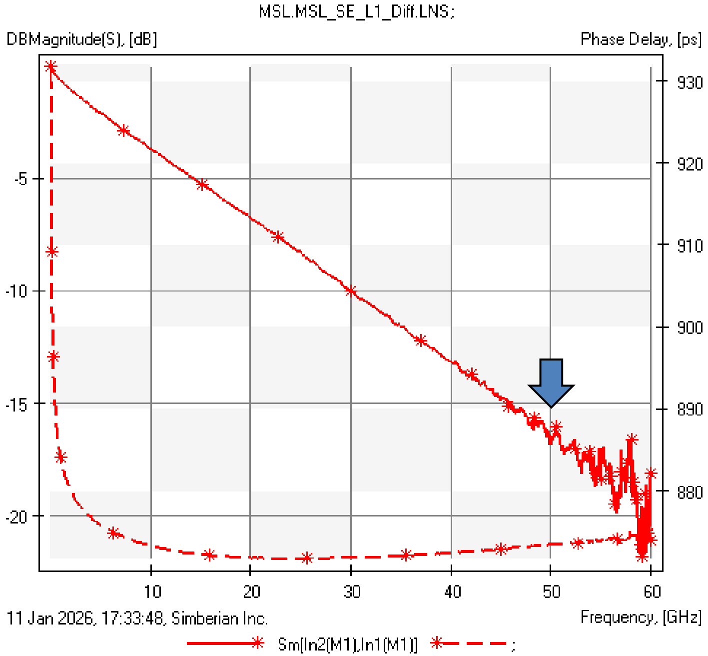


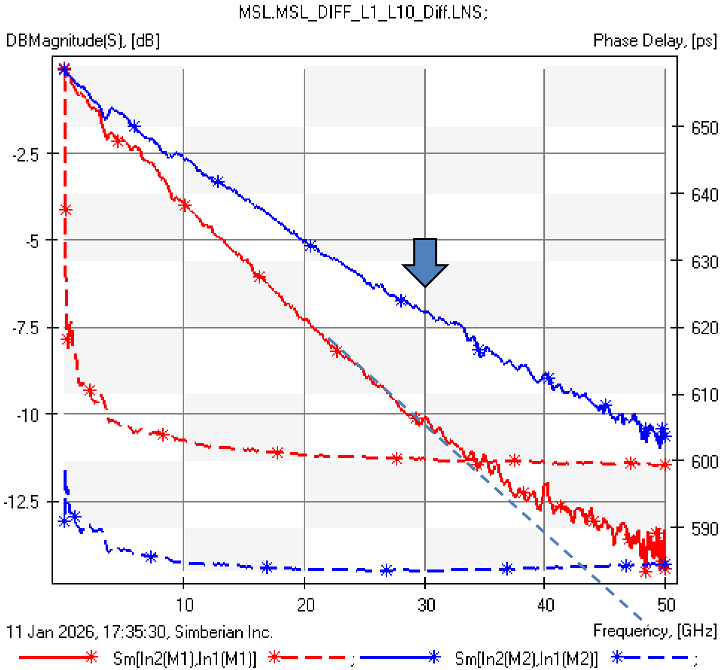


Prequalify with GMS-parameters: MSL

Solution CMP-70-PreQualify

DIFF Extraction: Modes are sorted by phase; Longitudinal symmetry is enforced;
SE magnitude are noisy above about 50GHz – restrict the identification to 50GHz;
DIFF magnitude looks strange and noisy above 30GHz – restrict bandwidth to 30GHz (consequence of the inconsistencies in impedance, symmetry violations, delay differences);





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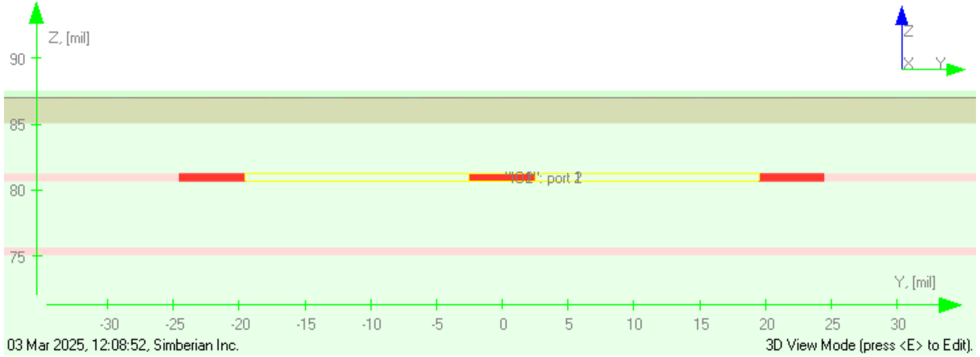
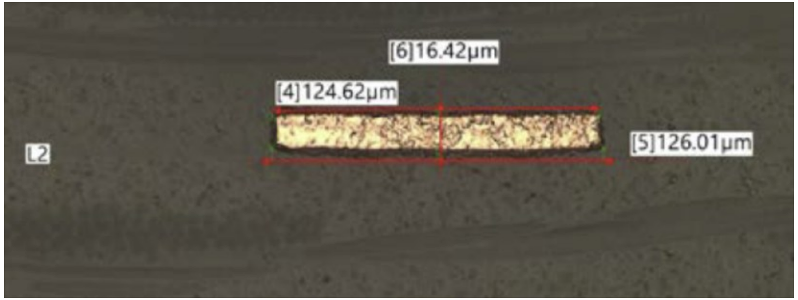
   a. Analyze: Separate Swimmers (Pass) from Sinkers (Fail)
   b. Investigate the Sinkers

SL SE: L2, N2564054

Width 5mil, 17mil clearance,
0.6 mil thickness



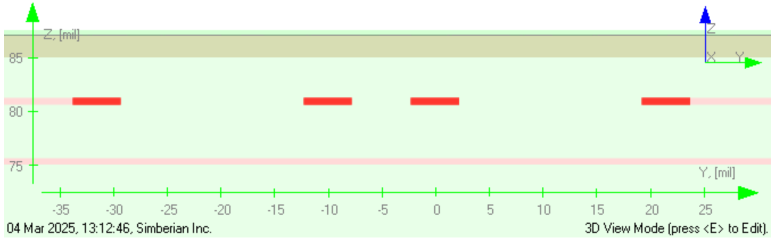
Width ~4.92mil,
Thickness ~0.65 mil (as shown)



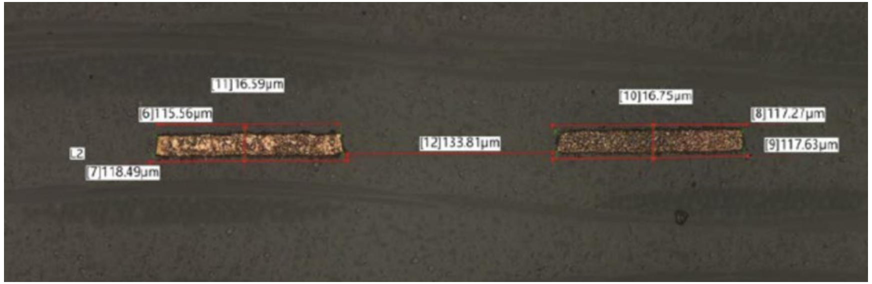
No adjustment or Width adjustment -0.1 for interior layers (minor increase in Zo)
No data on dielectric layer thickness variations

SL DIFF: L2, DP4+/DP4-

Width 4.5mil, 10 mil pitch, 17mil clearance, 0.6 mil thickness

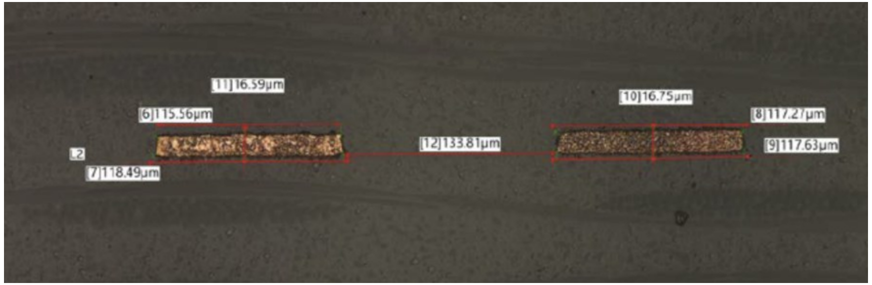


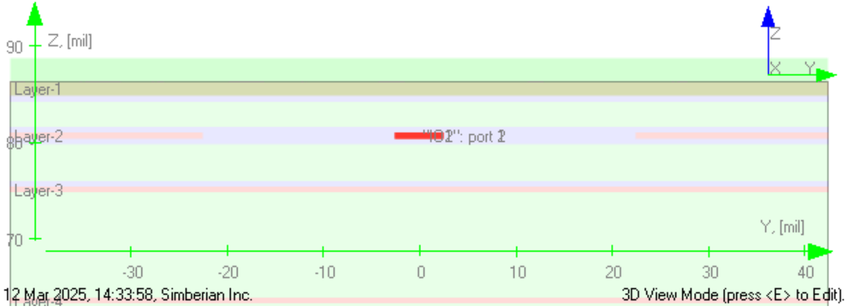
Width ~4.5mil,
Thickness ~0.61 mil (as shown),
9.9mil pitch



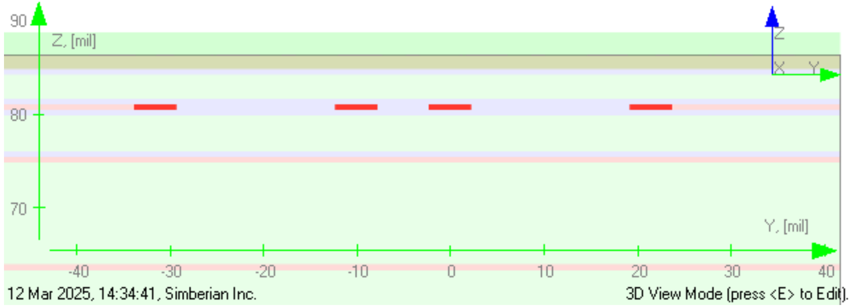
No adjustment or same as for strip (-0.1)
No data on dielectric layer thickness variations

SL DIFF – Resin Layer (for FEXT, Anisotropy)





No strip layer thickness adjustments
Add layer with resin with smaller Dk on both sides of strips
Optimize Dk of resin and Dk of core, to match PD of differential stripline

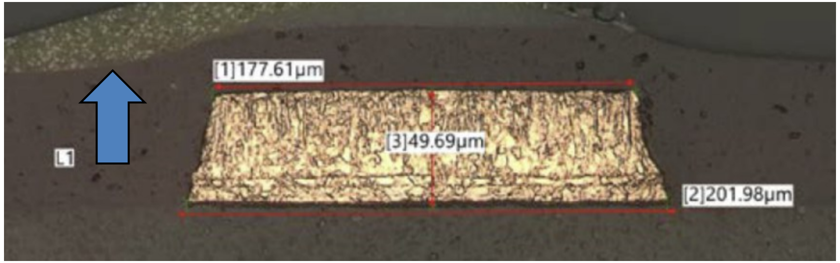


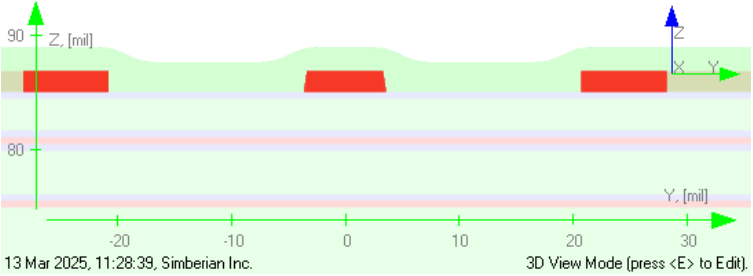
MSL SE: L1/L10

Design: width 7.5mil,
17mil clearance,
2 mil thickness,
0.5 mil conformal solder mask

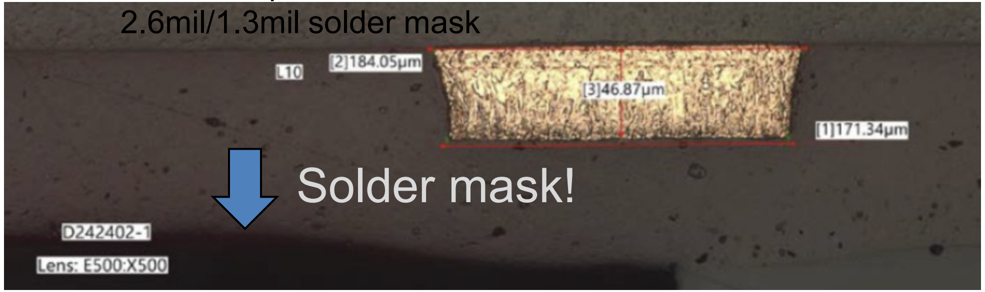
Reality: solder mask thickness 2.6/1.3 and trace widths 6.7/7.25
Width adjustments (-0.8,-0.25)

Width Wtop=7mil, Wbot=7.9mil, 1.8-1.96 mil thickness, 2.6mil/1.3mil solder mask



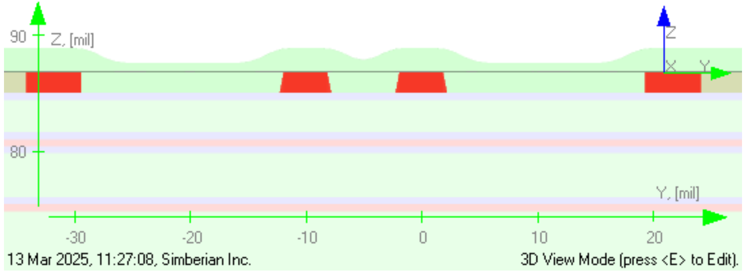


Width Wtop=7.25mil, Wbot=6.7mil, 1.8 mil thickness, 2.6mil/1.3mil solder mask



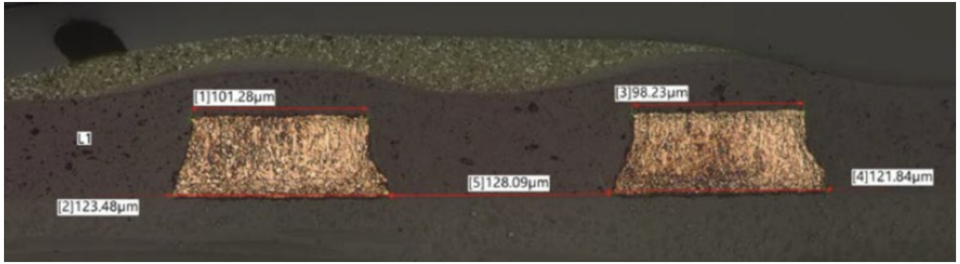
DIFF MSL: L1/L10

Design: Width 4.75mil,
10mil pitch (5.25mil edge-to-edge),
17mil clearance,
2 mil thickness,
0.5 mil conformal solder mask



Reality: Solder mask thickness 2.6/1.3 and width adjustments (-1.1/-0.5)

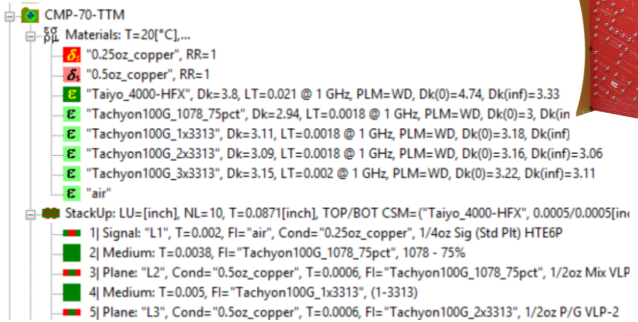
Hat-shape Wtop=3.85mil, Wbot=4.8mil, 9.84mil pitch,1.96 mil thickness, 2.6mil/1.3mil solder mask

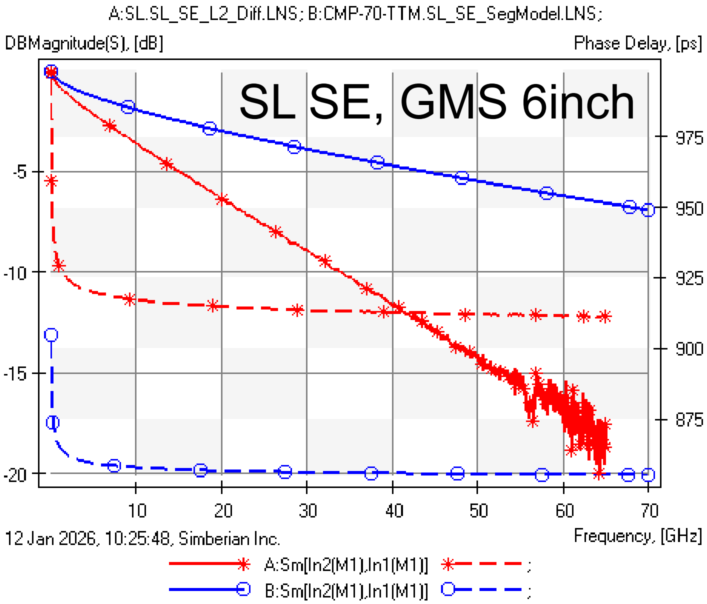


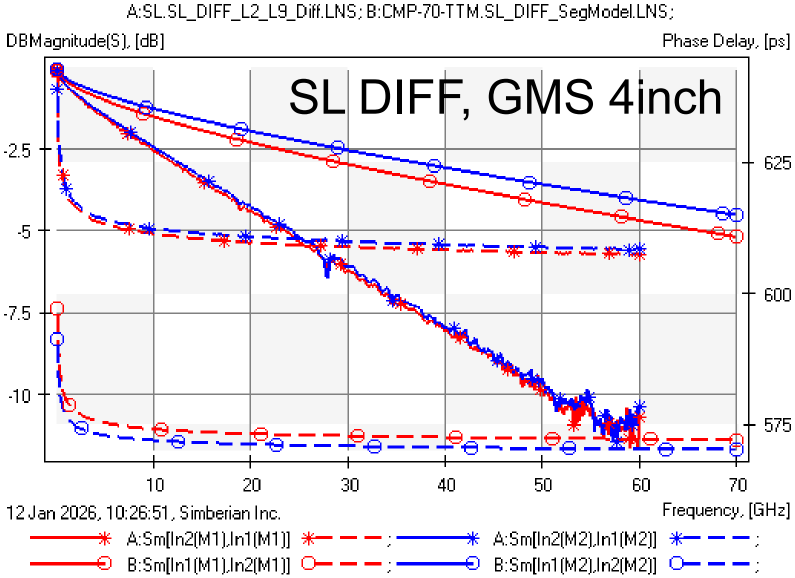
Hat-shape Wtop=4.35mil, Wbot=3.65mil, 9.84mil pitch,1.96 mil thickness, 2.6mil/1.3mil solder mask

SL Initial Modeling Results

Measured GMS-parameters (**curves with ***) compared with models with material parameters from manufacturer (**curves with o**)
Much lower losses (no roughness effect)
Much smaller delay (either roughness or lower Dk)
Solution CMP-70-PreQualify

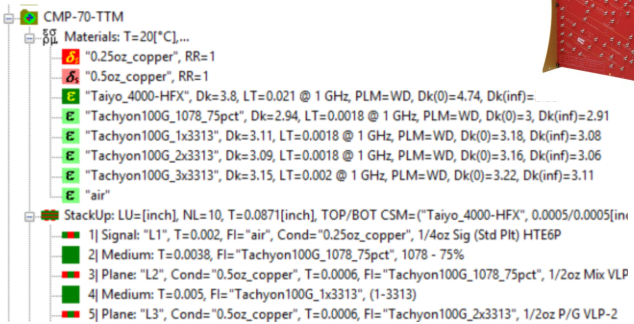


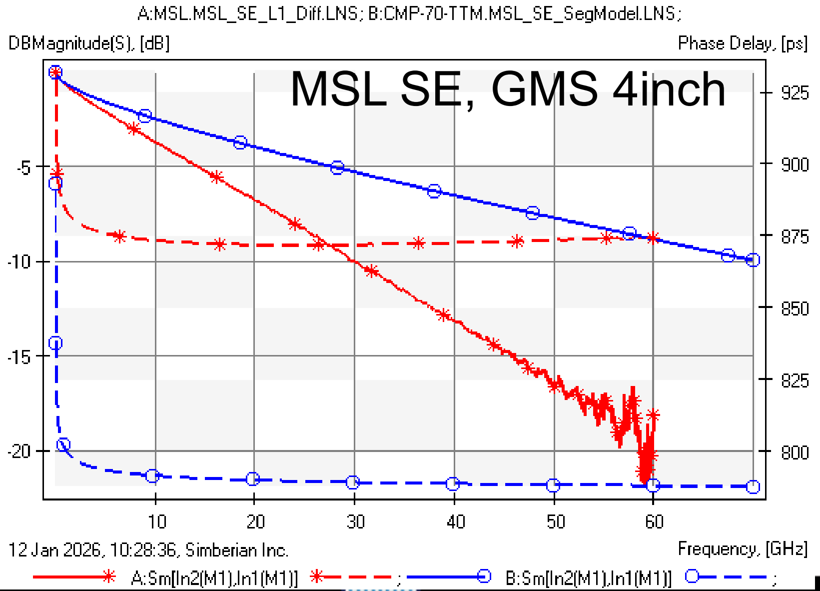


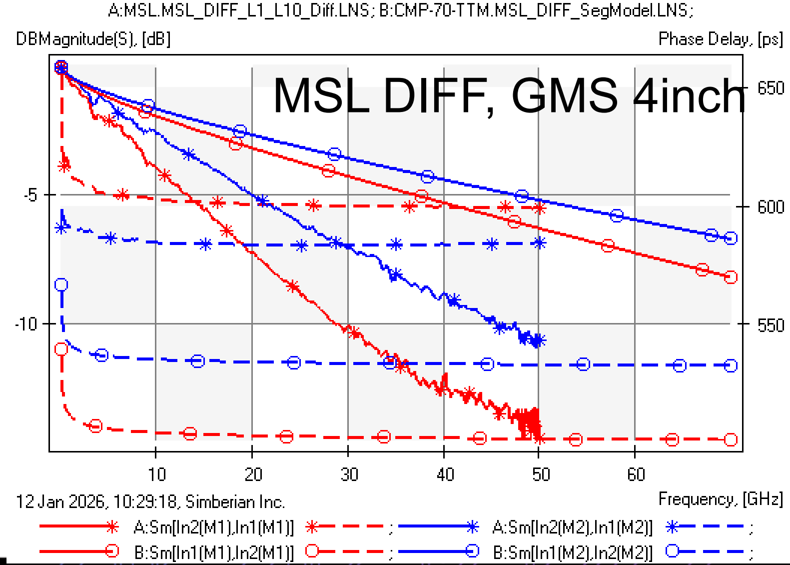


MSL Initial Modeling Results

Measured GMS-parameters (**curves with ***) compared with models with material parameters from manufacturer (**curves with o**)
Much lower losses (no roughness effect)
Much smaller delay (either roughness or lower Dk)
Solution CMP-70-PreQualify







The "Swim" Approach: A Systematic Workflow

1. Prequalify measurements with formal quality metrics
2. Identify dielectric and conductor roughness models
   a. Select structures for material model identification and pre-qualify them
   b. Identify manufacturing adjustments – cross-section geometry
   c. Identify models for dielectrics and conductor roughness
3. Run analysis for all 41 validation structures and compare with measurements (no further adjustments)
   a. Analyze: Separate Swimmers (Pass) from Sinkers (Fail)
   b. Investigate the Sinkers

Material Models to Identify

CMP-70-TTM: "C:\Users\shlep\Documents\Simbeor THz Solutions\CMP-70-TTM\"
CMP-70
Materials: T=20[°C],...
"0.25oz_copper", RR=1
"0.5oz_copper", RR=1
"Taiyo_4000-HFX", Dk=3.8, LT=0.021 @ 1 GHz, PLM=WD, Dk(0)=4.74, Dk(inf)=3.33
"Tachyon100G_1078_75pct", Dk=2.94, LT=0.0018 @ 1 GHz, PLM=WD, Dk(0)=3, Dk(inf)=2.91
"Tachyon100G_1x3313", Dk=3.11, LT=0.0018 @ 1 GHz, PLM=WD, Dk(0)=3.18, Dk(inf)=3.08
"Tachyon100G_2x3313", Dk=3.09, LT=0.0018 @ 1 GHz, PLM=WD, Dk(0)=3.16, Dk(inf)=3.06
"Tachyon100G_3x3313", Dk=3.15, LT=0.002 @ 1 GHz, PLM=WD, Dk(0)=3.22, Dk(inf)=3.11
"air"
StackUp: LU=[inch], NL=10, T=0.0871[inch], TOP/BOT CSM=("Taiyo_4000-HFX", 0.0005/0.0005[inch]);
1| Signal: "L1", T=0.002, Fl="air", Cond="0.25oz_copper"
2| Medium: T=0.0038, Fl="Tachyon100G_1078_75pct"
3| Signal: "L2", T=0.0006, Fl="Tachyon100G_1078_75pct", Cond="0.5oz_copper"
4| Medium: T=0.005, Fl="Tachyon100G_1x3313"
5| Plane: "L3", Cond="0.5oz_copper", T=0.0006, Fl="Tachyon100G_2x3313"
6| Medium: T=0.0109, Fl="Tachyon100G_2x3313"
7| Plane: "L4", Cond="0.5oz_copper", T=0.0006, Fl="Tachyon100G_2x3313"
8| Medium: T=0.014, Fl="Tachyon100G_3x3313"
9| Plane: "L5", Cond="0.5oz_copper", T=0.0006, Fl="Tachyon100G_2x3313"
10| Medium: T=0.0109, Fl="Tachyon100G_2x3313"
11| Plane: "L6", Cond="0.5oz_copper", T=0.0006, Fl="Tachyon100G_2x3313"
12| Medium: T=0.014, Fl="Tachyon100G_3x3313"
13| Plane: "L7", Cond="0.5oz_copper", T=0.0006, Fl="Tachyon100G_2x3313"
14| Medium: T=0.0109, Fl="Tachyon100G_2x3313"
15| Plane: "L8", Cond="0.5oz_copper", T=0.0006, Fl="Tachyon100G_2x3313"
16| Medium: T=0.005, Fl="Tachyon100G_1x3313"
17| Signal: "L9", T=0.0006, Fl="Tachyon100G_1078_75pct", Cond="0.5oz_copper"
18| Medium: T=0.0038, Fl="Tachyon100G_1078_75pct"
19| Signal: "L10", T=0.002, Fl="air", Cond="0.25oz_copper"

For traces in L1-L2 and L9-L10:

3 dielectric models:
Taiyo_4000-HFX (solder mask)
Tachyon100G_1078_75pct (prepreg)
Tachyon100G_1x3313 (core)

2 conductor models:
0.25oz_copper (plated L1 and L10)
0.5oz_copper (L2 and L9)

Problems: *Medium layer 2 appears in cross-section of MSL as well as SL;*
MSL has uncertainties in solder mask and defects in DIFF measurements (unreliable)

SL & MSL DIFF: Iterative Identification (1)

MATLAB script extract_iterative.m in ..\CMP-70_Simbeor_Kit_2025\Identification

C: ▸ Repository ▸ Simbeor ▸ CMP-70_Simbeor_Kit_2025 ▸ Identification ▸

Current Folder

- Name
- cases
  - MSL_DIFF_L1_L10.m
  - MSL_SE_L1.m
  - SL_DIFF_L2_L9.m
  - SL_SE_L2.m
- core
- solutions
- utils
- extract_iterative.m
- extract_separate.m

Cross-sections and Goals ("Trusted Vendor" approach – fixed Df for Tachyon)

Editor - C:\Repository\Simbeor\CMP-70_Simbeor_Kit_2025\Identification\extract_iterative.m

extract_iterative.m

```
% --- 2. Configuration Setup ---
scriptFullPath = mfilename('fullpath');
scriptFolder = fileparts(scriptFullPath);
solution_name = 'CMP-70-IdentAll_Iterative'; % New solution folder
parentFolder = fileparts(scriptFolder);

config = struct();
config.TouchstoneDir = fullfile(parentFolder, 'CMP-70_s-parameters_20240401');
config.DeEmbedLongSeg = true;
config.ComputeTDR = false;
config.SolutionDir = fullfile(pwd, 'solutions', solution_name);

if ~exist(config.SolutionDir, 'dir')
    mkdir(config.SolutionDir);
end

% --- 3. Initial Material Models ---
% ID_Group 1: Core/Prepreg (Optimized in SL)
% ID_Group 2: Resin/Mask (Optimized in MSL, sometimes fixed in SL)
config.mPrep  = struct('Name', 'Tachyon100G_1078_75pct', 'Type', 'Dielectric', .
    'Dk', 2.94, 'Df', 0.0018, 'ID_Group', 1);
config.mCore  = struct('Name', 'Tachyon100G_1x3313', 'Type', 'Dielectric', ...
    'Dk', 3.11, 'Df', 0.0018, 'ID_Group', 1);
config.mResin = struct('Name', 'Resin',   'Type', 'Dielectric', 'Dk', 3.32, ...
    'Df', 0.003, 'ID_Group', 2);
config.mMask = struct('Name', 'Taiyo_4000-HFX',   'Type', 'Dielectric', ...
    'Dk', 4.0, 'Df', 0.021, 'ID_Group', 2);
config.mCondInt = struct('Name', '0.5oz_copper', 'Type', 'Conductor', ...
          'Res', 1.0, 'SR', 0.01, 'RF', 2.0, 'ID', true);
config.mCondSurf = struct('Name', '0.25oz_copper', 'Type', 'Conductor', ...
          'Res', 1.0, 'SR', 0.01, 'RF', 2.0, 'ID', true);
```

Location of measured S-parameters for trace segments

Material Models to identify with seed values

SL & MSL DIFF: Iterative Identification (2)

MATLAB script extract_iterative.m in ..\CMP-70_Simbeor_Kit_2025\Identification

Baseline Initialization: Establish initial roughness and material values using single-ended structures (SL L2 & MSL L1).

Step A (Internal Layers): Optimize Core/Prepreg and Conductor models using differential striplines (L2 & L9).

Step B (Surface Layers): Optimize Resin and Solder Mask models using differential microstrips (L1 & L10), fixing the internal materials derived in Step A.

Convergence: Repeat Steps A and B until dielectric properties stabilize (e.g., ΔDk<0.01).

Editor - C:\Repository\Simbeor\CMP-70_Simbeor_Kit_2025\Identification\extract_iterative.m

extract_iterative.m

```
% ------------------------------------------------------------------
% Phase 2: Iterative Common Model (The Loop)
% ------------------------------------------------------------------
maxIterations = 2;
tolerance     = 1e-2;
prev_Dk_Prep  = 0;

fprintf('\nStarting Iterative Optimization (Max %d loops)...\n', maxIterations);

config_sl_diff = config;
config_sl_diff = copyMaterialsFromTo(config_sl_se, config_sl_diff);
config_msl_diff = config_sl_diff;

for iter = 1:maxIterations
    fprintf('\n=== Iteration %d of %d ===\n', iter, maxIterations);

    % --- Sub-step A: Stripline Differential (L2 & L9) ---
    config_sl_diff = copyMaterialsFromTo(config_msl_diff, config_sl_diff);
    config_sl_diff.mResin.ID_Group = 2;

    % Load geometry settings for SL_DIFF
    config_sl_diff= SL_DIFF_L2_L9(config_sl_diff);

    fprintf('Running SL_DIFF_L2_L9...\n');
    [bResult, config_sl_diff] = runMaterialIdentification(sLibName, config_sl_diff);
    calllib(sLibName, 'simbeorsdk_saveSolution', config.SolutionDir, solution_name);
```

Outcome: *A single, high-confidence material library valid for the entire PCB stackup.*

Identified Material Models

MATLAB script extract_iterative.m in ..\CMP-70_Simbeor_Kit_2025\Identification

IDENTIFIED MATERIAL MODELS

Wideband Debye dielectric models with Dk and Df @1GHz

--- Dielectrics ---

Name	Dk	Df
Tachyon100G_1078_75pct	3.0051	0.0018
Tachyon100G_1x3313	3.5314	0.0018
Resin	2.9797	0.0030
Taiyo_4000-HFX	4.3744	0.0210

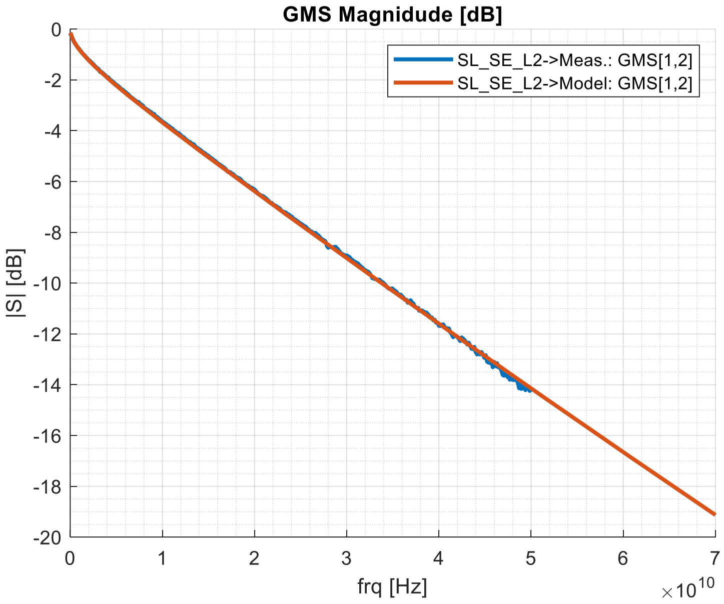
Huray-Bracken roughness models;
Roughness from MSL SE:
SR=0.11, RF=12

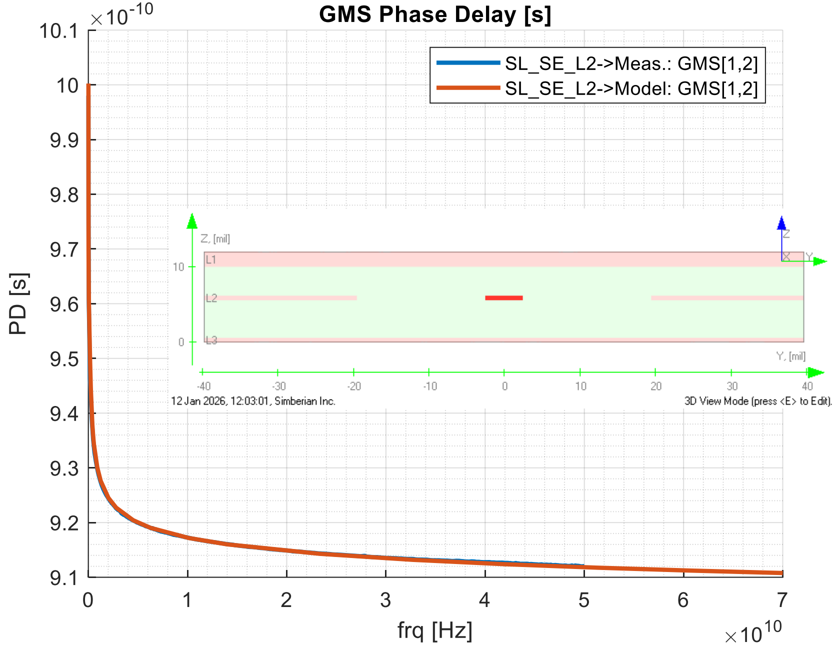
--- Conductors ---

Name	Rel Res	SR (um)	RF
0.5oz_copper	1.2000	0.1000	12.6114
0.25oz_copper	1.0000	0.1543	10.4319
0.25oz_copper_msl	1.0000	0.1113	12.0

SL SE: GMS Measured and Modeled

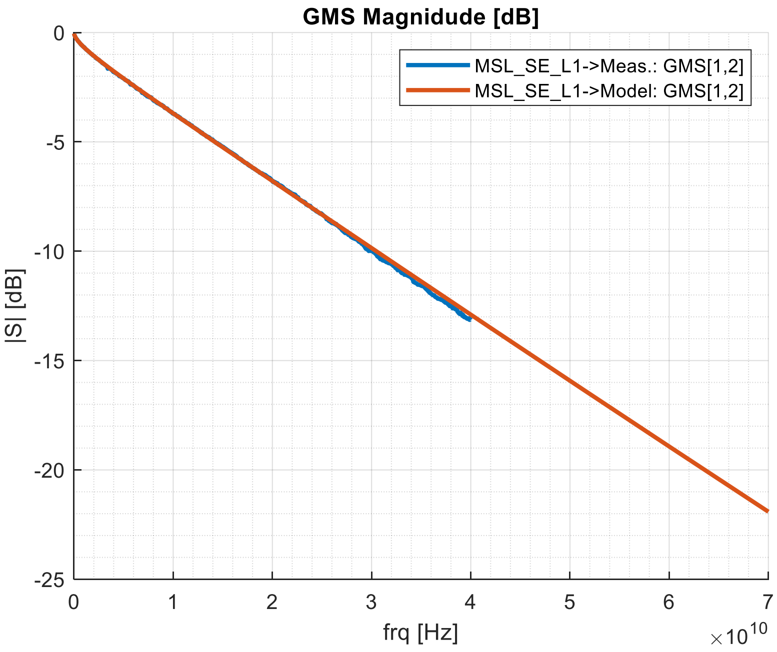
MATLAB script extract_iterative.m in ..\CMP-70_Simbeor_Kit_2025\Identification

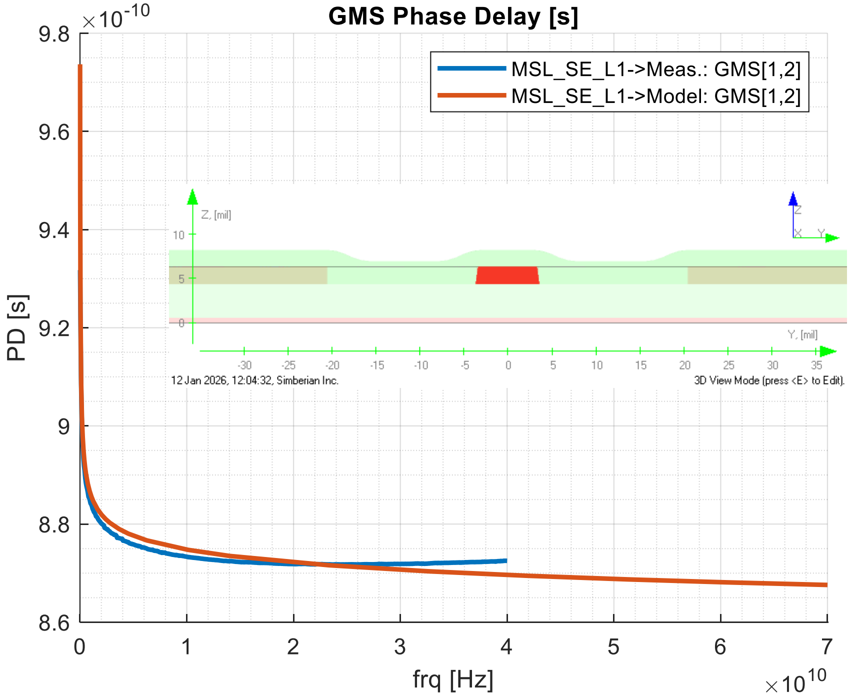




MSL SE: GMS Measured and Modeled

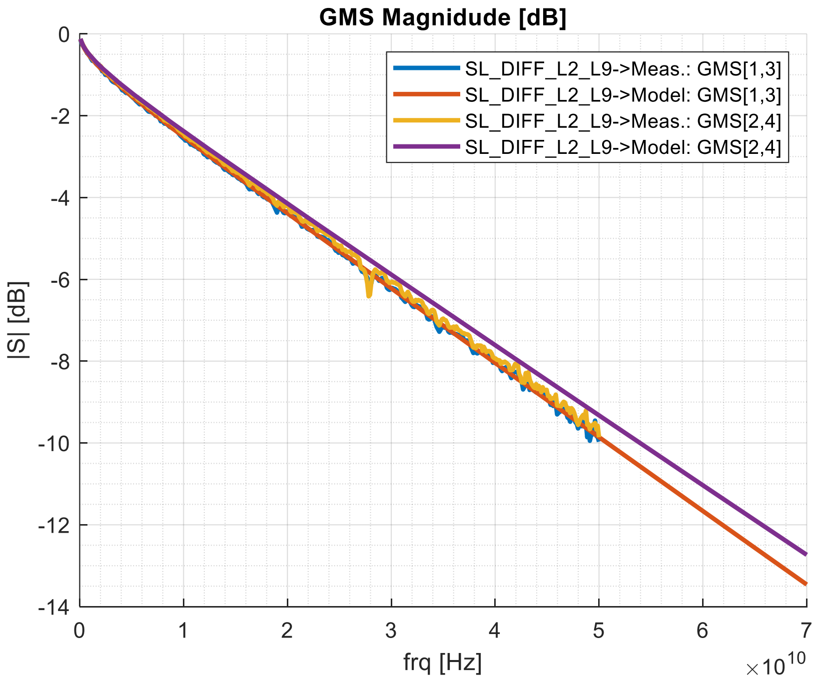
MATLAB script extract_iterative.m in ..\CMP-70_Simbeor_Kit_2025\Identification

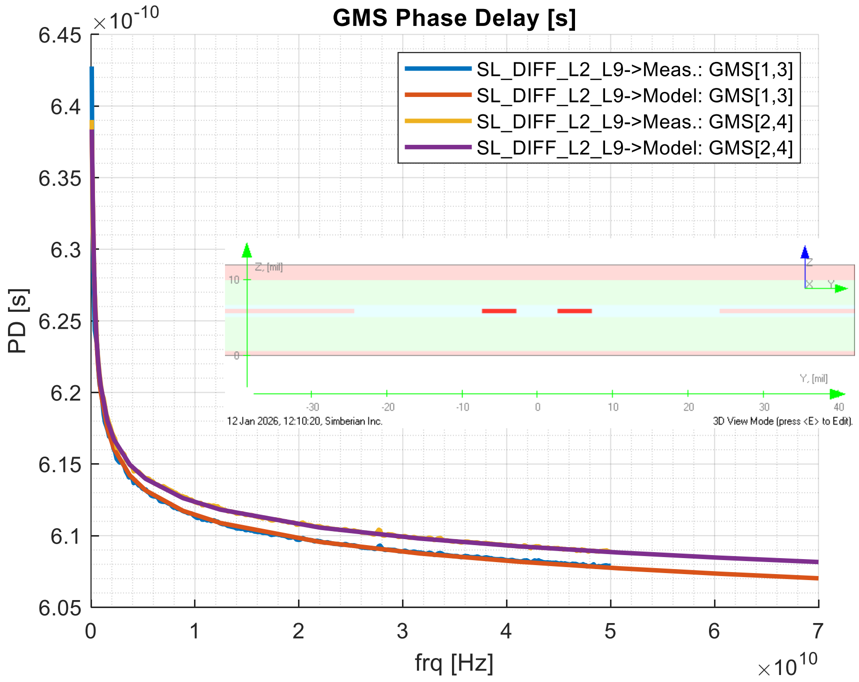




MSL SE: GMS Measured and Modeled

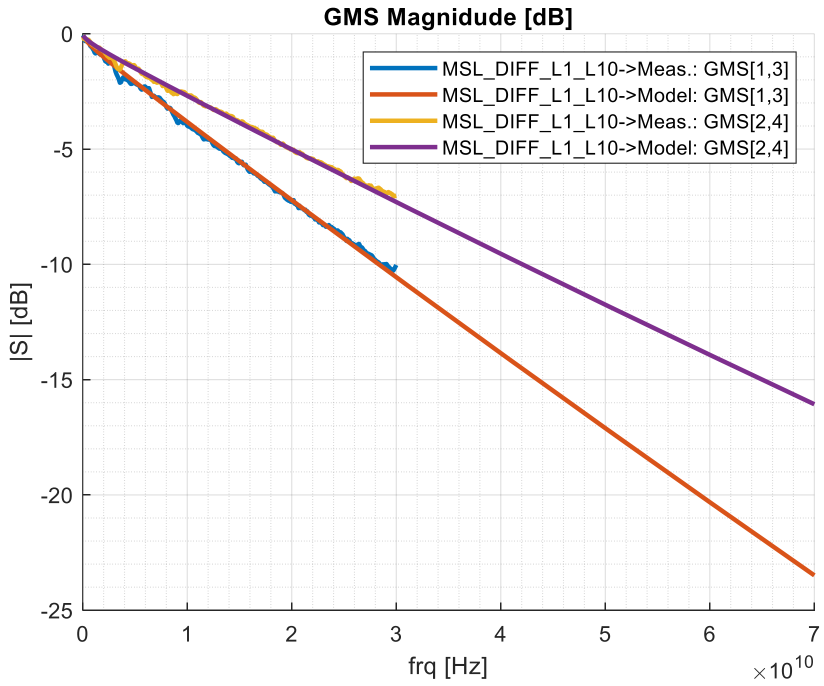
MATLAB script extract_iterative.m in ..\CMP-70_Simbeor_Kit_2025\Identification

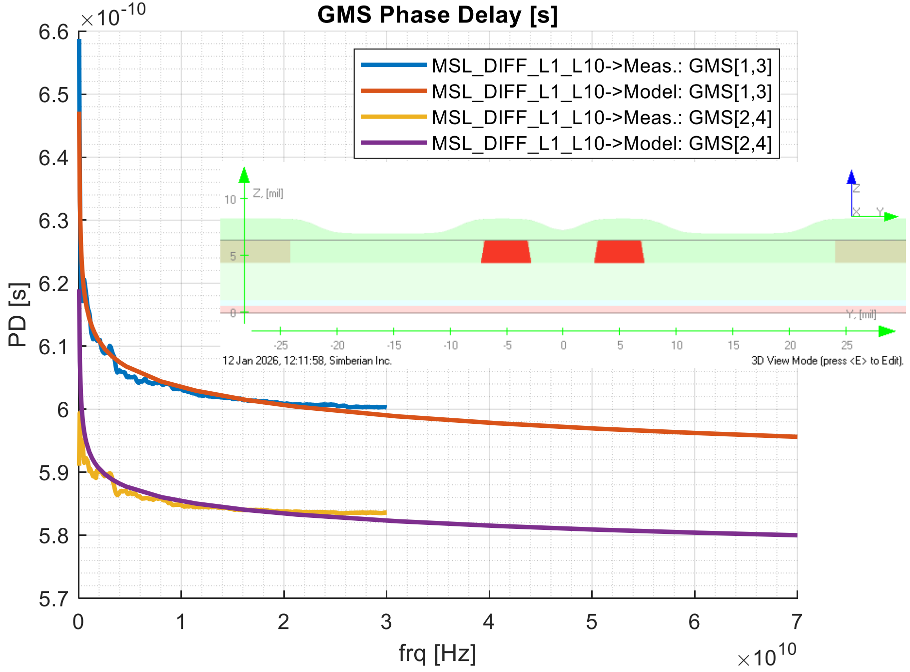




MSL DIFF: GMS Measured and Modeled

MATLAB script extract_iterative.m in ..\CMP-70_Simbeor_Kit_2025\Identification





Identified Materials & Stackup

Additional possible adjustment for MSL:
Fix Dk of solder mask to 4.1, to satisfy both SE and DIFF cases – suitable for MSL SE the actual MSK DIFF structures show smaller FEXT, comparing to the extracted for 4in (L1/L10)
Solution CMP-70-MatIdentified - ***export stackup to CMP-70-Ident.json for post-layout analysis reuse***

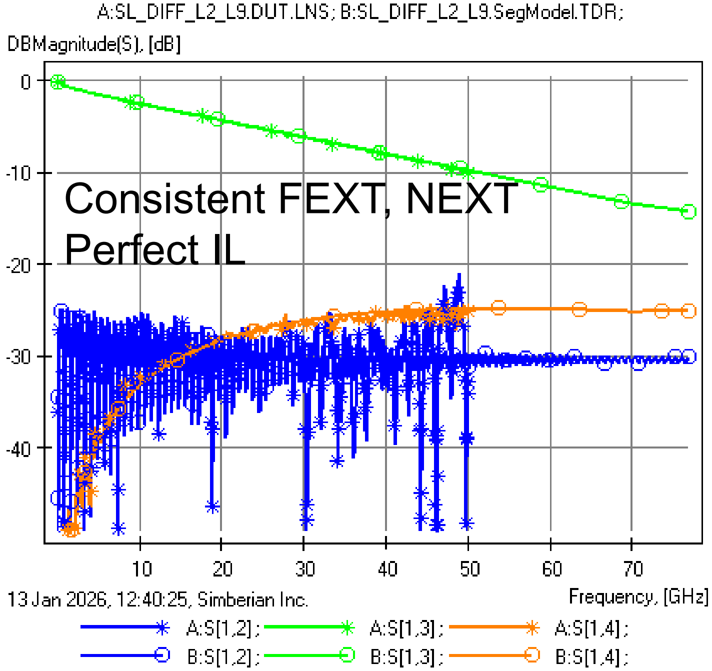
- CMP-70-Ident
  - Materials: T=20[°C],...
    - "0.25oz_copper", RR=1, HurayBracken: SR1=0.154265 [um], RF1=10.4319;
    - "0.25oz_copper_msl", RR=1, HurayBracken: SR1=0.111354 [um], RF1=12;
    - "0.5oz_copper", RR=1.2, HurayBracken: SR1=0.0998698 [um], RF1=12.6884;
    - "Taiyo_4000-HFX", Dk=4.37443, LT=0.021 @ 1 GHz, PLM=WD, Dk(0)=5.45, Dk(inf)=3.84
    - "Resin", Dk=2.97967, LT=0.003 @ 1 GHz, PLM=WD, Dk(0)=3.08, Dk(inf)=2.93
    - "Tachyon100G_1078_75pct", Dk=3.00508, LT=0.0018 @ 1 GHz, PLM=WD, Dk(0)=3.07, Dk(inf)=2.97
    - "Tachyon100G_1x3313", Dk=3.58033, LT=0.0018 @ 1 GHz, PLM=WD, Dk(0)=3.66, Dk(inf)=3.54
    - "Tachyon100G_2x3313", Dk=3.09, LT=0.0018 @ 1 GHz, PLM=WD, Dk(0)=3.16, Dk(inf)=3.06
    - "Tachyon100G_3x3313", Dk=3.15, LT=0.002 @ 1 GHz, PLM=WD, Dk(0)=3.22, Dk(inf)=3.11
    - "air"

Optionally, the interior layers can be also modeled as layers of resin and glass, to enhance anisotropy (no data to do it)

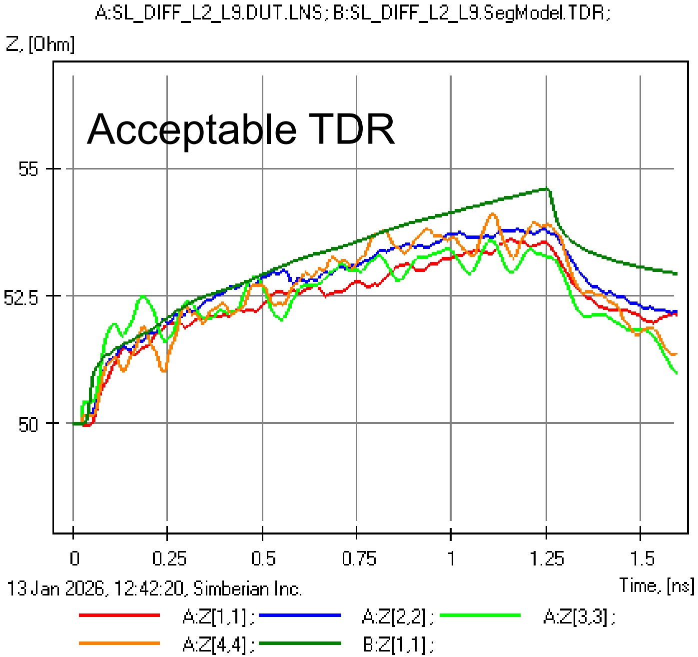
- StackUp: LU=[mil], NL=10, T=87.1[mil], TOP/BOT CSM=("Taiyo_4000-HFX", 1.3/2.6[mil]); Fron
  - 1| Signal: "L1", T=2, Fl="air", Cond="0.25oz_copper", 1/4oz Sig (Std Plt) HTE6P
  - 2| Medium: T=3.3, Fl="Tachyon100G_1078_75pct", 1078 - 75%
  - 3| Medium: T=0.5, Fl="Resin", 1078 - 75%
  - 4| Plane: "L2", Cond="0.5oz_copper", T=0.6, Fl="Resin", 1/2oz Mix VLP-2
  - 5| Medium: T=0.5, Fl="Resin", 1078 - 75%
  - 6| Medium: T=4.5, Fl="Tachyon100G_1x3313", (1-3313)
  - 7| Plane: "L3", Cond="0.5oz_copper", T=0.6, Fl="Tachyon100G_2x3313", 1/2oz P/G VLP-2
  - 8| Medium: T=10.9, Fl="Tachyon100G_2x3313", 3313 - 67.5%
  - 9| Plane: "L4", Cond="0.5oz_copper", T=0.6, Fl="Tachyon100G_2x3313", 1/2oz P/G VLP-2
  - 10| Medium: T=14, Fl="Tachyon100G_3x3313", (3-3313)
  - 11| Plane: "L5", Cond="0.5oz_copper", T=0.6, Fl="Tachyon100G_2x3313", 1/2oz P/G VLP-2
  - 12| Medium: T=10.9, Fl="Tachyon100G_2x3313", 3313 - 67.5%
  - 13| Plane: "L6", Cond="0.5oz_copper", T=0.6, Fl="Tachyon100G_2x3313", 1/2oz P/G VLP-2
  - 14| Medium: T=14, Fl="Tachyon100G_3x3313", (3-3313)
  - 15| Plane: "L7", Cond="0.5oz_copper", T=0.6, Fl="Tachyon100G_2x3313", 1/2oz P/G VLP-2
  - 16| Medium: T=10.9, Fl="Tachyon100G_2x3313", 3313 - 67.5%
  - 17| Plane: "L8", Cond="0.5oz_copper", T=0.6, Fl="Tachyon100G_2x3313", 1/2oz P/G VLP-2
  - 18| Medium: T=4.5, Fl="Tachyon100G_1x3313", (1-3313)
  - 19| Medium: T=0.5, Fl="Resin", 1078 - 75%
  - 20| Plane: "L9", Cond="0.5oz_copper", T=0.6, Fl="Resin", 1/2oz Mix VLP-2
  - 21| Medium: T=0.5, Fl="Resin", 1078 - 75%
  - 22| Medium: T=3.3, Fl="Tachyon100G_1078_75pct", 1078 - 75%
  - 23| Signal: "L10", T=2, Fl="air", Cond="0.25oz_copper", 1/4oz Sig (Std Plt) HTE6P

SL DIFF: Deembedded Segment 6in

MATLAB script extract_iterative.m in ..\CMP-70_Simbeor_Kit_2025\Identification
Deembedding with 2L+X algorithm



Final solution in CMP-70-MatIdentified

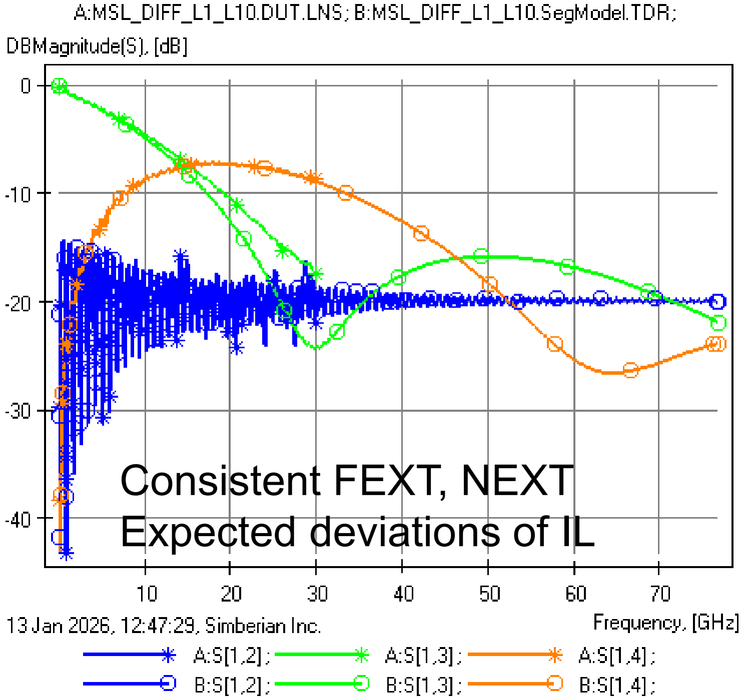


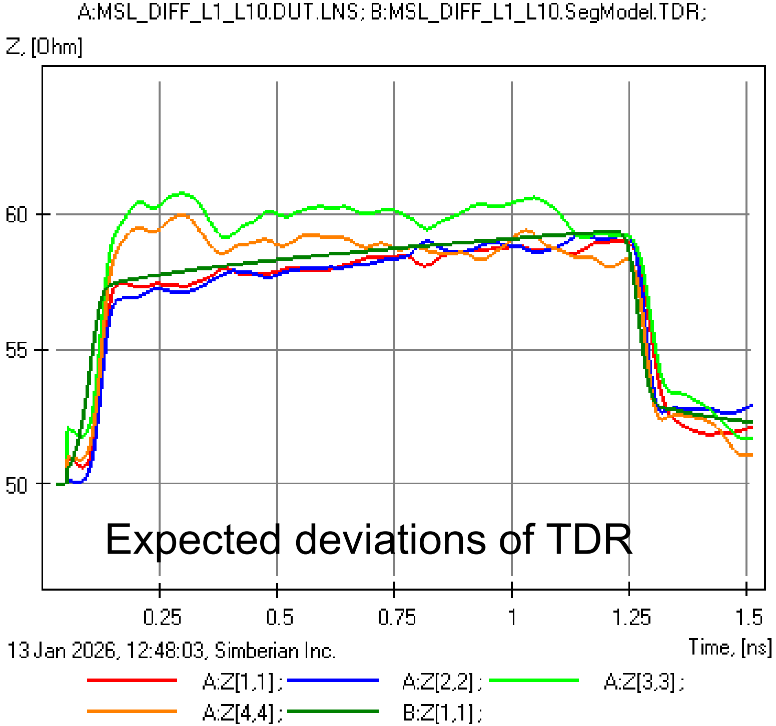
MSL DIFF: Deembedded Segment 4in

MATLAB script extract_iterative.m in ..\CMP-70_Simbeor_Kit_2025\Identification

Deembedding with 2L+X algorithm

Final solution in CMP-70-MatIdentified





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   a. Select structures for material model identification and pre-qualify them
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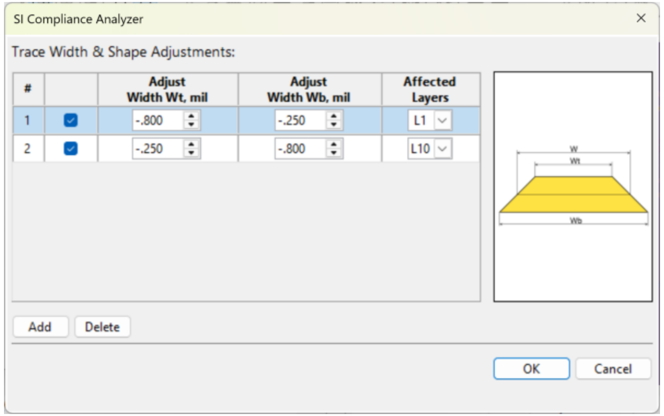
   c. Identify models for dielectrics and conductor roughness
3. Run analysis for all 41 validation structures and compare with measurements (no further adjustments)
   a. Analyze: Separate Swimmers (Pass) from Sinkers (Fail)
   b. Investigate the Sinkers

Post-Layout Analysis with Identified Materials

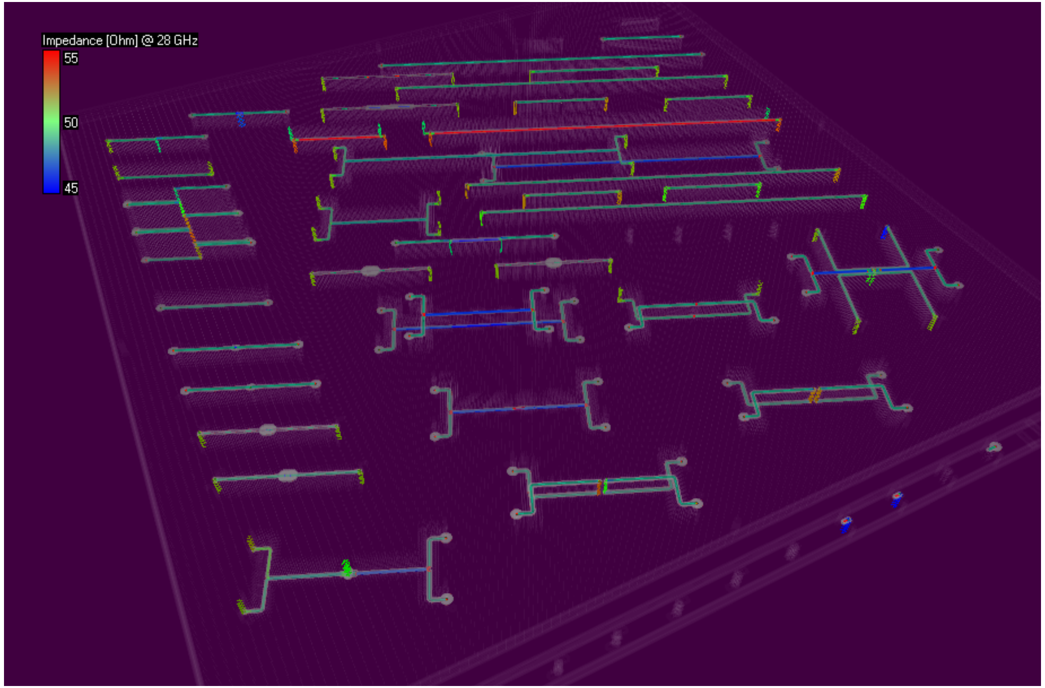
Simbeor Commander: Import CMP-70.brd with stackup from CMP-70-Ident.json for 112Gbps PAM4 signal with 14ps rise time

Set adjustment for width/shape: **Single-ended MSL -0.8/-0.25; Differential MSL -1.1/-0.5;** Stripline -0.1

Configure IOs to use Coaxial component ports (MSL.preset and SL.preset) and connector models

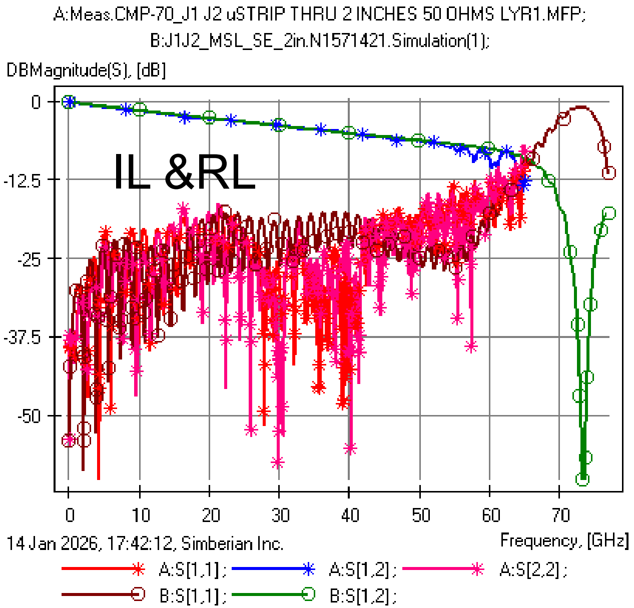


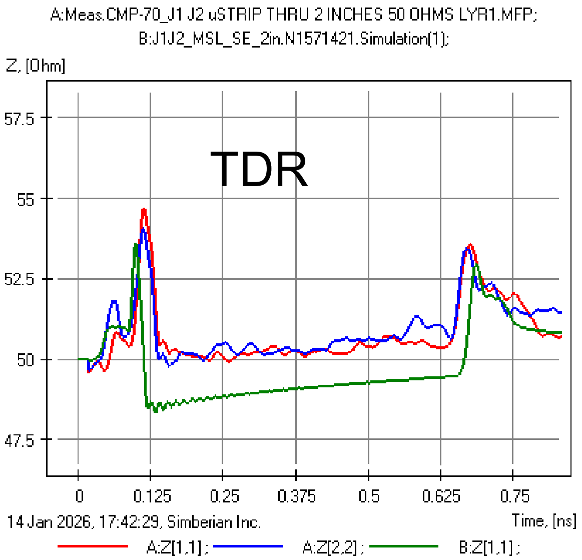
SI Compliance Analyzer -> ERC
(almost the same as before identification)



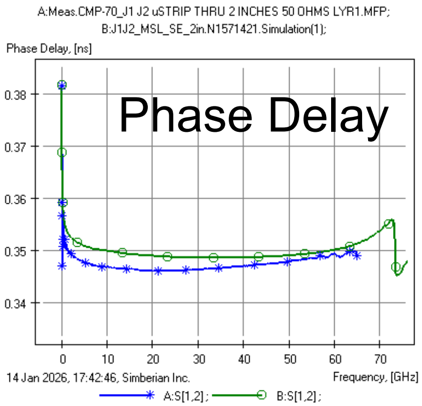
J1J2 MSL SE 2in

Solution ..\CMP-70_Simbeor_Kit_2025\Dec2025\CMP-70-SE(1)





Looks better than at the first attempt – how good it is? RL & IL are OFF at some frequencies, Lower TDR impedance…



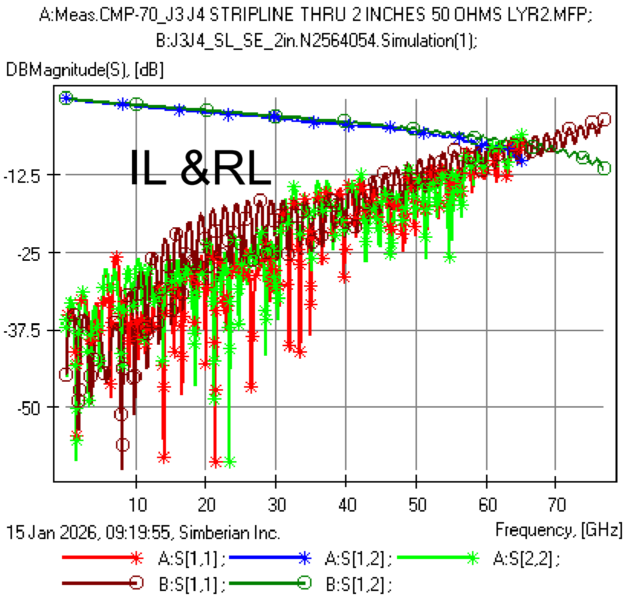
* **Overall SPS Score (100% BW):** 89.67 → **Acceptable**
* **Overall SPS Score (80% BW):** 91.47 → **Good**

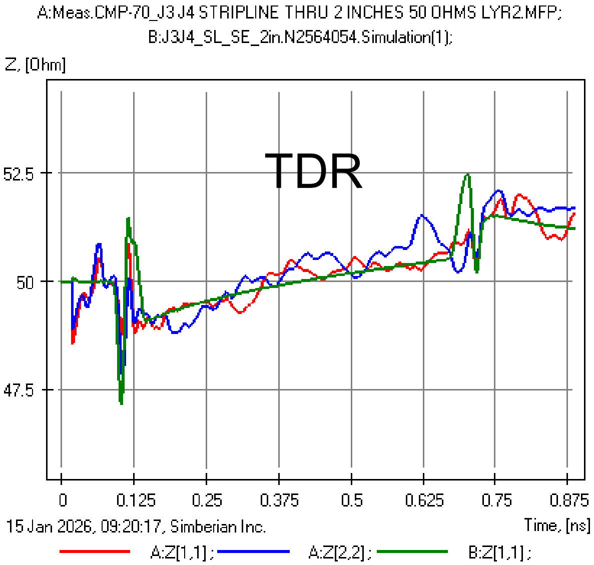
S-Par.	SPS (100% BW)	Rating (100% BW)	SPS (80% BW)	Rating (80% BW)
S11	92.41	Good	93.96	Good
S12	89.84	Acceptable	91.61	Good
S21	89.67	Acceptable	91.47	Good
S22	91.67	Good	93.24	Good

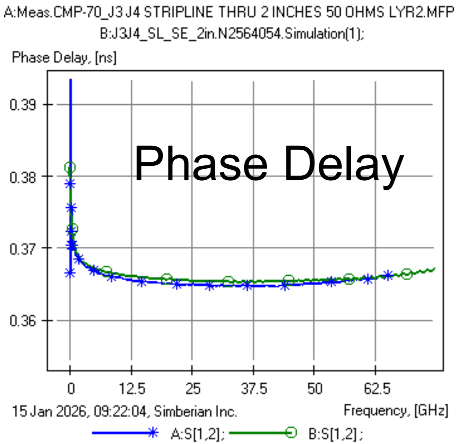
J3J4 SL SE 2in

Solution ..\CMP-70_Simbeor_Kit_2025\Dec2025\CMP-70-SE(1)

Looks much better than at the first attempt – RL & IL are closer; TDR is OFF at Launches…







* **Overall SPS Score (100% BW):** 94.32 → **Good**
* **Overall SPS Score (80% BW):** 95.36 → **Good**

S-Par.	SPS (100% BW)	Rating (100% BW)	SPS (80% BW)	Rating (80% BW)
S11	94.32	Good	95.36	Good
S12	95.28	Good	96.12	Good
S21	95.31	Good	96.21	Good
S22	94.57	Good	95.85	Good

How to Compare S-Parameters

- *'Looks better' isn't an engineering standard. How do we quantify 'better' for 40 different structures?*
- The validation requires formal and automated comparison of simulated and measured S-parameters
  - It can be done either with Feature Selective Validation (FSV)
    - A.P. Duffy, G. Zhang, FSV: State of the Art and Current Research Fronts, IEEE Electromagnetic Compatibility Magazine, Volume 9, #3, 2020, p. 55-62.
  - Or with recently introduced S-Parameter Similarity (SPS) metric
    - Y. Shlepnev "Evaluation of S-Parameters Similarity with Modified Hausdorff Distance", May 20, 2021 at http://arxiv.org/abs/2105.10057
    - Y. Shlepnev, Evaluation of S-Parameters Similarity with Modified Hausdorff Distance, 2021 IEEE 30st Conference on Electrical Performance of Electronic Packaging and Systems (EPEPS2021), October 19, 2021. – available at https://www.simberian.com/AppNotes.php
- Let's introduce SPS metric and compare it to FSV…

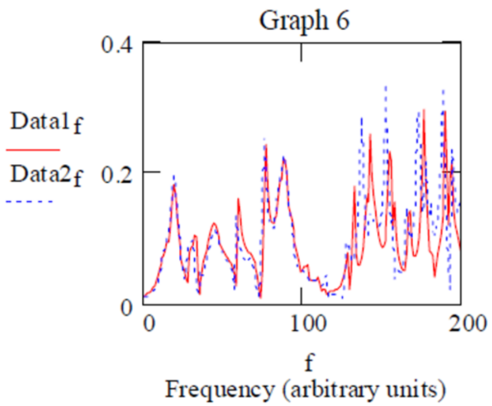
What is Feature Selective Validation (FSV)?

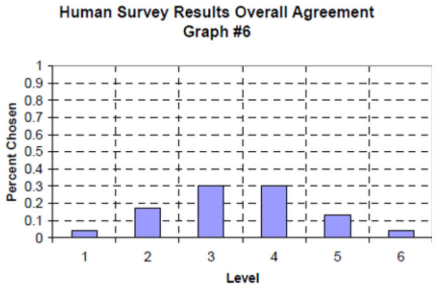
Definition: FSV is an objective validation technique designed to quantify the comparison between two datasets (typically **simulation vs. measurement**). It was developed to replace subjective visual inspections and simple correlation methods, which often fail to capture the "goodness of fit" accurately.

How It Works: The method mimics human visual perception by decomposing the data into two distinct components:

- **Amplitude Difference Measure (ADM):** Compares the "envelope" or overall intensity/trend of the data.
- **Feature Difference Measure (FDM):** Compares the "features," such as sharp peaks, notches, and rapid changes.

The Output: These two measures are combined to form a **Global Difference Measure (GDM) -** The resulting numerical values are mapped to natural language descriptors to provide a clear quality rating (e.g., < 0.1 is "Excellent", > 1.6 is "Very Poor").





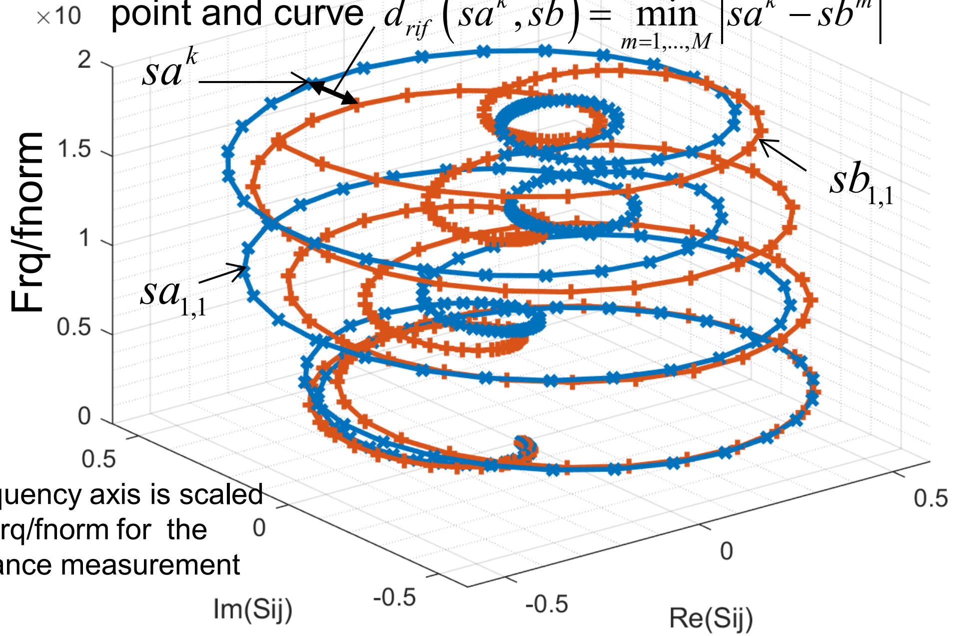
See more in A.P. Duffy, G. Zhang EMC'20

IEEE Std 1597.1

S-parameters Similarity (SPS) Metric

3D Spiral Plots of 2 S-parameters (Real-Imaginary-Frequency or RIF)

Distance in RIF space between point and curve $d_{rif}\left(sa^k, sb\right) = \min_{m=1,\ldots,M} \left|sa^k - sb^m\right|$



Frequency axis is scaled as Frq/fnorm for the distance measurement

Modified Housdorff Distance(MHD) for S-Matrix Element *i,j*

$$d_{MH}\left(sa, sb\right) = \frac{1}{K}\sum_{k=1}^{K} d_{rif}\left(sa^k, sb\right)$$

S-Parameters Similarity (SPS) Metrics:

$$SPS\left(sa_{i,j}, sb_{i,j}\right) = 100 \cdot \max\left(1 - d_{MH}\left(sa_{i,j}, sb_{i,j}\right), 0\right)\%$$

$$SPS\left(SA, SB\right) = \min\left(SPS\left(sa_{i,j}, sb_{i,j}\right), i, j = 1, \ldots, N\right)\%$$

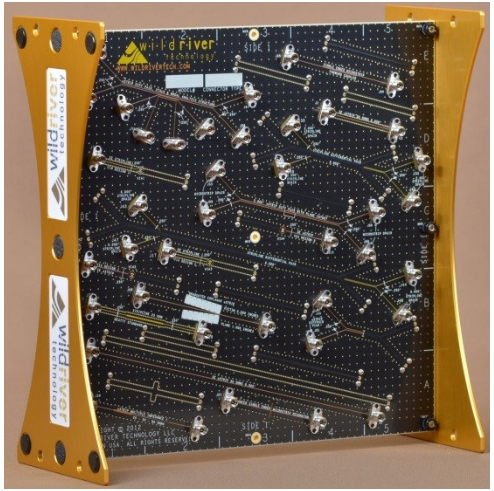
SPS in Human Language (relaxed comparing to introduced at EPEPS’21):

[99, 100]	**Excellent**
[90, 99)	**Good**
[80, 90)	**Acceptable**
[70, 80)	**Inconclusive**
[0, 70)	**Bad**

See more in Y.S. Shlepnev EPEPS’21

CMP-28 (Predecessor of CMP-70)

Designed and Measured by Wild River Technology
Modeled with Simbeor
Guide to CMP-28/32 Simbeor Kit, CMP-28 Rev. 4, Sept. 2014.



	Model	Measurement	SPS_SE 10 GHz	SPS_SE 35 GHz	SPS_SE 50 GHz
1	SL_SE_2inch_J6J5	cmp28_strpl_2in_50ohm_p1J6_p2J5_s2p	97.1513	92.5639	84.677
2	SL_SE_8inch_J7J8	cmp28_strpl_8inch_p1J7_p2J8_s2p	97.8176	91.8262	80.9387
3	SL_SE_Beatty_25Ohm_J28J27	cmp28_strpl_Beatty_25ohm_p1J28_p2J27_s2p	98.3164	91.7525	81.1544
4	SL_SE_Resonator_J23J24	cmp28_strpl_resonator_p1J23_p2J24_s2p	98.5621	92.8552	82.7012
5	SL_SE_Via_Capacitive_J18J17	cmp28_strpl_via_capacitive_p1J18_p2J17_s2p	94.9476	91.1739	82.8437
6	SL_SE_Via_Backdrilled_J14J13	cmp28_strpl_via_backdrilled_p1J14_p2J13_s2p	97.1172	90.8311	82.0804
7	SL_SE_2inch_Capacitive_J9J10	cmp28_strpl_2in_Capacitive_p1J10_p2J09_s2p	97.7805	93.0992	87.3275
8	SL_SE_2inch_Inductive_J11_J12	cmp28_strpl_2in_Inductive_p1J12_p2J11_s2p	97.8352	93.8351	87.8757
9	SL_DF_2inch	cmp28_strpl_diff_2inch_J39J40J35J36_s4p	95.9985	91.087	83.0354
10	SL_DF_6inch	cmp28_strpl_diff_6inch_J47J48J43J44_s4p	96.8208	93.0776	85.1746
11	MS_SE_2in_J1_J2	cmp28_mstrp_2in_p1J1_p2J2	97.9111	94.7303	91.8845
12	MS_SE_8in_J4_J3	cmp28_mstrp_8inch_p1J4_p2J3	97.6372	95.3771	91.645
13	MS_SE_Beatty_25Ohm_J25_J26	cmp28_mstrp_Beatty_25ohm_p1J25_p2J26	96.5268	93.3182	89.9407
14	MS_SE_Resonator_J21_J22	cmp28_mstrp_resonator_p1J21_p2J22	98.0708	94.1929	90.5811
15	MS_SE_GND_Voids_J74_J75	cmp28_gnd_voids_p1J74_p2J75	97.6512	88.4187	83.5582
16	MS_SE_GraduateCoplanar_J70_J69	cmp28_graduate_coplanar_p1J70_p2J69	97.6924	94.4118	91.4621
17	MS_SE_Via_Inductive_J15_J16	cmp28_mstrp_via_inductive_p1J15_p2J16	96.6664	93.596	90.0153
18	MS_SE_Via_Capasitive_J19_J20	cmp28_mstrp_via_capacitive_p1J19_p2J20	96.5088	93.969	90.1057
19	MS_SE_Via_Pathology_J65_J66	cmp28_via_pathology_p1J65_p2J66	97.2525	91.9582	88.486
20	MS_DF_2inch	cmp28_mstrp_diff_2inch_J38J37J34J33	95.4645	93.3429	90.407
21	MS_DF_6inch	cmp28_mstrp_diff_6inch_J46J45J42J41	95.5751	93.9318	90.9123
22	MS_DF_GND_Cutout	cmp28_mstrp_diff_gnd_cutout_J59J60J55J56	94.4506	91.4807	88.7113
23	MS_DF_Vias	cmp28_mstrp_diff_vias_J49J50J51J52	95.6808	91.6811	88.4878

[80, 90) **Acceptable;** [90, 99) **Good;** [99, 100] **Excellent;**

FSV vs SPS for 35 GHz Bandwidth

FSV:
[0, 0.1] Excellent
(0.1, 0.2] Very Good
(0.2, 0.4] Good
(0.4, 0.8] Fair
(0.8, 1.6] Poor
(1.6, inf) Very Poor

SPS:
[99, 100] **Excellent**
[90, 99) **Good**
[80, 90) **Acceptable**
[70, 80) **Inconclusive**
[0, 70) **Bad**

FSV, 35 GHz

NO.	S11			S21			GDM Average	
	ADM	FDM	GDM	ADM	FDM	GDM	(GDM_S11+GDM_S21)/2	Qualitative
1	0.33	0.43	**0.59**	0.15	0.18	**0.26**	0.43	Fair
2	0.41	0.54	**0.76**	0.04	0.05	**0.07**	0.42	Fair
3	0.16	0.24	**0.33**	0.12	0.13	**0.19**	0.26	Good
4	0.25	0.35	**0.47**	0.09	0.16	**0.20**	0.34	Good
5	0.35	0.47	**0.66**	0.25	0.27	**0.41**	0.54	Fair
6	0.40	0.49	**0.72**	0.42	0.40	**0.64**	0.68	Fair
7	0.17	0.28	**0.36**	0.14	0.14	**0.22**	0.29	Good
8	0.35	0.37	**0.56**	0.19	0.23	**0.33**	0.44	Fair
9	0.39	0.44	**0.65**	0.11	0.19	**0.23**	0.44	Fair
10	0.43	0.44	**0.70**	0.05	0.06	**0.09**	0.40	Fair
11	0.45	0.51	**0.75**	0.11	0.15	**0.20**	0.48	Fair
12	0.44	0.60	**0.82**	0.03	0.04	**0.05**	0.44	Fair
13	0.24	0.40	**0.52**	0.15	0.18	**0.26**	0.39	Good
14	0.31	0.50	**0.66**	0.11	0.19	**0.24**	0.45	Fair
15	0.37	0.55	**0.73**	0.47	0.50	**0.75**	0.74	Fair-Poor
16	0.33	0.45	**0.63**	0.13	0.21	**0.28**	0.45	Fair
17	0.29	0.60	**0.73**	0.13	0.15	**0.22**	0.48	Fair
18	0.32	0.45	**0.61**	0.14	0.20	**0.27**	0.44	Fair
19	0.35	0.51	**0.69**	0.14	0.18	**0.25**	0.47	Fair
20	0.50	0.56	**0.83**	0.60	0.55	**0.91**	0.87	Poor
21	0.46	0.59	**0.83**	0.63	0.78	**1.13**	0.98	Poor
22	0.45	0.61	**0.85**	0.34	0.69	**0.83**	0.84	Poor
23	0.43	0.65	**0.86**	0.34	0.42	**0.61**	0.73	Fair-Poor

SPS, 35 GHz

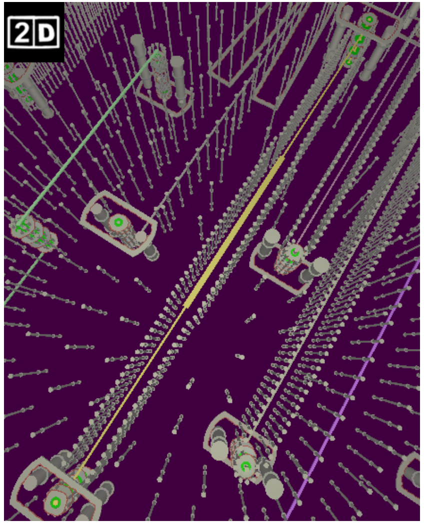
	SPS_SE 35 GHz
1	92.5639
2	91.8262
3	91.7525
4	92.8552
5	91.1739
6	90.8311
7	93.0992
8	93.8351
9	91.087
10	93.0776
11	94.7303
12	95.3771
13	93.3182
14	94.1929
15	88.4187
16	94.4118
17	93.596
18	93.969
19	91.9582
20	93.3429
21	93.9318
22	91.4807
23	91.6811

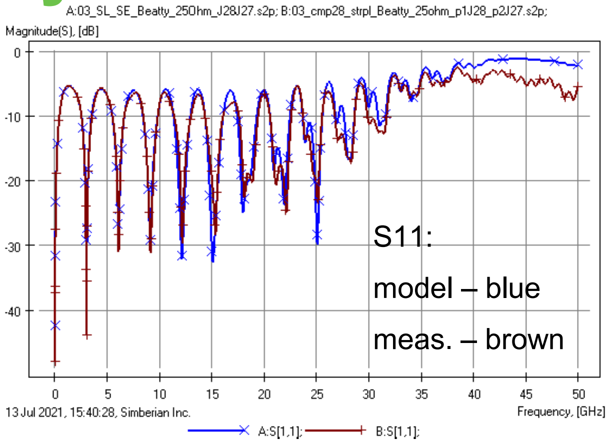
Inconsistencies in cases 20-22 with high losses |Sij|<0.1 – see analysis in *A. Duffy, G. Zhang, Y. Shlepnev, Comparison of Interconnect Model Validation with FSV and SPS Metrics , IBIS Virtual Summit with DesignCon 2021, San Jose, California August 19, 2021*.

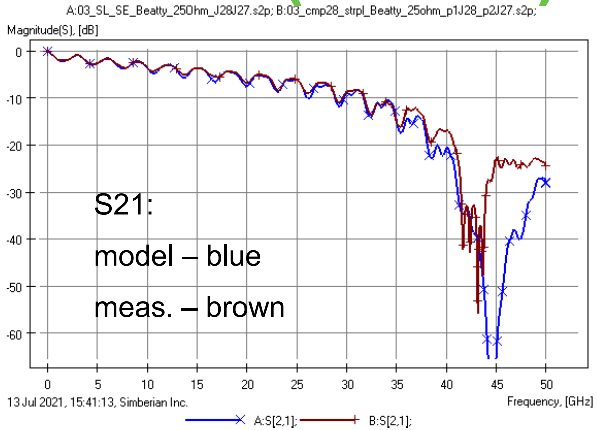
#3 – Strip Beatty – SPS Good/FSV Good (35GHz)

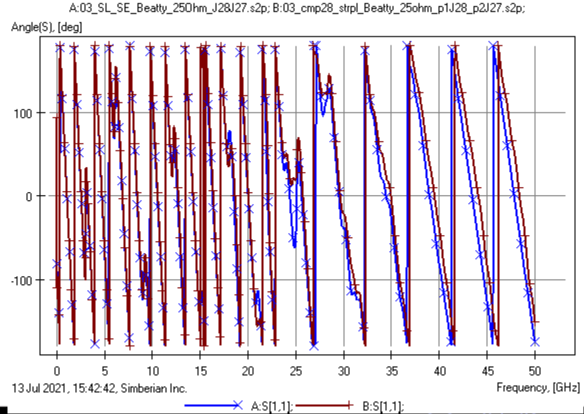
SPS(35)=91.75%

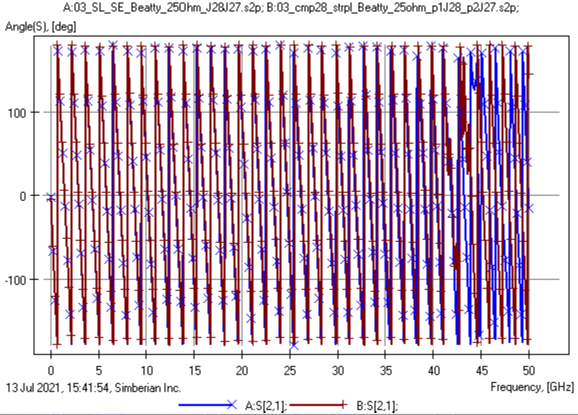
93.8279	96.1705
96.1928	91.7525







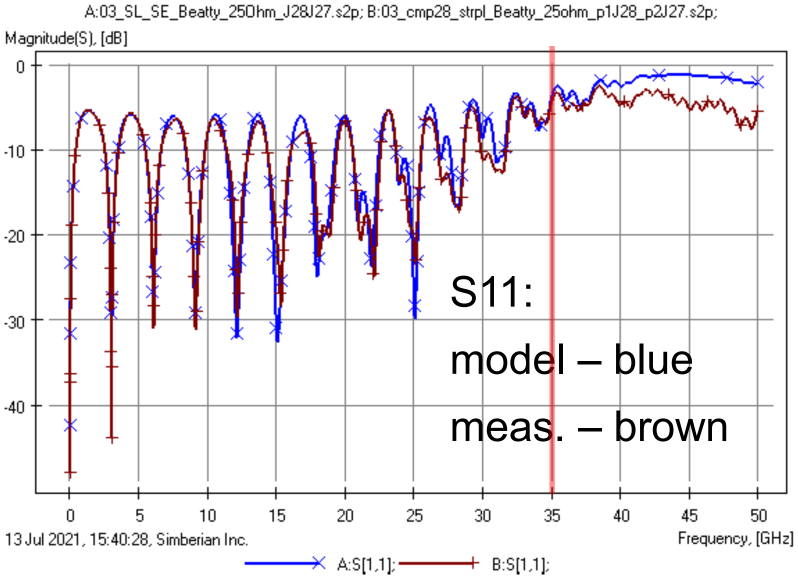


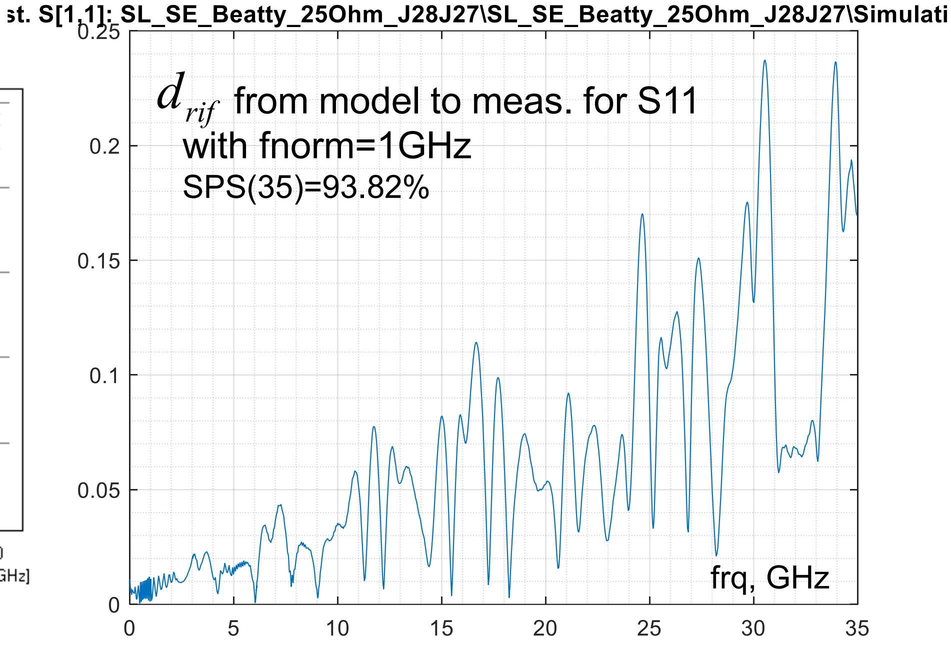


#3 – Strip Beatty - S11 – Good/Good

FSV

NO.	S11			S21			GDM Average	Qualitative
	ADM	FDM	GDM	ADM	FDM	GDM	(GDM_S11+GDM_S21)/2	
3	0.16	0.24	**0.33**	0.12	0.13	**0.19**	0.26	Good

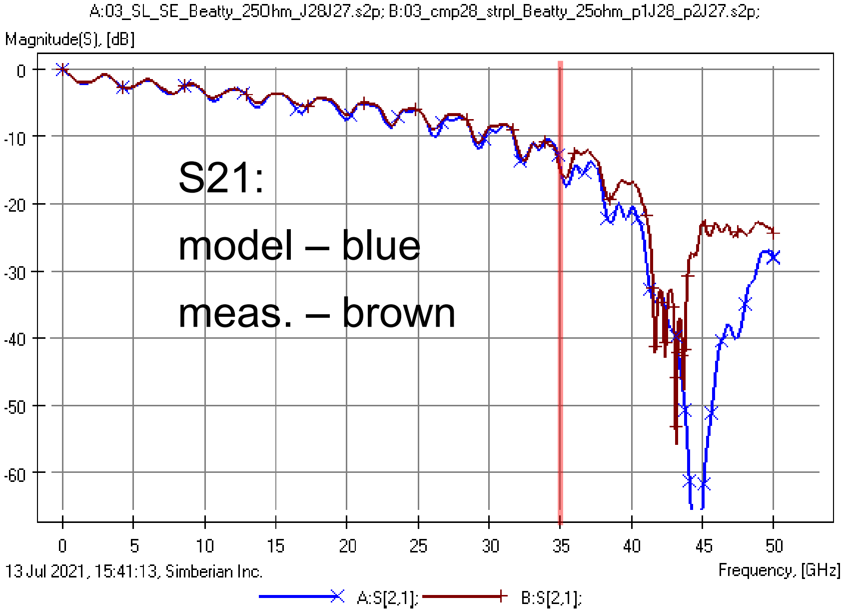


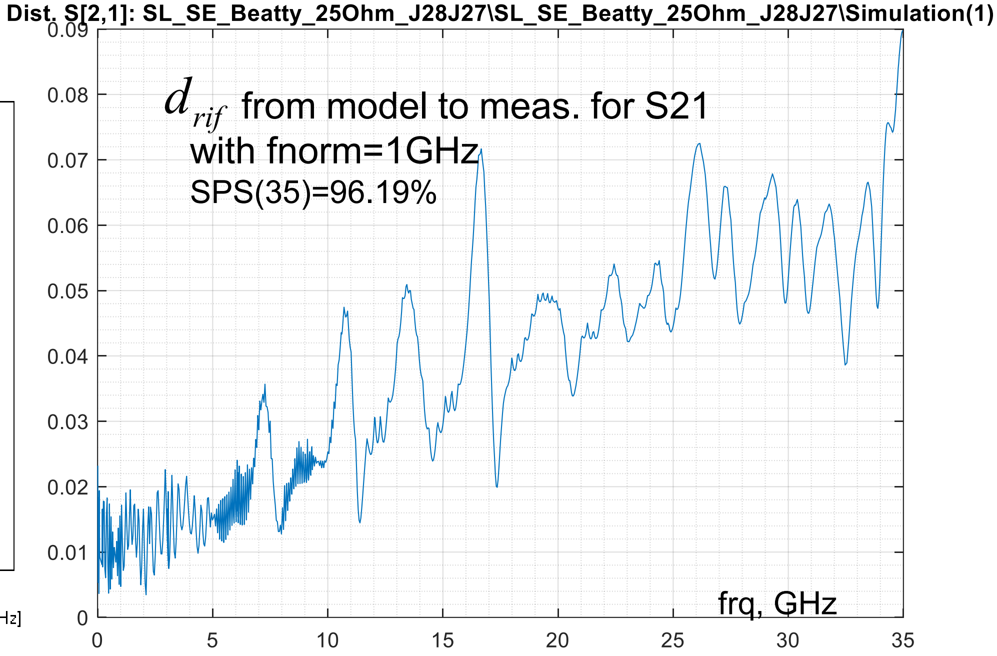


#3 – Strip Beatty – S21 – Good/Very Good

FSV

NO.	S11			S21			GDM Average	Qualitative
	ADM	FDM	GDM	ADM	FDM	GDM	(GDM_S11+GDM_S21)/2	
3	0.16	0.24	**0.33**	0.12	0.13	**0.19**	0.26	Good

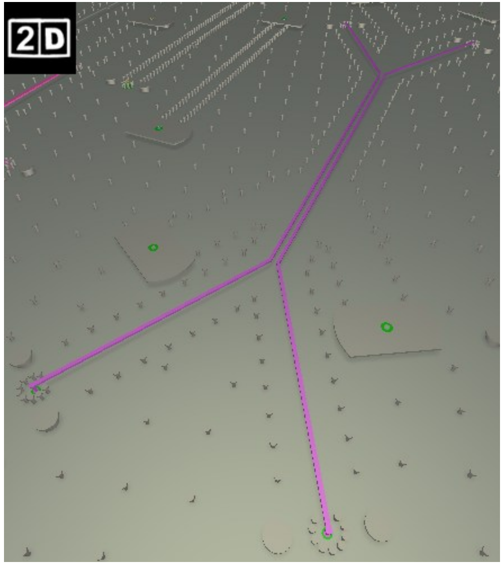


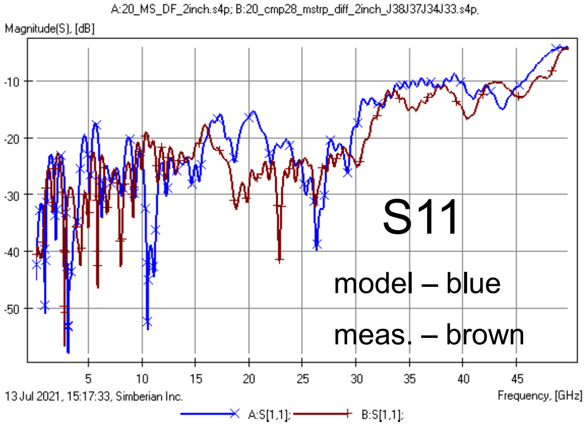


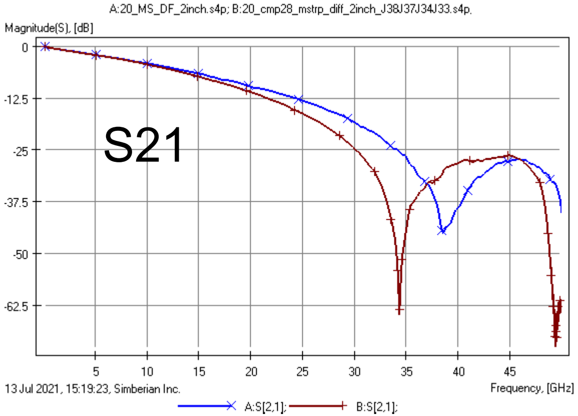
#20 – Diff. 2-in MSL – SPS Good/FSV Poor

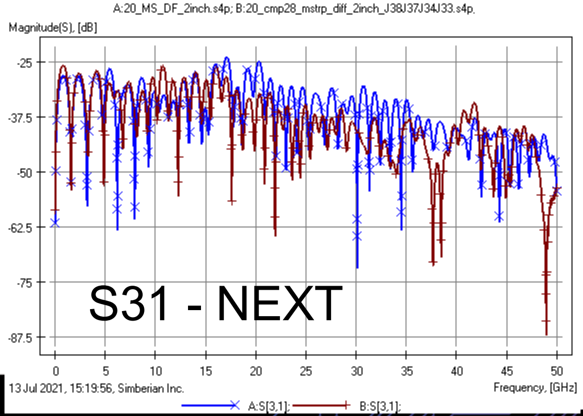
Single-Ended
SPS(35) = 93.34%

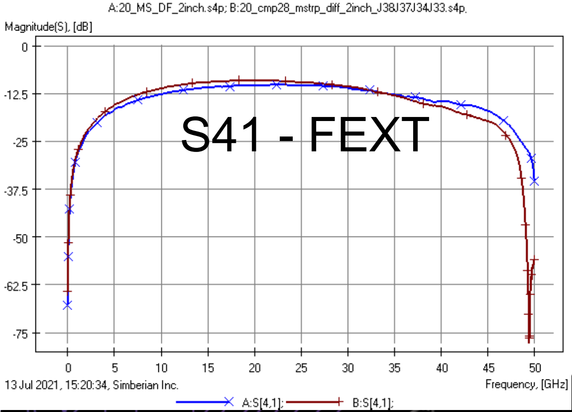
93.6896	96.0340	98.5680	96.8778
96.0421	93.8026	96.5445	98.4246
98.5675	96.5439	93.3429	95.9427
96.8520	98.4240	95.9464	93.4017







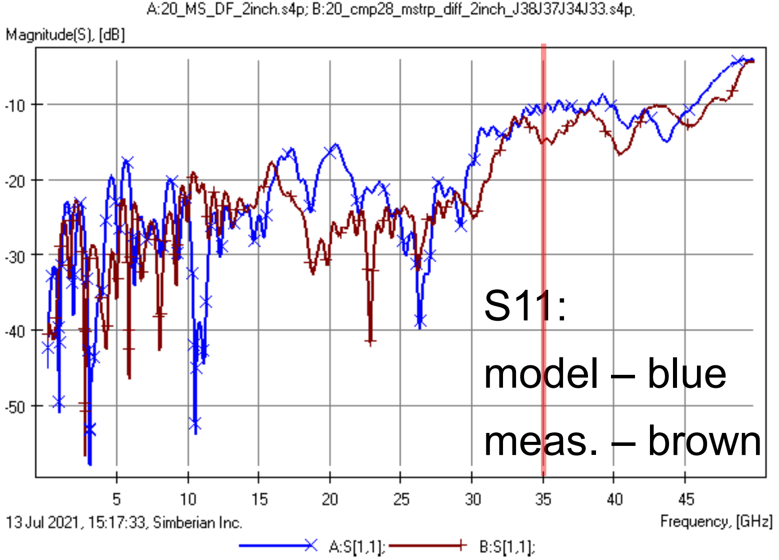


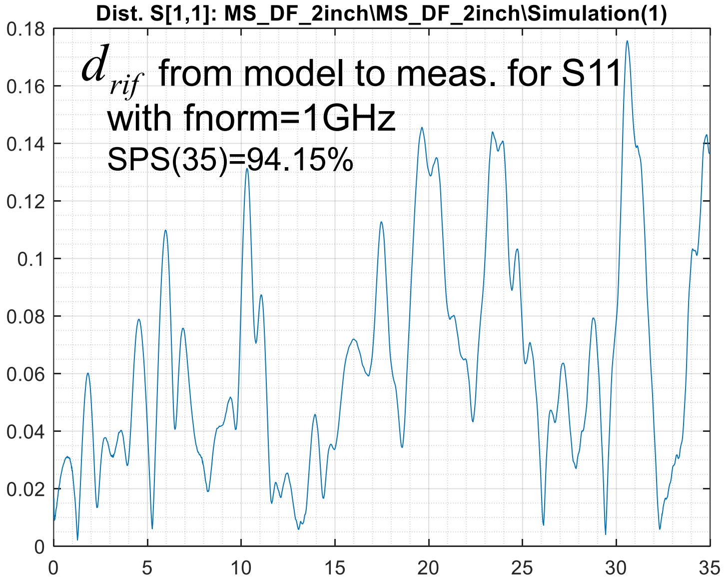


#20 – Diff. 2-in MSL – S11 – Good/ Poor

FSV

NO.	S11			S21			GDM Average	Qualitative
	ADM	FDM	GDM	ADM	FDM	GDM	(GDM_S11+GDM_S21)/2	
20	0.50	0.56	**0.83**	0.60	0.55	**0.91**	0.87	Poor

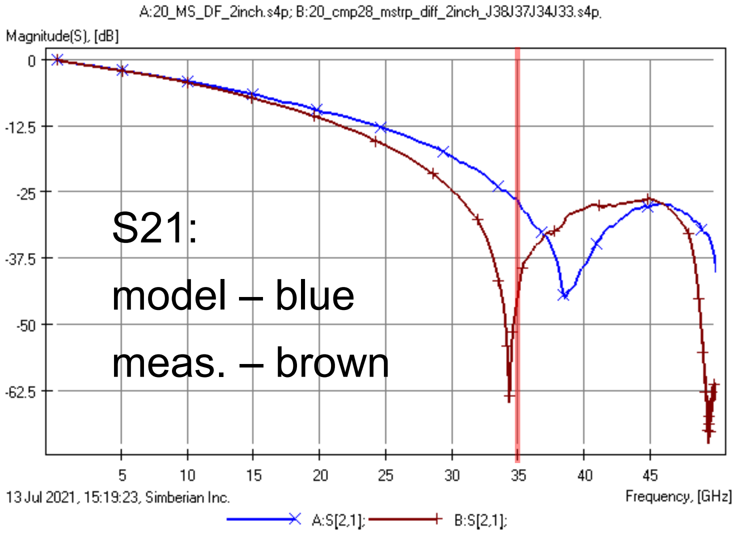


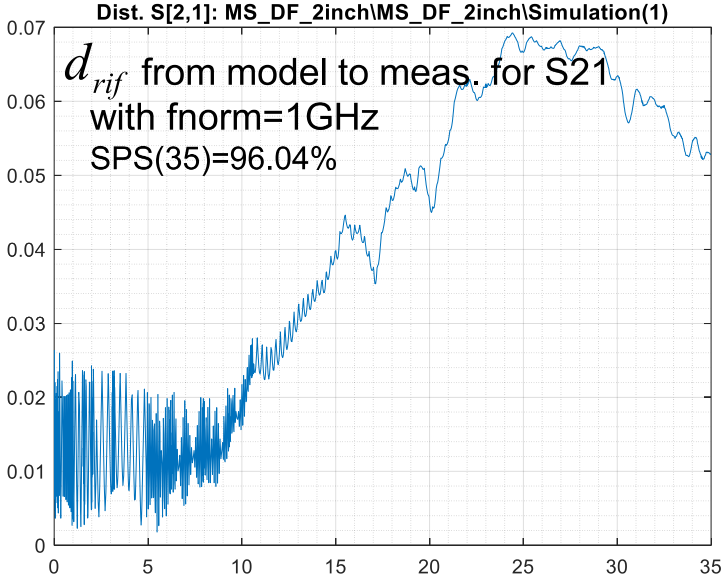


#20 – Diff. 2-in uStrip – S21 – Good/Poor

FSV

NO.	S11			S21			GDM Average	Qualitative
	ADM	FDM	GDM	ADM	FDM	GDM	(GDM_S11+GDM_S21)/2	
20	0.50	0.56	**0.83**	0.60	0.55	**0.91**	0.87	Poor

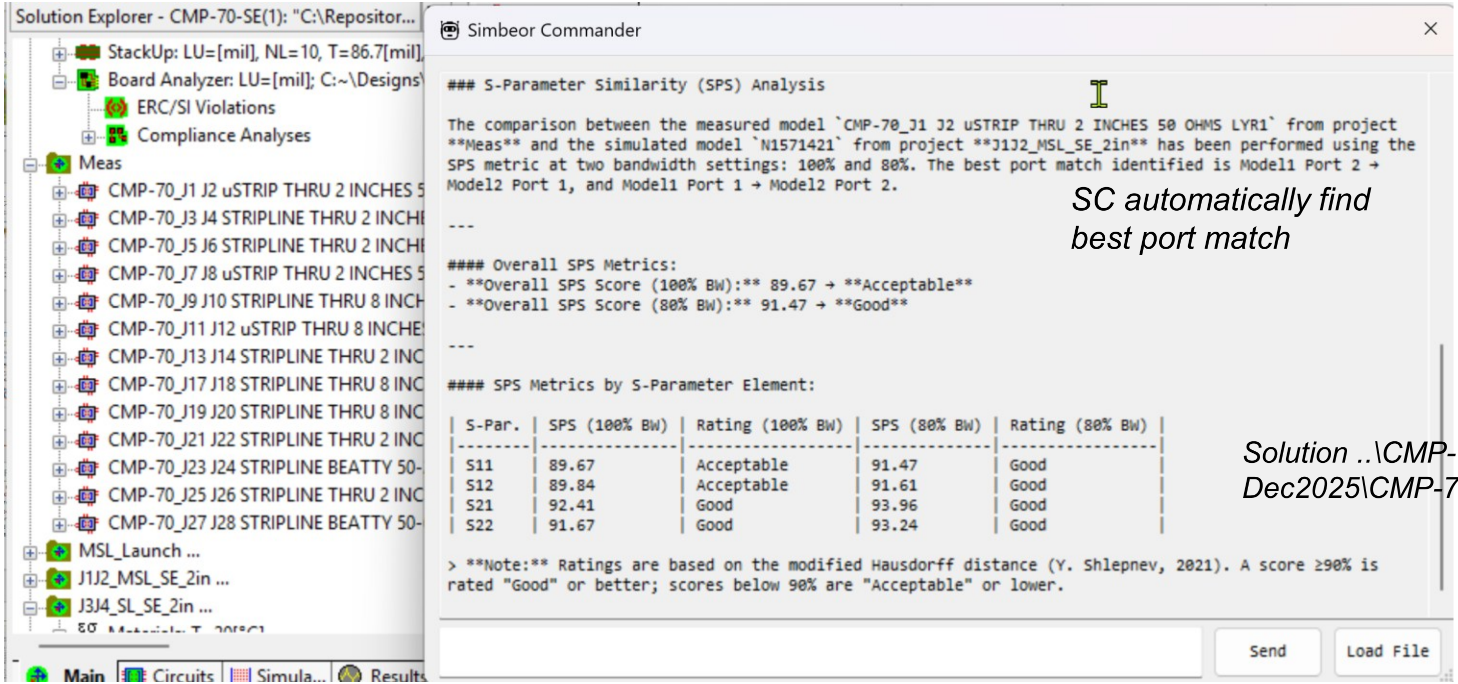




SPS is less sensitive to S-parameters with small magnitude

SPS Computation in Simbeor – J1J2 MSL 2in

```
Example of prompt in Simbeor Commander: Compare "CMP-70_J1 J2 uSTRIP THRU 2 INCHES 50 OHMS LYR1"
from Meas project with N1571421 from J1J2_MSL_SE_2in; need  SPP metric for each matrix element
and overall - compare wtih 100% bandwidth and with 80% bandwidth
```



SC automatically find best port match

Solution ..\CMP-70_Simbeor_Kit_2025\Dec2025\CMP-70-SE(1)

CMP-70 Analysis-to-Measurement Correlation

	Case ID	SPS Score 65GHz	SPS Score 52GHz
2	J1J2_MSL_SE_2in	89.67 (Acceptable)	91.47 (Good)
3	J3J4_SL_SE_2in	94.32 (Good)	95.36 (Good)
4	J5J6_SL_SE_2in	94.11 (Good)	95.44 (Good)
5	J7J8_MSL_SE_2in	90.68 (Good)	92.36 (Good)
6	J9J10_SL_SE_8in	93.34 (Good)	94.28 (Good)
7	J11J12_MSL_SE_8in	90.57 (Good)	93.05 (Good)
8	J13J14_SL_SE_60_2in	94.51 (Good)	95.37 (Good)
9	J17J18_SL_SE_60_8in	92.44 (Good)	93.56 (Good)
10	J19J20_SL_SE_40_8in	86.75 (Acceptable)	89.30 (Acceptable)
11	J21J22_SL_SE_CapLaunch	93.27 (Good)	94.33 (Good)
12	J23J24_SL_Beatty_50_25_50	94.34 (Good)	96.41 (Good)
13	J25J26_SL_SE_IndLaunch	93.88 (Good)	94.83 (Good)
14	J27J28_SL_Beatty_50_60_50	94.34 (Good)	96.41 (Good)
15	J31J32_MSL_SE_Via_TooInductive	87.50 (Acceptable)	90.47 (Good)
16	J33J34_MSL_SE_Via_Inductive	87.08 (Acceptable)	90.33 (Good)
17	J35J36_MSL_SE_Via_Matched	87.07 (Acceptable)	90.25 (Good)
18	J37J38_MSL_SE_Via_Capacitive	84.30 (Acceptable)	87.30 (Acceptable)
19	J39J40_MSL_SE_Via_TooCapacitive	80.03 (Acceptable)	83.09 (Acceptable)
20	J41J42_MSL_SL_SE_Via	88.53 (Acceptable)	91.77 (Good)
21	J43J44_SL_SE_BalancedRes	85.11 (Acceptable)	89.66 (Acceptable)
22	J46J47_SL_SE_GradualCoplanar	87.30 (Acceptable)	89.92 (Good)

	Case ID	SPS Score 65GHz	SPS Score 52GHz	SPS Score 32.5GHz
23	J48J49_MSL_SL_ViaFieldPath	87.68 (Acceptable)	90.17 (Good)	
24	J50J51_SL_SE_WhiskerStubs	90.82 (Good)	94.78 (Good)	
25	J52J53_MSL_SE_Cap_Cutout	78.36 (Inconclusive)	84.31 (Acceptable)	
26	J54J55_MSL_SE_Cap_NoCutout	70.54 (Inconclusive)	78.81 (Inconclusive)	
27	J58J59_SL_SE_RadialStub_50	86.66 (Acceptable)	92.83 (Good)	
28	J60J61_SL_SE_RadialStub_84	82.35 (Acceptable)	87.97 (Acceptable)	
29	J62J63_MSL_ViaResonator	80.78 (Acceptable)	85.09 (Acceptable)	92.86 (Good)
30	J64J67_MSL_SE_ViaXtalk	75.98 (Inconclusive)	80.90 (Acceptable)	
31	J69J72_MSL_Diff_2in	89.16 (Acceptable)	90.86 (Good)	
32	J73J76_SL_Diff_2in	92.92 (Good)	94.54 (Good)	
33	J77J80_MSL_Diff_6in	89.19 (Acceptable)	92.97 (Good)	
34	J81J84_SL_Diff_6in	92.81 (Good)	93.85 (Good)	
35	J85J88_Diff_Beatty	88.21 (Acceptable)	91.49 (Good)	
36	J89J92_Diff_PlaneCutout	87.00 (Acceptable)	90.10 (Good)	
37	J97J104_Diff_ViaTrans_Coupled	82.60 (Acceptable)	85.10 (Acceptable)	92.9 (Good)
38	J109J112_MSL_SL_Zaxis_Xtalk	69.20 (Inconclusive)	74.90 (Inconclusive)	87.75 (Acceptable)
39	J113J114_SL_SE_CapLaunch	87.14 (Acceptable)	93.42 (Good)	
40	J115J116_SL_SE_IndLaunch	88.36 (Acceptable)	94.51 (Good)	
41	J117J118_SL_SE_Whiskers_84	82.79 (Acceptable)	93.90 (Good)	
42	J119J122_MSL_SE_ViaXtalk_L2	76.86 (Inconclusive)	82.18 (Acceptable)	

No Caps

Let's compare a few interesting cases…

Worst S-matrix Element for Each Case (SPS 100%)

1	Case ID	Worst Snp	SPS (100%)	Port Mapping (Meas Sxy→ Sim Smn)
2	J1J2_MSL_SE_2in	S21	89.67	Meas S21 → Sim S12
3	J3J4_SL_SE_2in	S11	94.32	Meas S11 → Sim S11
4	J5J6_SL_SE_2in	S22	94.11	Meas S22 → Sim S22
5	J7J8_MSL_SE_2in	S12	90.68	Meas S12 → Sim S12
6	J9J10_SL_SE_8in	S12	93.34	Meas S12 → Sim S12
7	J11J12_MSL_SE_8in	S11	90.57	Meas S11 → Sim S11
8	J13J14_SL_SE_60_2in	S12	94.51	Meas S12 → Sim S12
9	J17J18_SL_SE_60_8in	S12	92.44	Meas S12 → Sim S12
10	J19J20_SL_SE_40_8in	S11	86.75	Meas S11 → Sim S11
11	J21J22_SL_SE_CapLaunch	S12	93.27	Meas S12 → Sim S12
12	J23J24_SL_Beatty_50_25_50	S22	94.34	Meas S22 → Sim S22
13	J25J26_SL_SE_IndLaunch	S11	93.88	Meas S11 → Sim S22
14	J27J28_SL_Beatty_50_60_50	S22	94.34	Meas S22 → Sim S22
15	J31J32_MSL_SE_Via_TooInductive	S12	87.5	Meas S12 → Sim S21
16	J33J34_MSL_SE_Via_Inductive	S12	87.08	Meas S12 → Sim S12
17	J35J36_MSL_SE_Via_Matched	S12	87.07	Meas S12 → Sim S12
18	J37J38_MSL_SE_Via_Capacitive	S12	84.3	Meas S12 → Sim S12
19	J39J40_MSL_SE_Via_TooCapaciti\	S12	80.03	Meas S12 → Sim S12
20	J41J42_MSL_SL_SE_Via	S11	88.53	Meas S11 → Sim S11
21	J43J44_SL_SE_BalancedRes	S11	85.11	Meas S11 → Sim S22
22	J46J47_SL_SE_GradualCoplanar	S12	87.3	Meas S12 → Sim S12

1	Case ID	Worst Snp	SPS (100%)	Port Mapping (Meas Sxy→ Sim Smn)	
23	J48J49_MSL_SL_ViaFieldPath	S11	87.68	Meas S11 → Sim S11	
24	J50J51_SL_SE_WhiskerStubs	S11	90.82	Meas S11 → Sim S22	
25	J52J53_MSL_SE_Cap_Cutout	S11	78.36	Meas S11 → Sim S22	
26	J54J55_MSL_SE_Cap_NoCutout	S11	70.54	Meas S11 → Sim S22	
27	J58J59_SL_SE_RadialStub_50	S11	86.66	Meas S11 → Sim S22	
28	J60J61_SL_SE_RadialStub_84	S22	82.35	Meas S22 → Sim S22	
29	J62J63_MSL_ViaResonator	S11	80.78	Meas S11 → Sim S11	refl.
30	J64J67_MSL_SE_ViaXtalk	S34	75.98	Meas S34 → Sim S12	
31	J69J72_MSL_Diff_2in	S33	89.16	Meas S33 → Sim S22	
32	J73J76_SL_Diff_2in	S24	92.92	Meas S24 → Sim S34	
33	J77J80_MSL_Diff_6in	S44	89.19	Meas S44 → Sim S33	refl.
34	J81J84_SL_Diff_6in	S13	92.81	Meas S13 → Sim S12	next
35	J85J88_Diff_Beatty	S11	88.21	Meas S11 → Sim S11	
36	J89J92_Diff_PlaneCutout	S22	87.02	Meas S22 → Sim S33	
37	J97J104_Diff_ViaTrans_Coupled	S15	82.6	Meas S15 → Sim S23	
38	J109J112_MSL_SL_Zaxis_Xtalk	S13	69.2	Meas S13 → Sim S12	next
39	J113J114_SL_SE_CapLaunch	S22	87.14	Meas S22 → Sim S22	
40	J115J116_SL_SE_IndLaunch	S22	88.36	Meas S22 → Sim S11	
41	J117J118_SL_SE_Whiskers_84	S11	82.79	Meas S11 → Sim S22	
42	J119J122_MSL_SE_ViaXtalk_L2	S13	76.86	Meas S13 → Sim S12	next

J62J63 – MSL SE Via Resonator

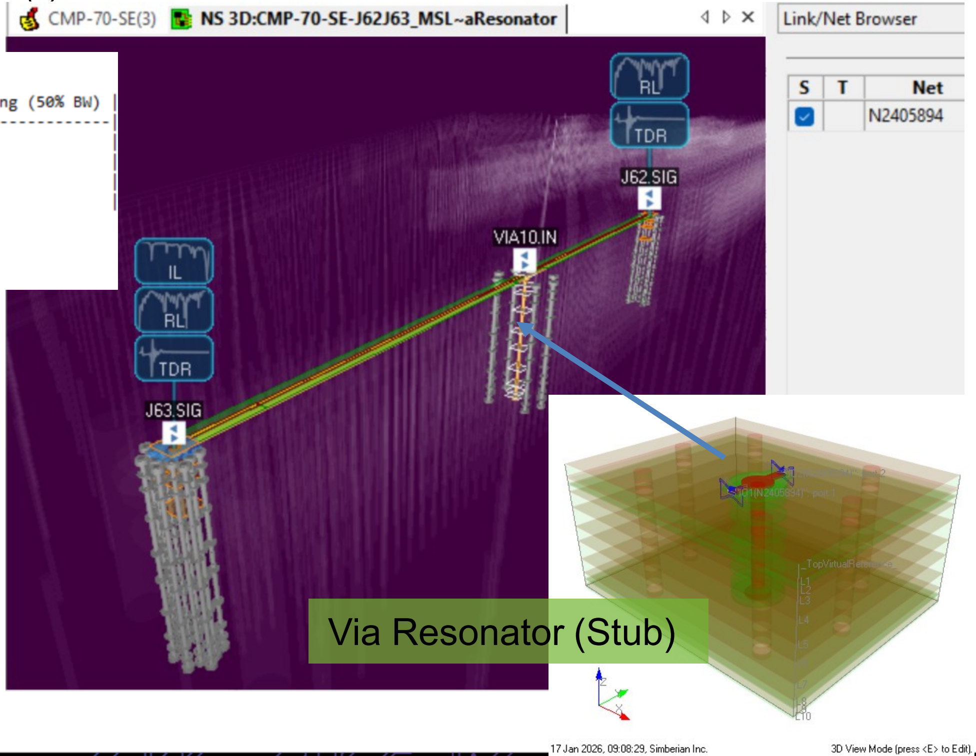
J62/J63	N2405894	MSL Via Resonator (Resonant)	Anisotropy Test	"CMP-70_J62 J63 MICROSTRIP ANISOTROPIC RESONATOR.S2P"

Solution ..\CMP-70_Simbeor_Kit_2025\Dec2025\CMP-70-SE(3)

SPS Metrics by S-Parameter Element

S-Par.	SPS (100% BW)	Rating (100% BW)	SPS (80% BW)	Rating (80% BW)	SPS (50% BW)	Rating (50% BW)
S11	80.78	Acceptable	85.09	Acceptable	92.86	Good
S12	83.08	Acceptable	85.59	Acceptable	93.11	Good
S21	83.04	Acceptable	85.53	Acceptable	93.08	Good
S22	81.58	Acceptable	85.24	Acceptable	92.88	Good

* **Overall SPS Score (100% BW):** 80.78 → **Acceptable**
* **Overall SPS Score (80% BW):** 85.09 → **Acceptable**
* **Overall SPS Score (50% BW):** 92.86 → **Good**



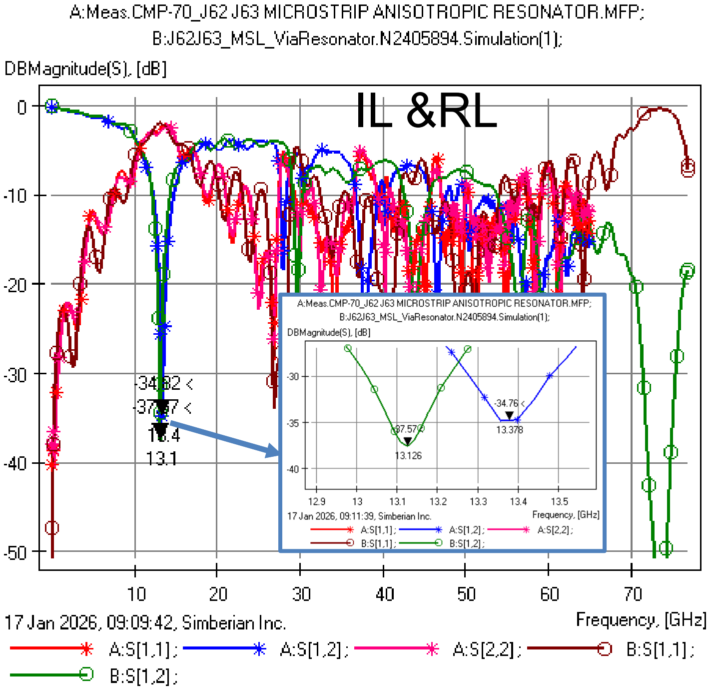
Note: Compare it with the results obtained with Cadence Clarity in "Free signal integrity? How understanding anisotropic materials and tolerances could increase performance at 112/224Gbps and beyond", DesignCon 2025

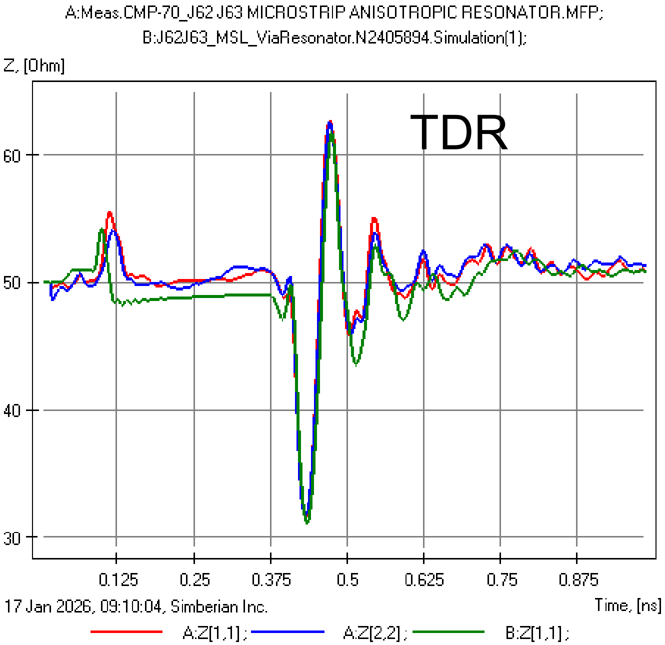
J62J63 – MSL SE Via Resonator

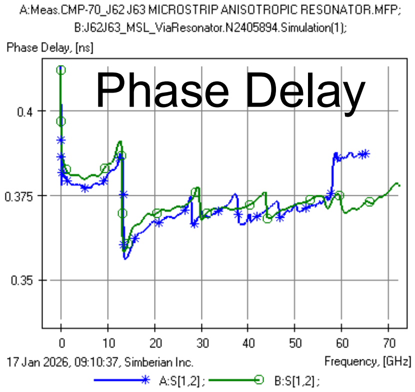
J62/J63	N2405894	MSL Via Resonator (Resonant)	Anisotropy Test	"CMP-70_J62 J63 MICROSTRIP ANISOTROPIC RESONATOR.S2P"

Solution ..\CMP-70_Simbeor_Kit_2025\Dec2025\CMP-70-SE(3)

~2% shift in resonance; No Anisotropy







J77J78J79J80 – MSL DIFF 6in

J77/J78	DP2+	MSL 100 Ohm DIFF, 6 inches, L10	Identification	"CMP-70_J77J78J79J80_uSTRIP_DIFFERENTIAL_THRU_LYR_10_6_INCHES.s4p"
J79/J80	DP2-	MSL 100 Ohm DIFF, 6 inches, L10		same

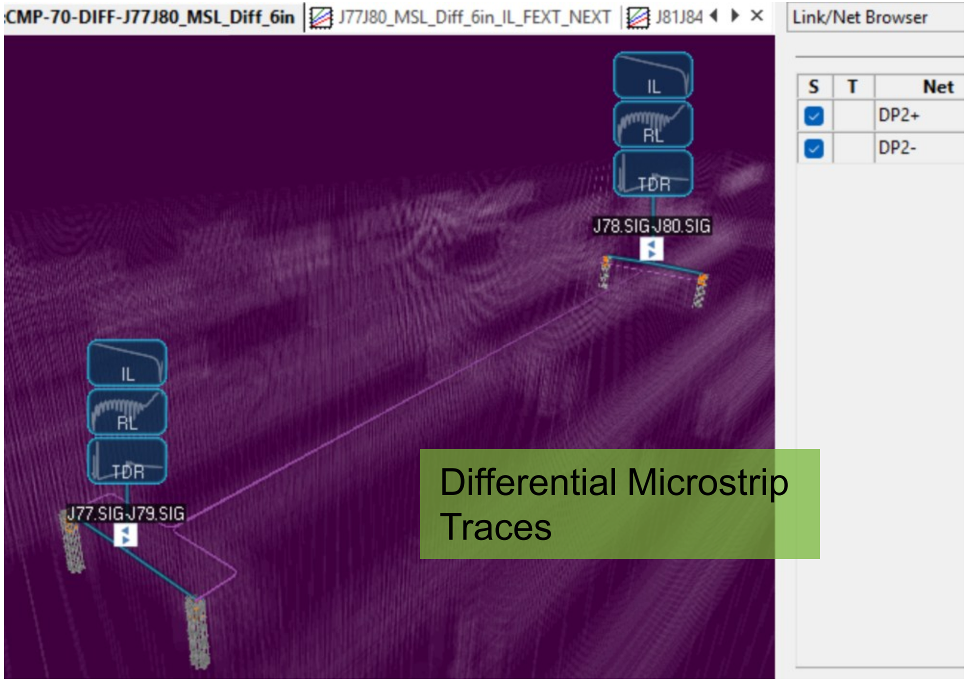
Solution ..\CMP-70_Simbeor_Kit_2025\Dec2025\CMP-70-DIFF(1)

```
Identified Port Mapping (Meas -> Sim.)**[2 → 1, 4 → 3, 1 → 4, 3 → 2]**

#### Overall SPS Score
* **Overall SPS Score (100% BW):** 89.19 → **Acceptable**
* **Overall SPS Score (80% BW):** 92.97 → **Good**

#### SPS Metrics per S-Parameter Element
```

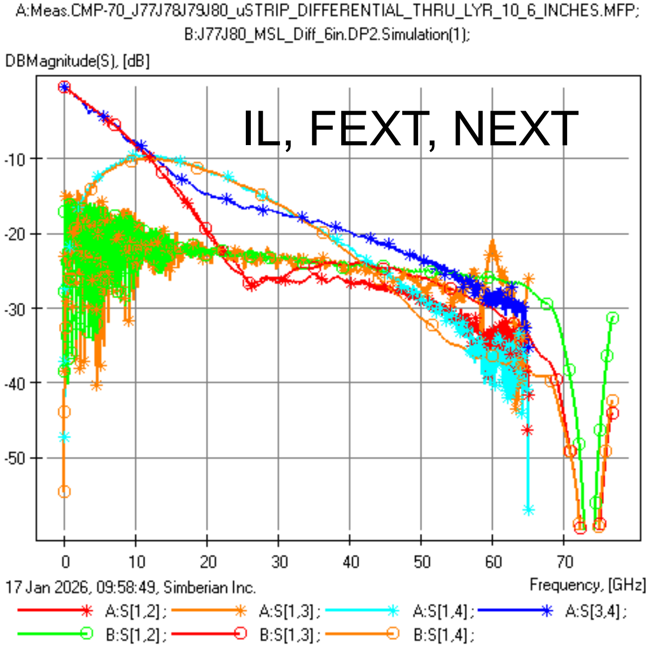
S-Par.	SPS (100% BW)	Rating (100% BW)	SPS (80% BW)	Rating (80% BW)
S11	90.24	Good	93.12	Good
S12	94.55	Good	95.20	Good
S13	92.46	Good	93.42	Good
S14	97.02	Good	97.45	Good
S21	94.52	Good	95.15	Good
S22	90.40	Good	92.97	Good
S23	97.02	Good	97.46	Good
S24	95.40	Good	95.88	Good
S31	92.48	Good	93.39	Good
S32	97.05	Good	97.49	Good
S33	89.96	Acceptable	94.23	Good
S34	94.12	Good	95.62	Good
S41	96.99	Good	97.41	Good
S42	95.38	Good	95.90	Good
S43	94.07	Good	95.59	Good
S44	89.19	Acceptable	93.72	Good

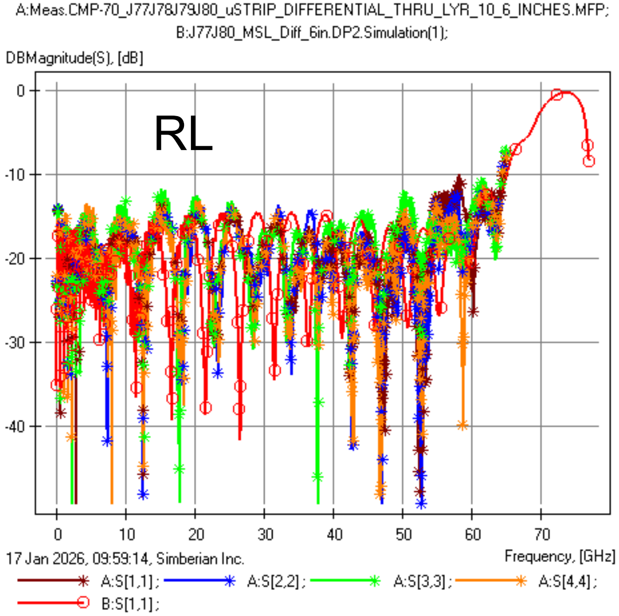


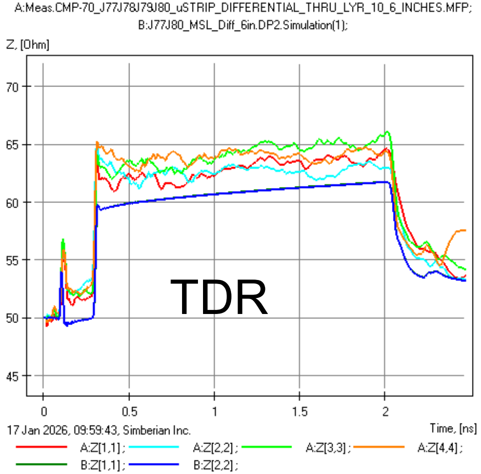
J77J78J79J80 – MSL DIFF 6in

J77/J78	DP2+	MSL 100 Ohm DIFF, 6 inches, L10	Identification	"CMP-70_J77J78J79J80_uSTRIP_DIFFERENTIAL_THRU_LYR_10_6_INCHES.s4p"
J79/J80	DP2-	MSL 100 Ohm DIFF, 6 inches, L10		same

Solution ..\CMP-70_Simbeor_Kit_2025\Dec2025\CMP-70-DIFF(1)



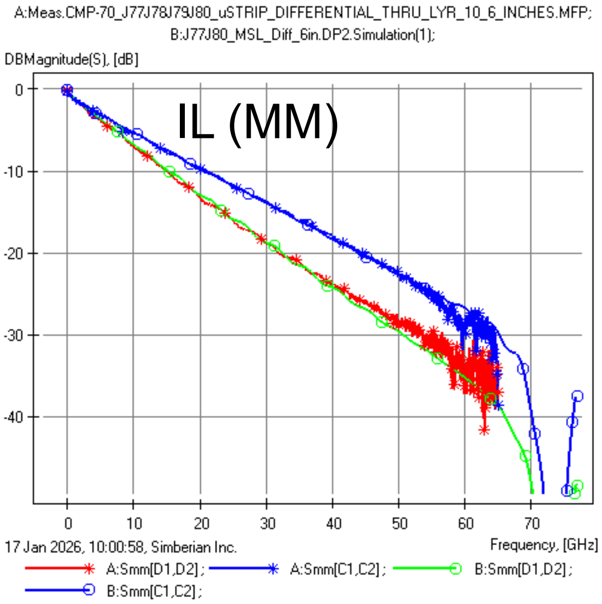


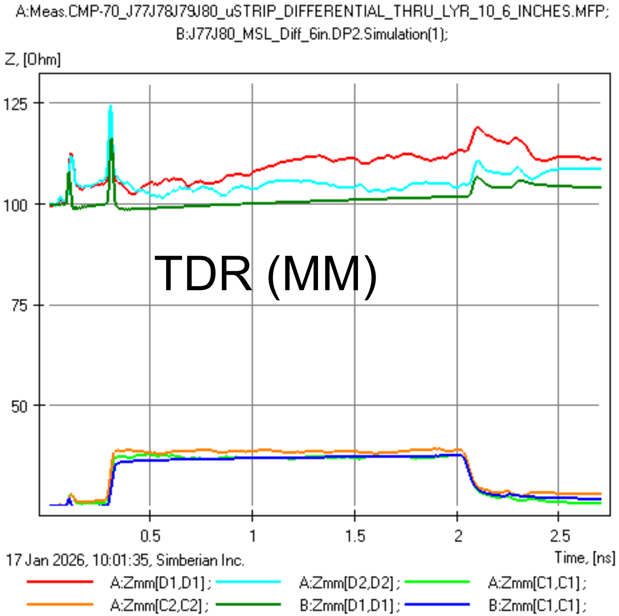


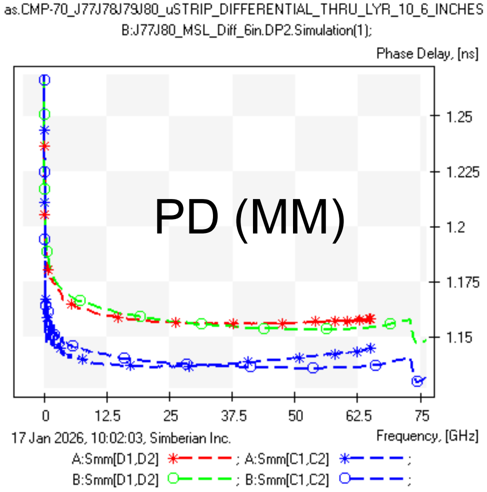
J77J78J79J80 – MSL DIFF 6in

J77/J78	DP2+	MSL 100 Ohm DIFF, 6 inches, L10	Identification	"CMP-70_J77J78J79J80_uSTRIP_DIFFERENTIAL_THRU_LYR_10_6_INCHES.s4p"
J79/J80	DP2-	MSL 100 Ohm DIFF, 6 inches, L10		same

Solution ..\CMP-70_Simbeor_Kit_2025\Dec2025\CMP-70-DIFF(1)







J81J82J83J84 – SL DIFF 6in

J81/J82	DP4+	SL 100 Ohm DIFF, 6 inches, L2	Identification	"CMP-70_J81J82J83J84_STRIPLINE_DIFFERENTIAL_THRU_LYR2_6_INCHES.s4p"
J83/J84	DP4-	SL 100 Ohm DIFF, 6 inches, L2		same

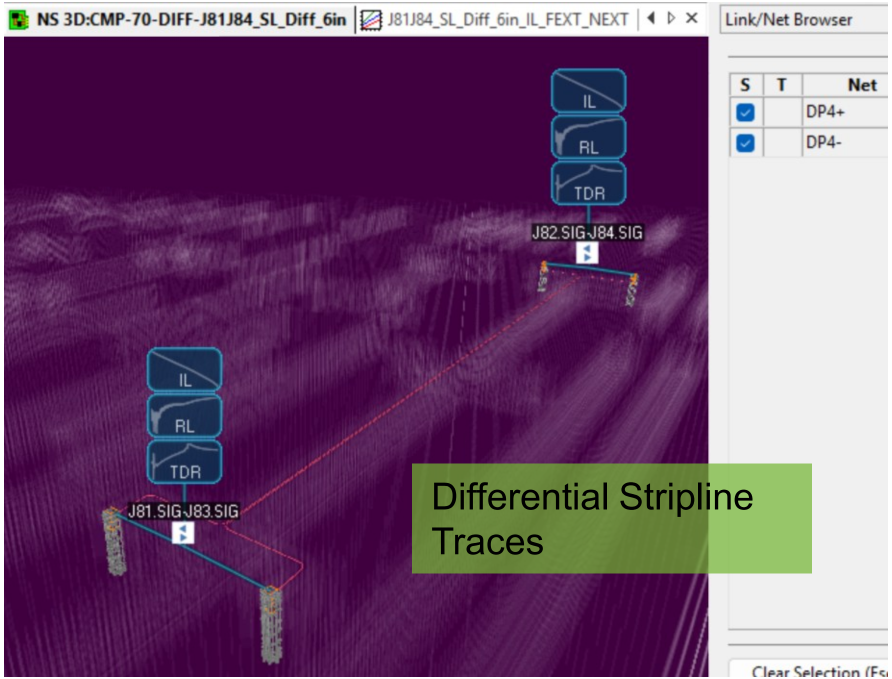
Solution ..\CMP-70_Simbeor_Kit_2025\Dec2025\CMP-70-DIFF(1)

Identified Port Mapping (Meas -> Sim.)**[1 → 1, 3 → 2, 2 → 3, 4 → 4]**

Overall SPS Score
* **Overall SPS Score (100% BW):** 92.81 → **Good**
* **Overall SPS Score (80% BW):** 93.85 → **Good**

SPS Metrics per S-Parameter Element

S-Par.	SPS (100% BW)	Rating (100% BW)	SPS (80% BW)	Rating (80% BW)
S11	94.68	Good	95.97	Good
S12	98.62	Good	98.88	Good
S13	92.81	Good	93.85	Good
S14	97.92	Good	98.31	Good
S21	98.63	Good	98.89	Good
S22	94.61	Good	95.75	Good
S23	97.94	Good	98.32	Good
S24	93.00	Good	94.02	Good
S31	92.85	Good	93.88	Good
S32	97.93	Good	98.32	Good
S33	95.30	Good	96.35	Good
S34	98.52	Good	98.79	Good
S41	97.93	Good	98.32	Good
S42	93.03	Good	94.04	Good
S43	98.53	Good	98.80	Good
S44	94.79	Good	95.66	Good



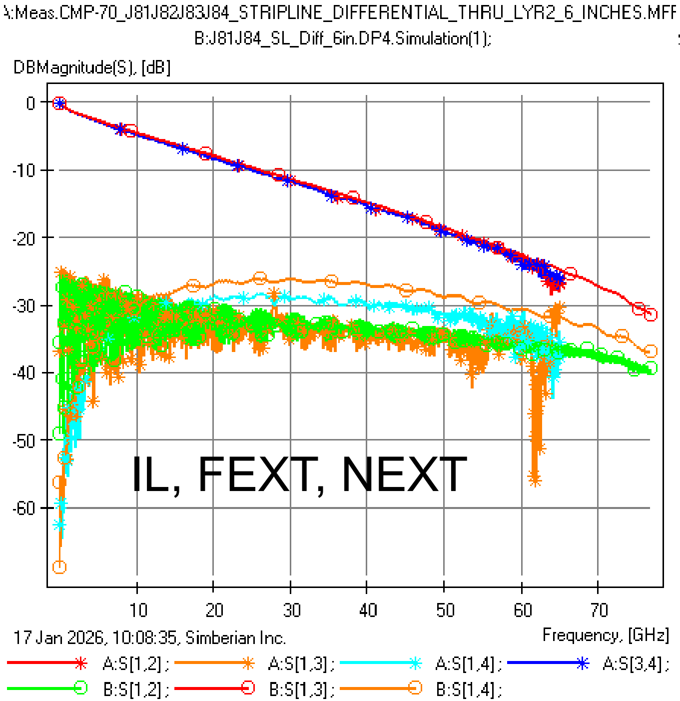
Differential Stripline Traces

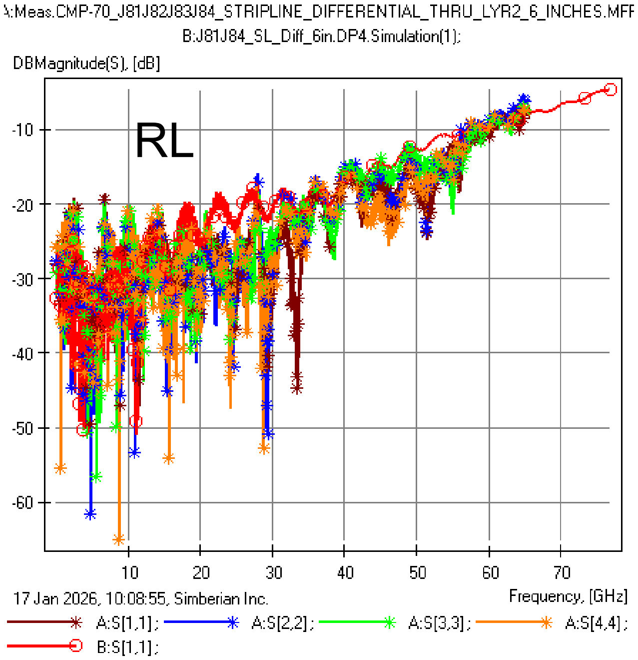
Note: Compare it with the results obtained with Cadence Clarity in "Free signal integrity? How understanding anisotropic materials and tolerances could increase performance at 112/224Gbps and beyond", DesignCon 2025

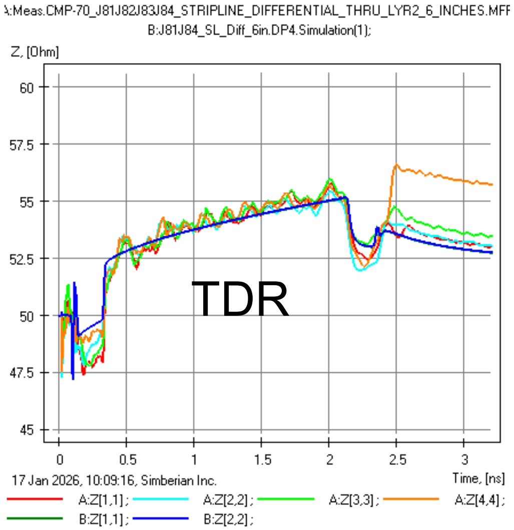
J81J82J83J84 – SL DIFF 6in

J81/J82	DP4+	SL 100 Ohm DIFF, 6 inches, L2	Identification	"CMP-70_J81J82J83J84_STRIPLINE_DIFFERENTIAL_THRU_LYR2_6_INCHES.s4p"
J83/J84	DP4-	SL 100 Ohm DIFF, 6 inches, L2		same

Solution ..\CMP-70_Simbeor_Kit_2025\Dec2025\CMP-70-DIFF(1)



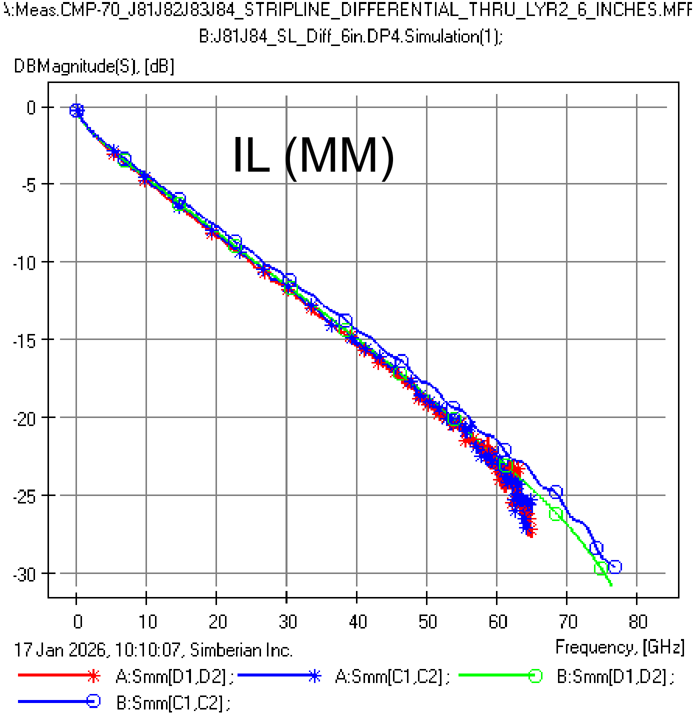


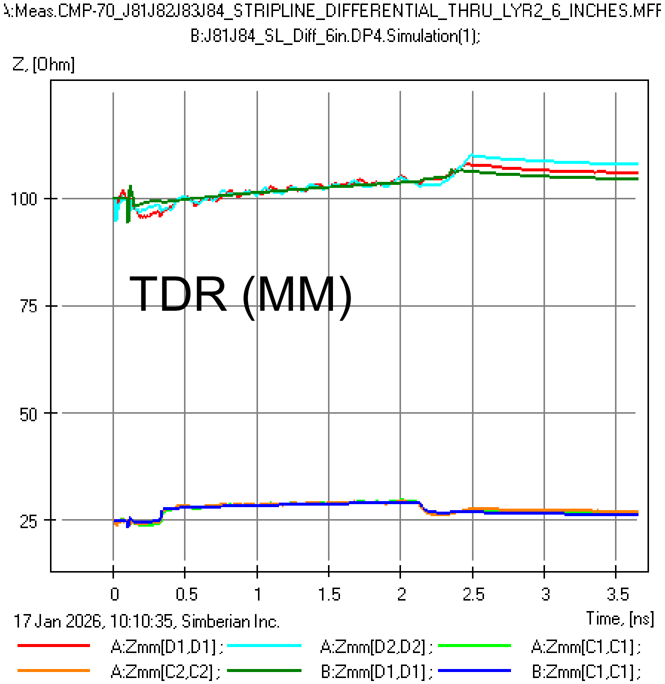


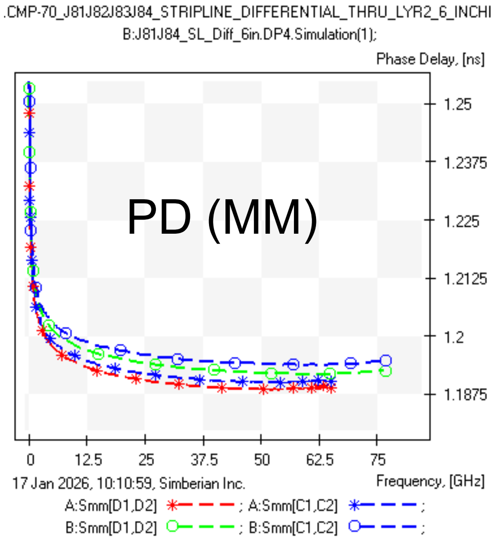
J81J82J83J84 – SL DIFF 6in

J81/J82	DP4+	SL 100 Ohm DIFF, 6 inches, L2	Identification	"CMP-70_J81J82J83J84_STRIPLINE_DIFFERENTIAL_THRU_LYR2_6_INCHES.s4p"
J83/J84	DP4-	SL 100 Ohm DIFF, 6 inches, L2		same

Solution ..\CMP-70_Simbeor_Kit_2025\Dec2025\CMP-70-DIFF(1)







J109J110J111J112 – MSL to SL XTalk

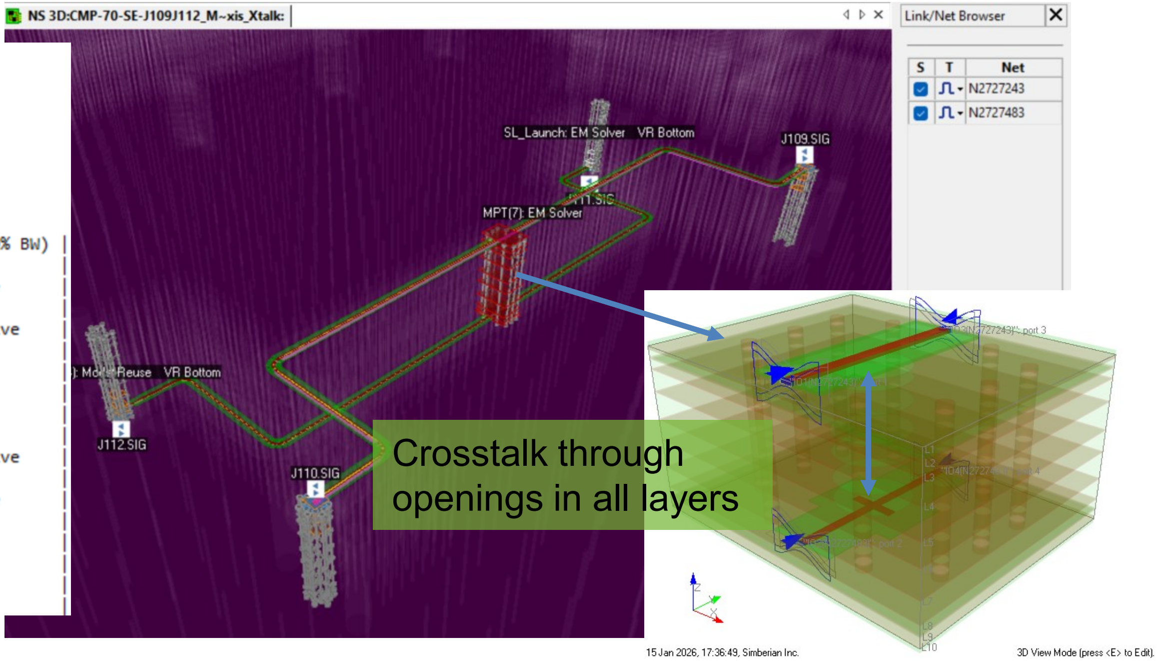
J109/J110	N2727243	MSL-SL SE Z-axis crosstalk Link1	Crosstalk	"CMP-70_J109J110J111J112_uSTRIP_STRIPLINE_Z-AXIS_CROSSTALK.s4p"
J111/J112	N2727483	MSL-SL SE Z-axis crosstalk Link2		same

Solution ..\CMP-70_Simbeor_Kit_2025\Dec2025\CMP-70-SE(4)

Port Mapping for Maximum Similarity
The best match of ports that produces maximal similarity is:
* Measured Model Port 1 → Simulated Model Port 1
* Measured Model Port 2 → Simulated Model Port 3
* Measured Model Port 3 → Simulated Model Port 2
* Measured Model Port 4 → Simulated Model Port 4

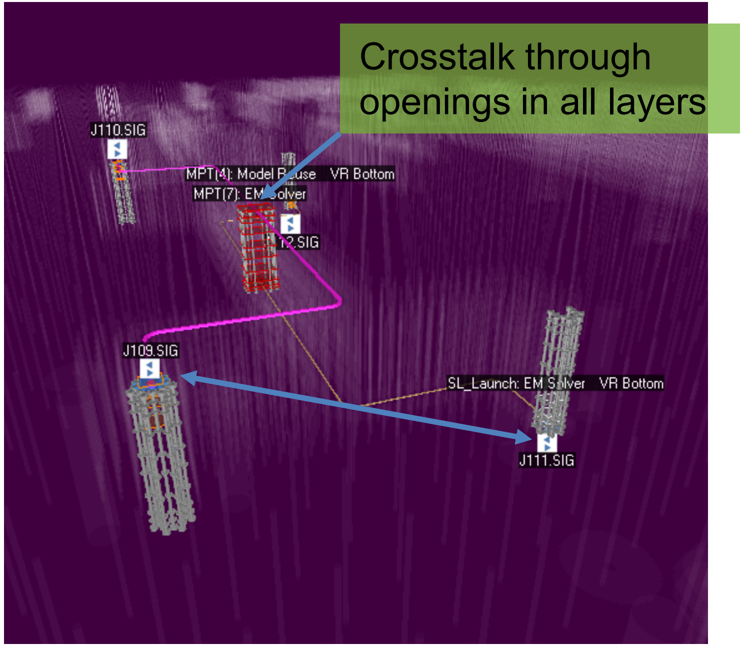
SPS Metrics per S-Parameter Element

S-Par.	SPS (100% BW)	Rating (100% BW)	SPS (80% BW)	Rating (80% BW)
S11	76.38	Inconclusive	81.92	Acceptable
S12	98.81	Good	99.10	Excellent
S13	69.20	Bad	74.90	Inconclusive
S14	98.86	Good	99.12	Excellent
S21	98.80	Good	99.09	Excellent
S22	84.10	Acceptable	92.73	Good
S23	98.77	Good	99.02	Excellent
S24	91.42	Good	94.10	Good
S31	69.26	Bad	74.95	Inconclusive
S32	98.78	Good	99.02	Excellent
S33	76.31	Inconclusive	81.80	Acceptable
S34	98.82	Good	99.06	Excellent
S41	98.85	Good	99.12	Excellent
S42	91.53	Good	94.17	Good
S43	98.82	Good	99.06	Excellent
S44	84.17	Acceptable	92.40	Good

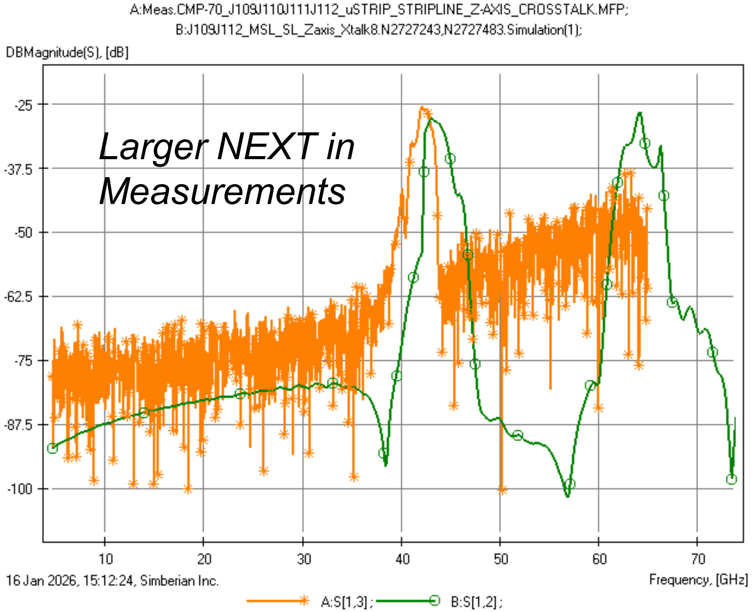


J109J110J111J112 – MSL to SL XTalk

Solution ..\CMP-70_Simbeor_Kit_2025\Dec2025\CMP-70-SE(4)



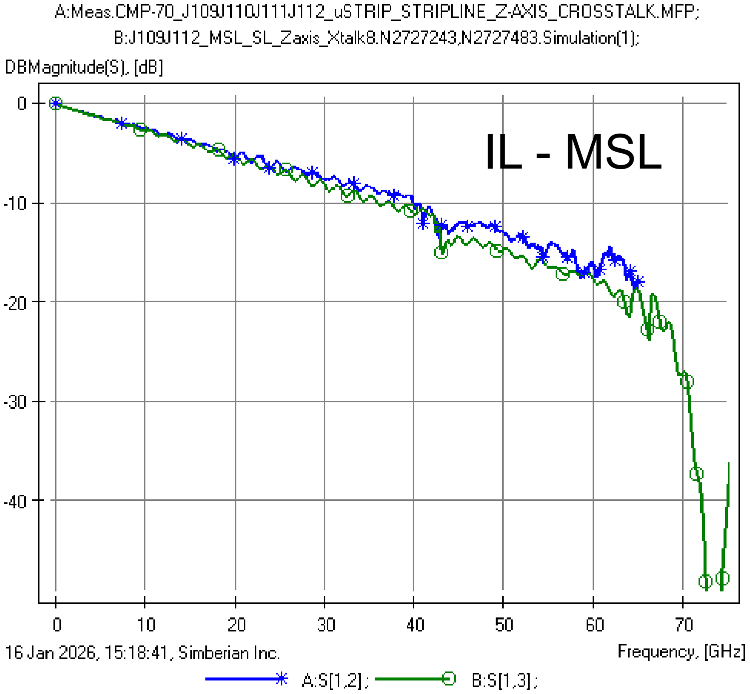
May be even acceptable?

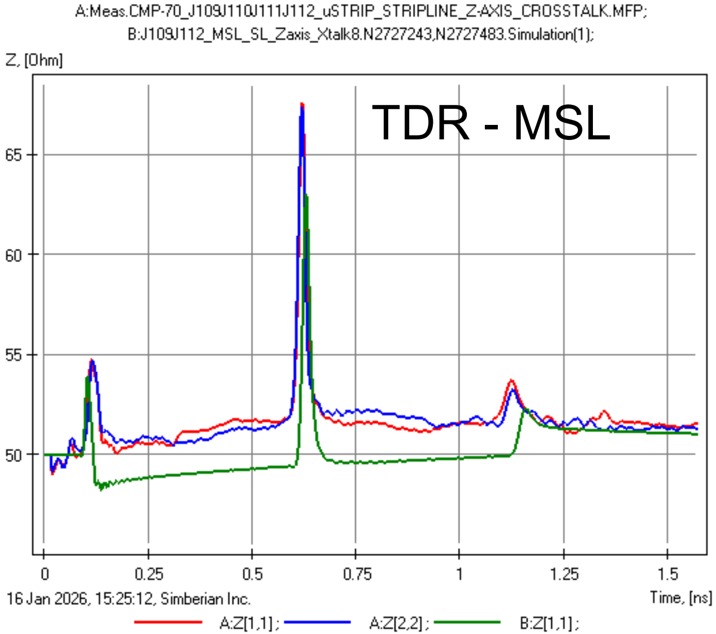


J109J110J111J112 – MSL to SL XTalk

J109/J110	N2727243	MSL-SL SE Z-axis crosstalk Link1	Crosstalk	"CMP-70_J109J110J111J112_uSTRIP_STRIPLINE_Z-AXIS_CROSSTALK.s4p"
J111/J112	N2727483	MSL-SL SE Z-axis crosstalk Link2		same

Solution ..\CMP-70_Simbeor_Kit_2025\Dec2025\CMP-70-SE(4)

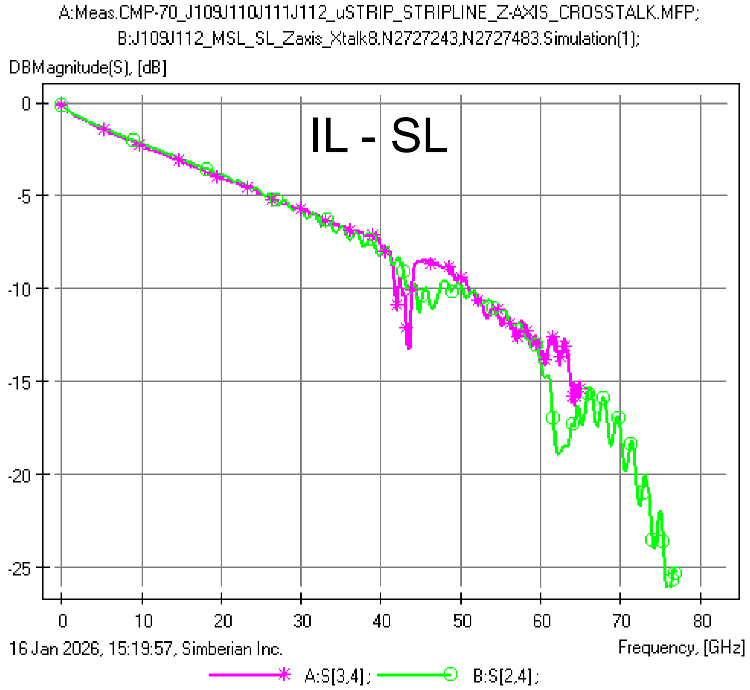


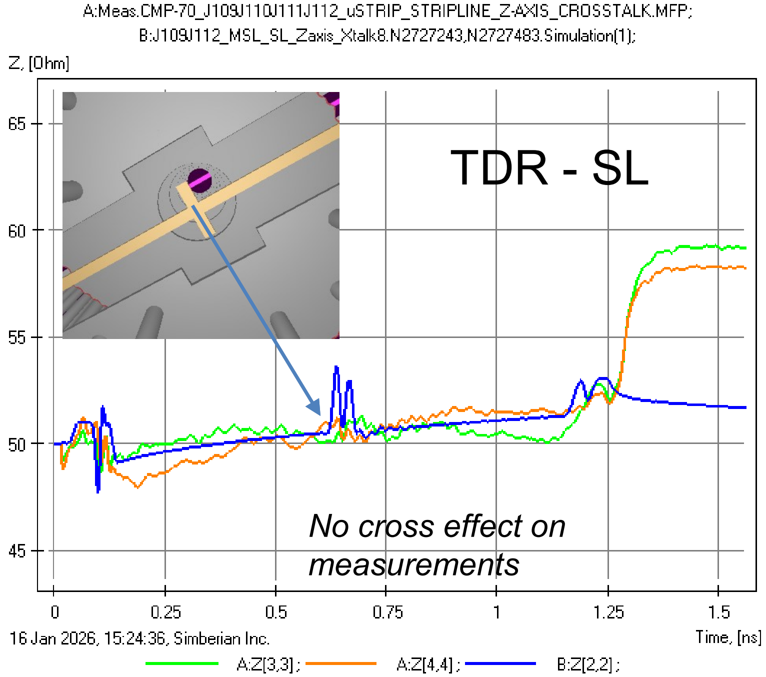


J109J110J111J112 – MSL to SL XTalk

J109/J110	N2727243	MSL-SL SE Z-axis crosstalk Link1	Crosstalk	"CMP-70_J109J110J111J112_uSTRIP_STRIPLINE_Z-AXIS_CROSSTALK.s4p"
J111/J112	N2727483	MSL-SL SE Z-axis crosstalk Link2		same

Solution ..\CMP-70_Simbeor_Kit_2025\Dec2025\CMP-70-SE(4)





J119J120J121J122 – MSL SE Via XTalk

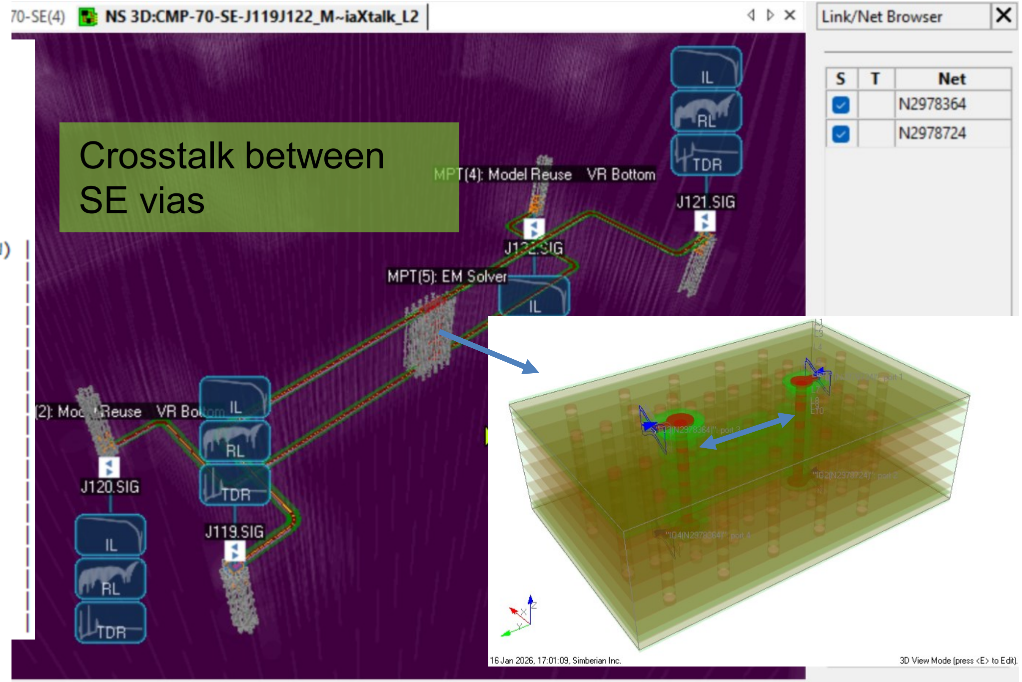
J119/J120	N2978364	MSL SE Via Crosstalk - Link1	Crosstalk	"CMP-70_J119J120J121J122_uSTRIP_SE_VIA_CROSSTALK_ANTENNA_CAP-IND.s4p
J121/J122	N2978724	MSL SE Via Crosstalk - Link2		same

Solution ..\CMP-70_Simbeor_Kit_2025\Dec2025\CMP-70-SE(4)

```
#### Port Mapping for Maximum Similarity
The best match of ports that produces maximal similarity is:
* Measured Model Port 1 → Simulated Model Port 1
* Measured Model Port 2 → Simulated Model Port 3
* Measured Model Port 3 → Simulated Model Port 2
* Measured Model Port 4 → Simulated Model Port 4

#### SPS Metrics per S-Parameter Element
```

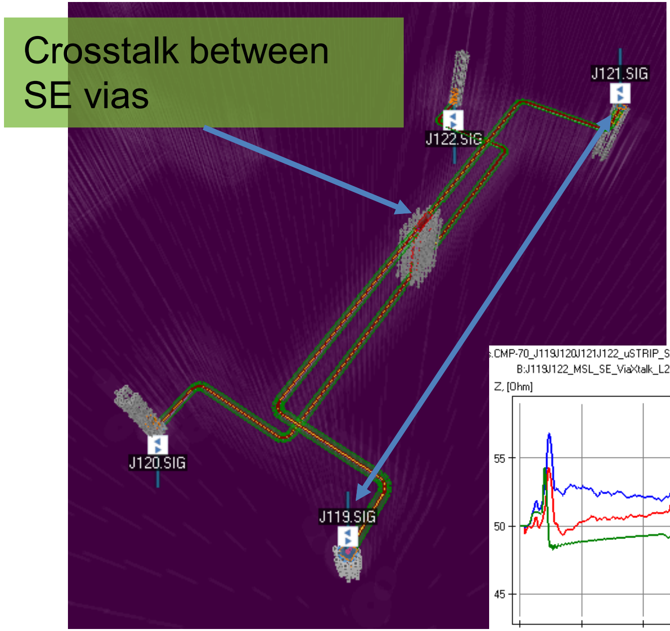
S-Par.	SPS (100% BW)	Rating (100% BW)	SPS (80% BW)	Rating (80% BW)
S11	88.45	Acceptable	91.34	Good
S12	98.97	Good	99.24	Excellent
S13	76.86	Inconclusive	82.18	Acceptable
S14	98.98	Good	99.24	Excellent
S21	98.97	Good	99.24	Excellent
S22	84.83	Acceptable	88.48	Acceptable
S23	98.98	Good	99.24	Excellent
S24	80.19	Inconclusive	84.54	Acceptable
S31	76.95	Inconclusive	82.25	Acceptable
S32	98.99	Good	99.24	Excellent
S33	88.98	Acceptable	91.26	Good
S34	99.00	Excellent	99.24	Excellent
S41	98.97	Good	99.24	Excellent
S42	80.31	Inconclusive	84.61	Acceptable
S43	98.99	Good	99.24	Excellent
S44	87.12	Acceptable	90.86	Good

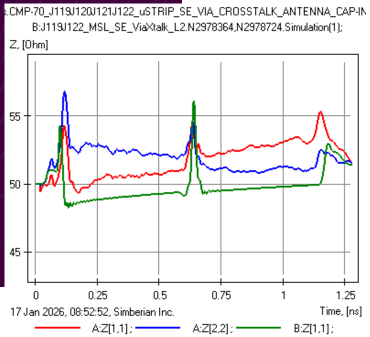


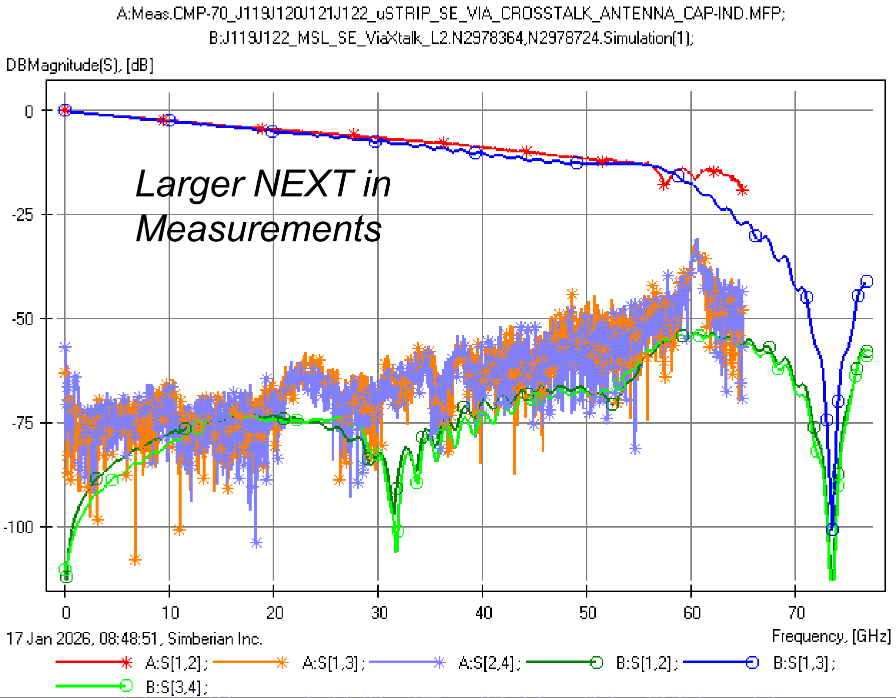
J119J120J121J122 – MSL SE Via XTalk

J119/J120	N2978364	MSL SE Via Crosstalk - Link1	Crosstalk	"CMP-70_J119J120J121J122_uSTRIP_SE_VIA_CROSSTALK_ANTENNA_CAP-IND.s4p
J121/J122	N2978724	MSL SE Via Crosstalk - Link2		same

Solution ..\CMP-70_Simbeor_Kit_2025\Dec2025\CMP-70-SE(4)







CMP-70 Predictability Conclusion

- **Stripline structures** in this kit are significantly more predictable and correlate better with simulation than **Microstrip structures**
- Users modeling Microstrips should expect slightly lower correlation scores (typically 3-5 points lower for simple lines, and up to 10-20 points lower for complex structures) compared to Striplines

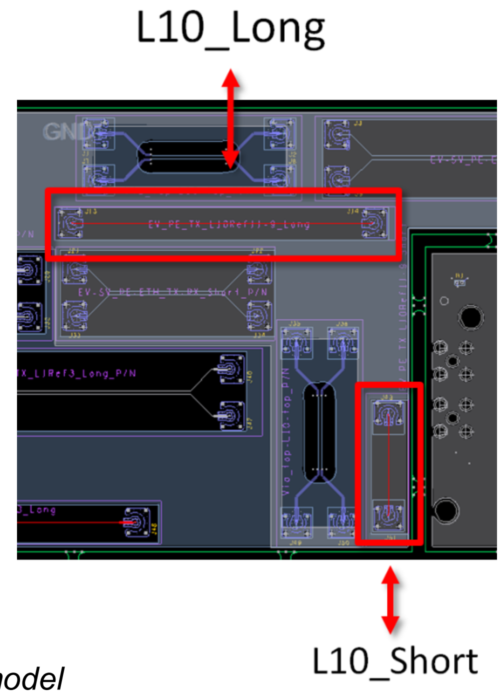
Feature Category	Structure Type	Typical SPS (100% BW)	Typical Rating
Simple T-Lines	Stripline	~93 - 94%	Good
	Microstrip	~89 - 90%	Acceptable / Good
Launches / Vias	Stripline	~93%	Good
	Microstrip	~80 - 87%	Acceptable
Complex / Xtalk	Stripline	~90 - 94%	Good
	Microstrip	~69 - 76%	Inconclusive

The Hurdles and Possible Solutions

Unpredictability in Traces -> Probabilistic Models
Unpredictability of Vias ->The Waveguiding Approach
Unvalidated EDA Tools (just a reminder) 😱

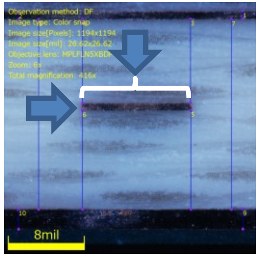
Manufacturing Variations Investigation

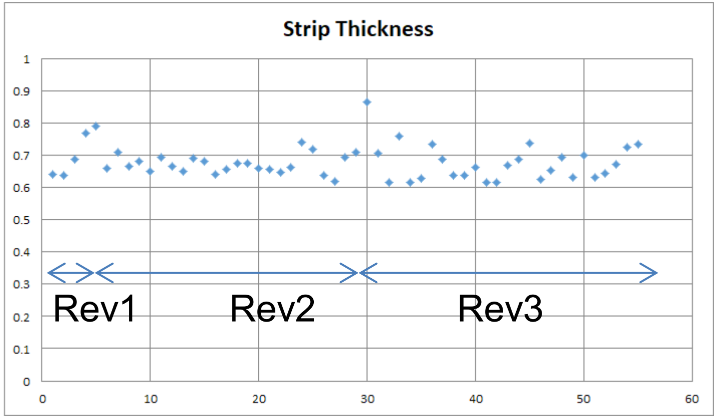
- Short and long segments of striplines with length difference 1.5 inch were placed on coupons (for extraction of GMS-parameters or Gamma)
- Megtron 7 and smooth HVLP copper were used, to meet 56 Gbps channel performance requirements
- Two adaptors from the snap-on MMPX connectors to 1.85f and to 2.92m are used for each structure
- Three batches of the same board were manufactured with some modifications of the launches
  – 5 boards were manufactured in the first batch (Rev1)
  – 20 boards in the second batch (Rev2)
  – 30 in the third batch (Rev3)

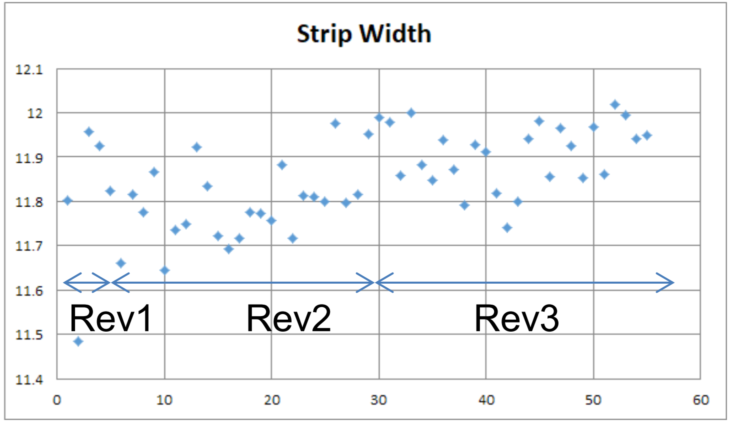


A. Manukovsky, Y. Shlepnev, Measurement-assisted extraction of PCB interconnect model parameters with fabrication variations, EPEPS 2019.

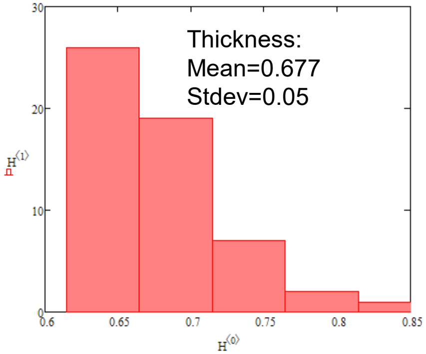
Cross-Sectioning – Strip Geometry

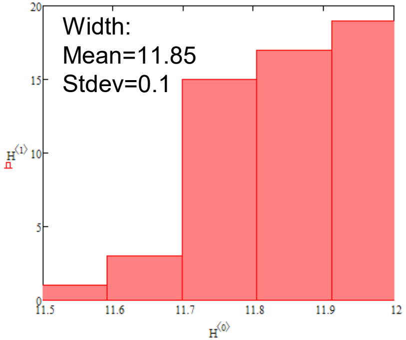




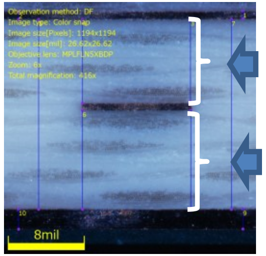


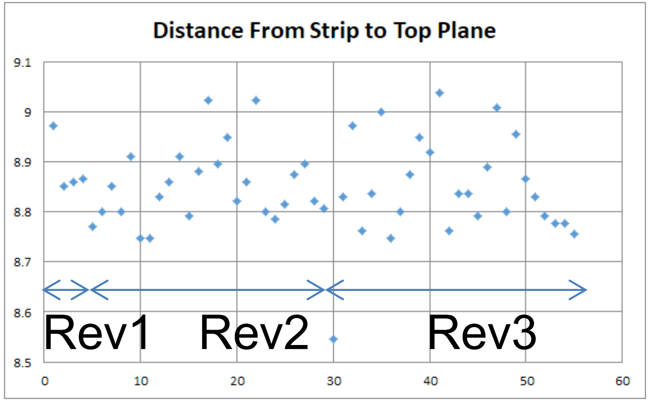
Over 30% variation in the cross-section! It should produce substantial effect on impedance and losses, if we assume that the trace thickness and width are changing along each segment

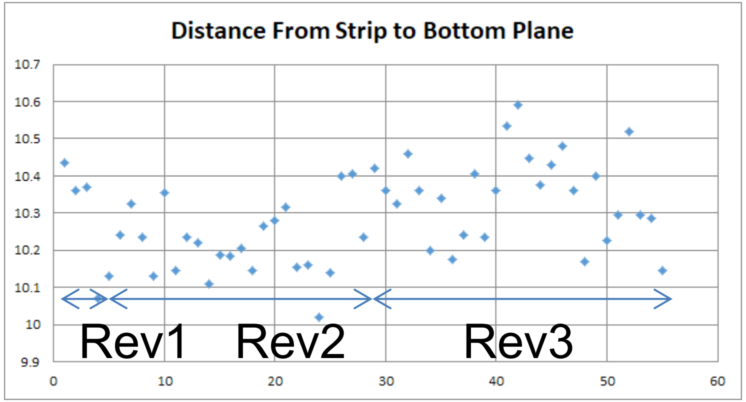




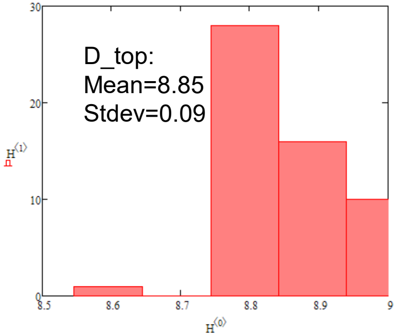
Cross-sectioning- laminate thickness

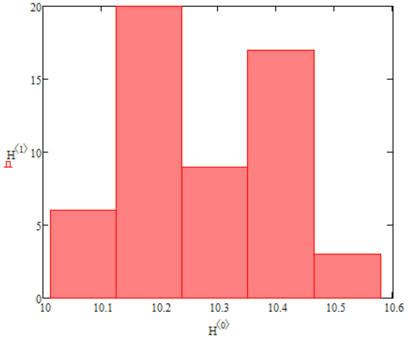






Insignificant variations in the laminate thickness – should not affect the impedance significantly, but still contribute
Should not have effect on losses



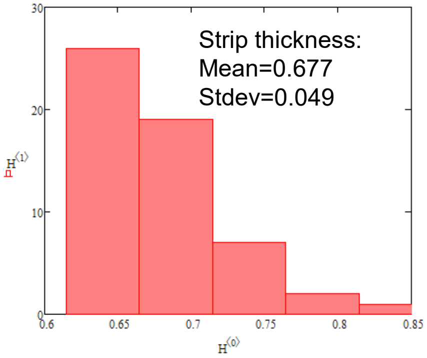


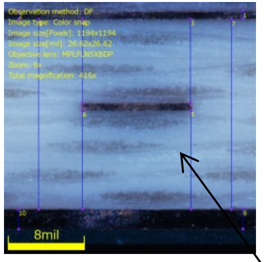
D_bottom:
Mean=10.28
Stdev=0.13

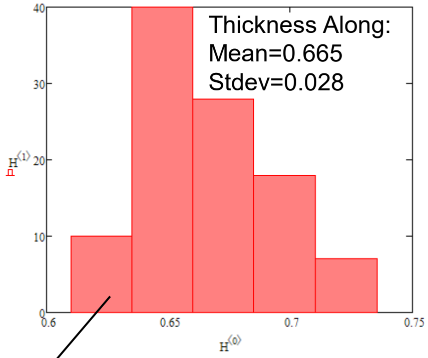
Cross-Sectioning Summary

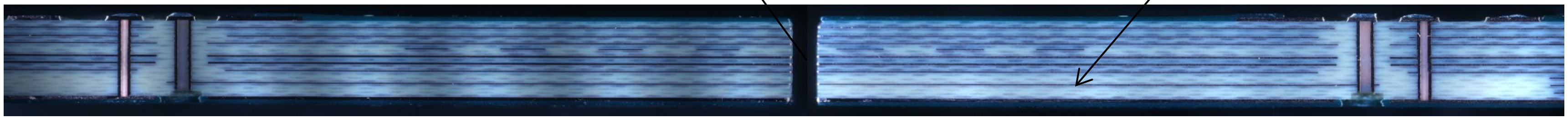
Meas. Value [mil]	Min	Average	Max	Sdt. Dev.
Top Ref. plane thickness	0.658	0.751	0.889	0.069
Strip to top plane distance	8.546	8.845	9.037	0.097
Strip to bot. plane distance	10.146	10.349	10.592	0.112
Strip width	11.74	11.905	12.019	0.074
Strip thickness (batch)	0.614	0.677	0.864	0.049
Strip thickness along one trace	0.61	0.665	0.709	0.028

Additional cross-sectioning along strip (surprise – no explanations from manufacturer)



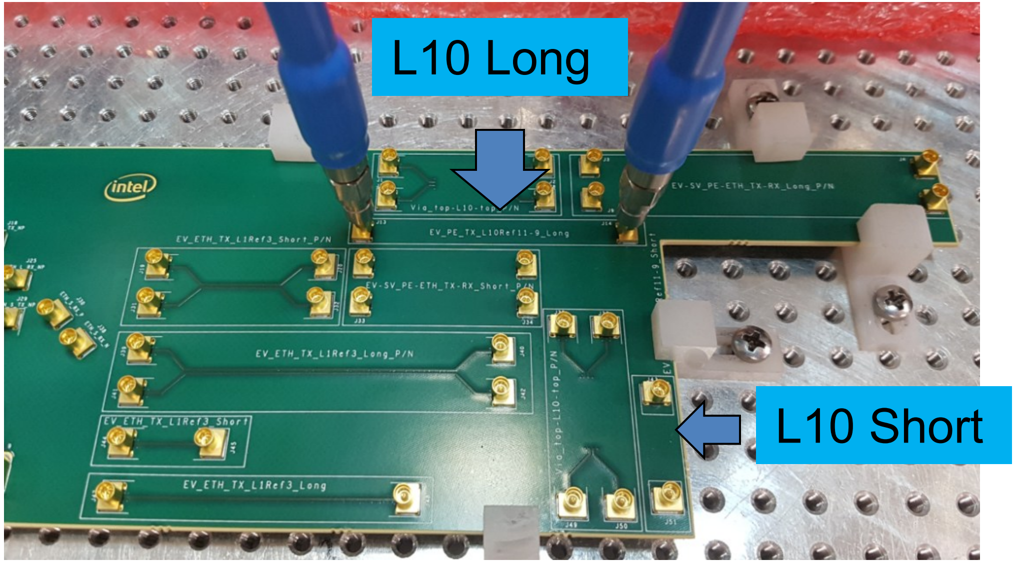






Measurements

- Network Analyser with 67 GHz bandwidth
- Mechanical Standard Calibration Kit

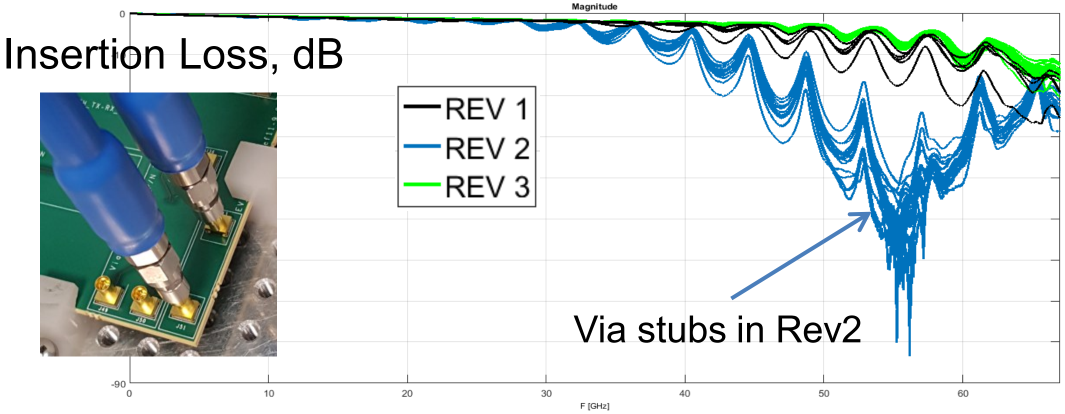


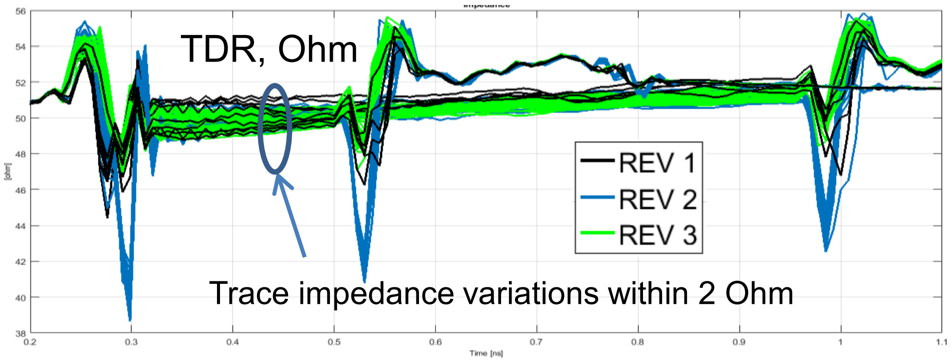
Measurements results

Excellent quality metrics (IEEE P370)

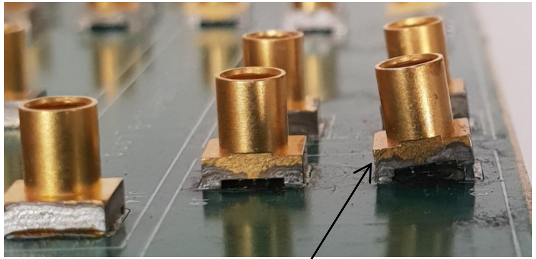
File name	Quality	Passivity	Reciprocity	Causality
C:\Repository\Simbeor\Support\Intel\Oct2_2018_DesignCon2019\Measure...				
BC001_L10_Short_Rev2.s2p	99	99.9	99.6	-
BC002_L10_Short_Rev2.s2p	98.9	99.9	99.6	-
BC003_L10_Short_Rev2.s2p	94	99.9	99.5	-
BC004_L10_Short_Rev2.s2p	98.9	99.9	99.6	-
BC005_L10_Short_Rev2.s2p	98.9	99.9	99.5	-
BC006_L10_Short_Rev2.s2p	98.8	99.9	99.5	-
BC007_L10_Short_Rev2.s2p	98.4	99.9	99.5	-
BC008_L10_Short_Rev2.s2p	99	99.9	99.6	-
BC009_L10_Short_Rev2.s2p	98.5	99.9	99.6	-
BC010_L10_Short_Rev2.s2p	98.9	99.9	99.5	-
BC011_L10_Short_Rev2.s2p	98.9	99.9	99.5	-
BC012_L10_Short_Rev2.s2p	99.1	99.9	99.6	-
BC013_L10_Short_Rev2.s2p	98.7	99.9	99.5	-
BC014_L10_Short_Rev2.s2p	98.6	99.9	99.5	-
BC015_L10_Short_Rev2.s2p	98.3	99.9	98.6	-
BC016_L10_Short_Rev2.s2p	98.9	99.9	99.5	-
BC017_L10_Short_Rev2.s2p	99	99.9	99.5	-
BC018_L10_Short_Rev2.s2p	99.1	99.9	99.4	-
BC019_L10_Short_Rev2.s2p	99	99.9	99.4	-
BC020_L10_Short_Rev2.s2p	98.6	99.9	99.3	-
BC021_L10_Short_Rev3.s2p	99.1	99.9	98.6	-
BC022_L10_Short_Rev3.s2p	99.1	99.9	99.2	-
BC023_L10_Short_Rev3.s2p	99.2	99.9	99	-
BC024_L10_Short_Rev3.s2p	99	99.9	98.9	-
BC025_L10_Short_Rev3.s2p	98.9	99.9	99.1	-
BC026_L10_Short_Rev3.s2p	98.9	99.9	98.9	-

Rev3 looks like the best for the identification

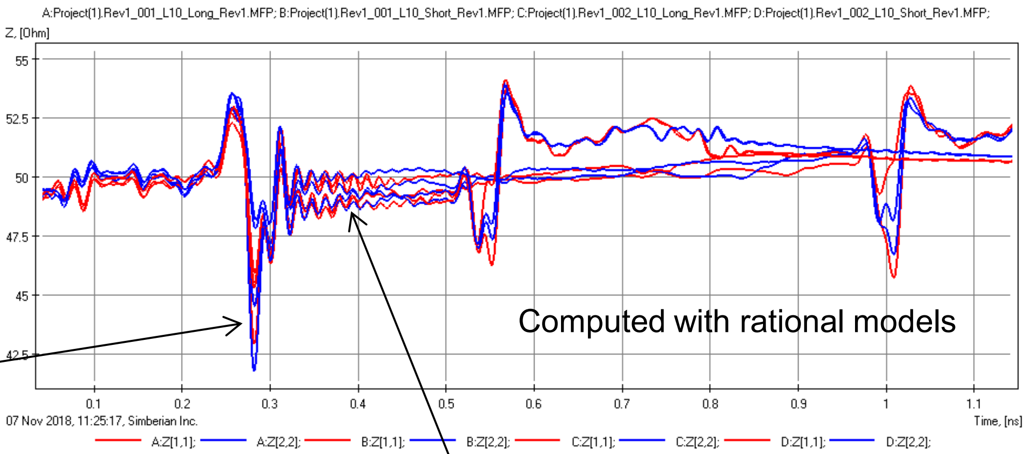




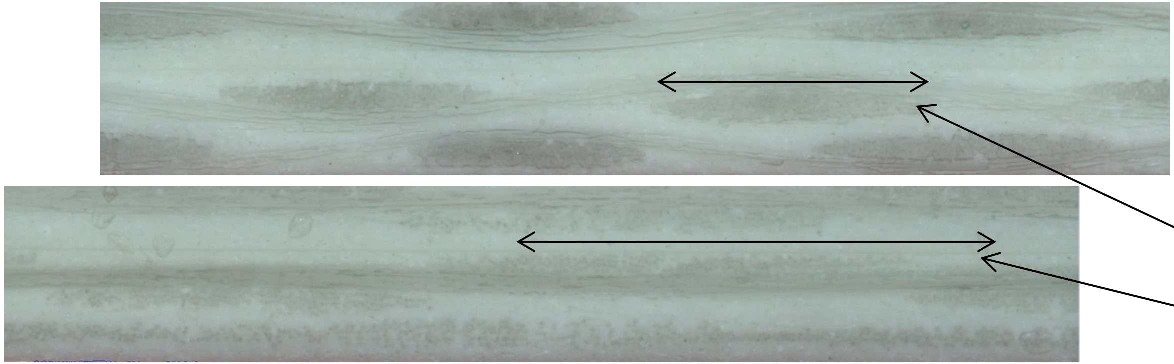
TDR Close-Up for Rev1



Over 5 Ohm impedance variations in connector to launch transition areas



About 1 Ohm impedance offset observed between short and long due to the orthogonal orientation of segments (FWE)



Fiber along short line (bunched)

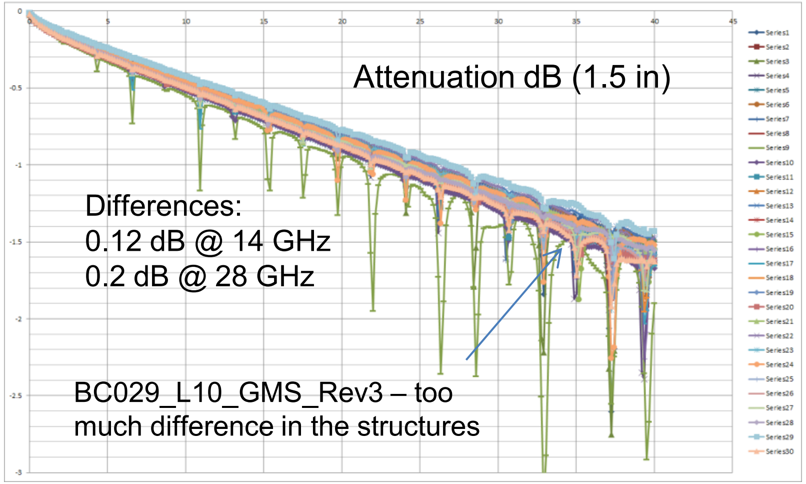
Fiber along long line (spread)

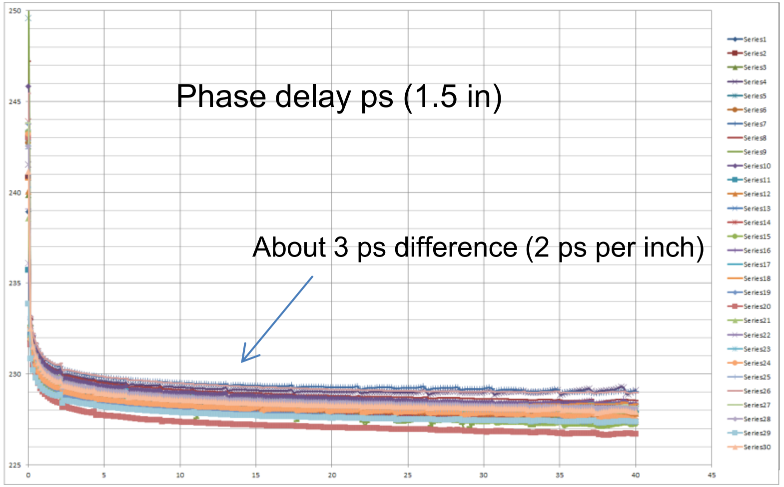
Generalized Modal S-parameters

$$GMT = eigenvals\left(T2 \cdot T1^{-1}\right) = \begin{pmatrix} \exp(-\Gamma \cdot L) & 0 \\ 0 & \exp(\Gamma \cdot L) \end{pmatrix} \Rightarrow GMS = \begin{pmatrix} 0 & \exp(-\Gamma \cdot L) \\ \exp(-\Gamma \cdot L) & 0 \end{pmatrix}$$

T1, T2 - scattering T-matrices of short and long segments

Frequency, GHz





1. BC021_L10_GMS_Rev3
2. BC022_L10_GMS_Rev3
3. BC023_L10_GMS_Rev3
4. BC024_L10_GMS_Rev3
5. BC025_L10_GMS_Rev3
6. BC026_L10_GMS_Rev3
7. BC027_L10_GMS_Rev3
8. BC028_L10_GMS_Rev3
9. BC029_L10_GMS_Rev3
10. BC030_L10_GMS_Rev3
11. BC031_L10_GMS_Rev3
12. BC032_L10_GMS_Rev3
13. BC033_L10_GMS_Rev3
14. BC034_L10_GMS_Rev3
15. BC035_L10_GMS_Rev3
16. BC036_L10_GMS_Rev3
17. BC037_L10_GMS_Rev3
18. BC038_L10_GMS_Rev3
19. BC039_L10_GMS_Rev3
20. BC040_L10_GMS_Rev3
21. BC041_L10_GMS_Rev3
22. BC042_L10_GMS_Rev3
23. BC043_L10_GMS_Rev3
24. BC044_L10_GMS_Rev3
25. BC045_L10_GMS_Rev3
26. BC046_L10_GMS_Rev3
27. BC047_L10_GMS_Rev3
28. BC048_L10_GMS_Rev3
29. BC049_L10_GMS_Rev3
30. BC050_L10_GMS_Rev3

Frequency, GHz

Extracted from 30 pairs up to 40 GHz – too noisy above
Periodic spikes are due to geometry difference in connectors/launches
Can run identification up to 35 GHz and extrapolate by material models

Extracted with Simbeor SDK

Comprehensive Statistical Model

- *Fix all cross-section parameters to batch mean values;*
- *Identify Dk @ 1 GHz first by matching GMS phase delay from 2 to 40 GHz;*
- *Identify relative resistivity (RR) with loss tangent LT @ 1 GHz simultaneously by matching GMS attenuation from 0.01 to 2 GHz;*
- *Identify roughness model parameters SR and RF by matching GMS attenuation from 2 to 25-35 GHz;*
- *Correct Dk @ 1 GHz by matching GMS phase delay from 2 to 40 GHz;*

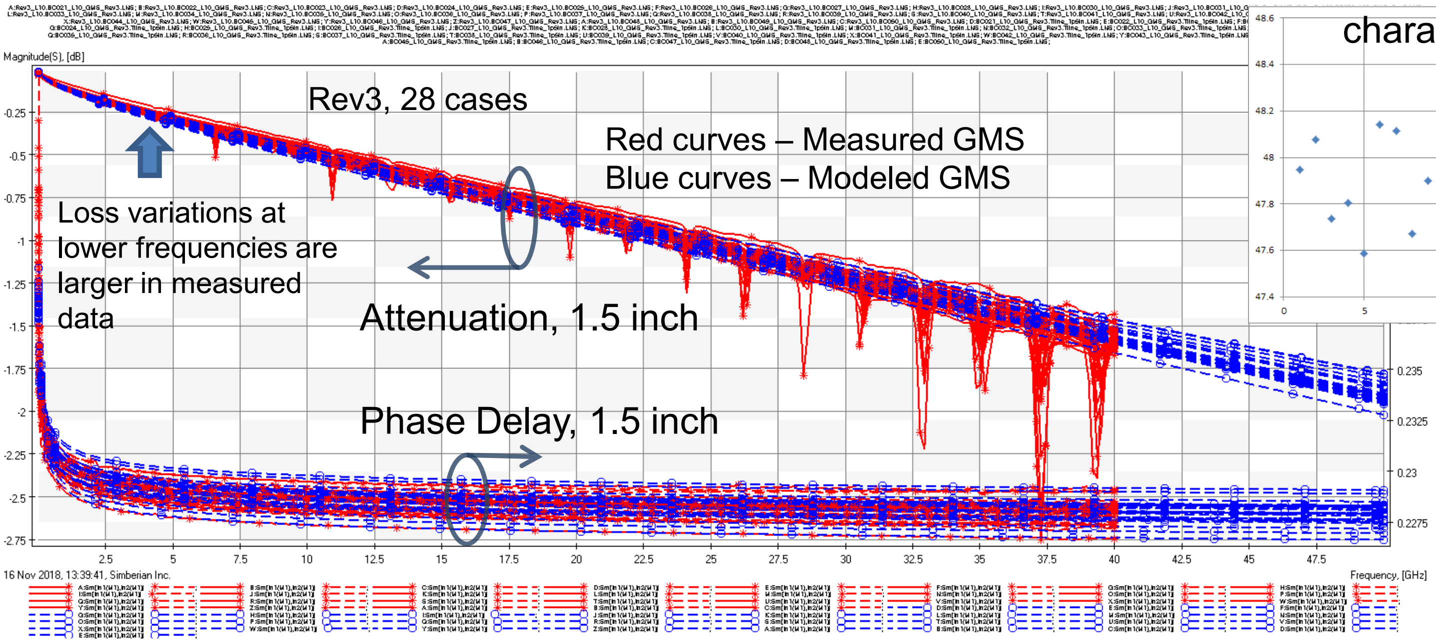
	Min	Average	Max	Std. Dev.
Relative Resistivity, RR	1.12	1.36	1.8	0.2
Surface Roughness, SR [um]	0.13	0.146	0.23	0.023
Roughness Factor, RF	6.2	8.8	9.9	0.8
Dk @ 1 GHz	3.15	3.187	3.22	0.016
LT @ 1 GHz	0.0005	0.0011	0.002	2.7e-4

Automated with Simbeor SDK

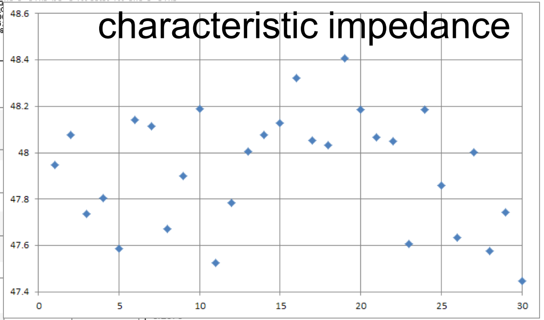
A. Manukovsky, Y. Shlepnev, Measurement-assisted extraction of PCB interconnect model parameters with fabrication variations, EPEPS 2019.

Fixed Cross-Section and Simultaneous Identification of RR and LT

LT and RR are adjusted simultaneously, Dk, SR and RF are adjusted



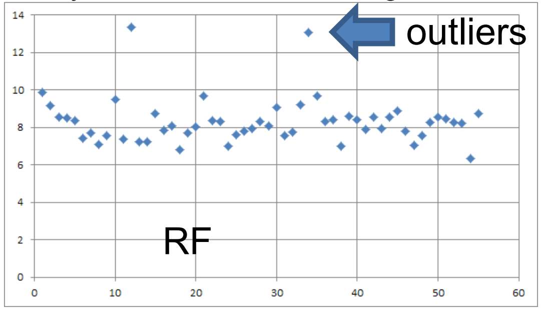
About 1 Ohm variation in characteristic impedance

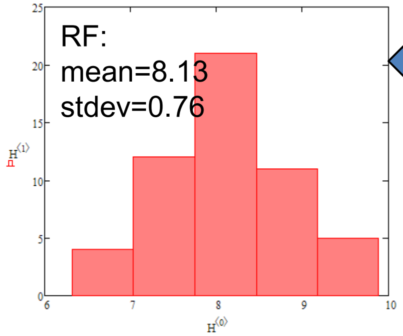


This model is acceptable, but still too complicated for practical use

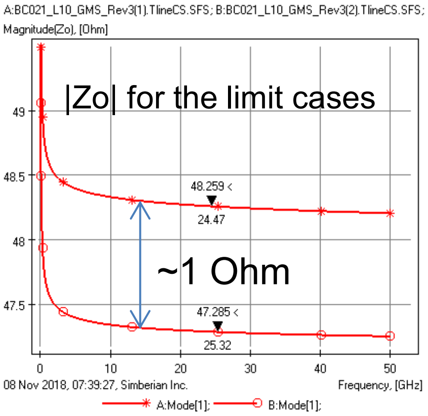
Simplest Statistical Model (Tst=0.677, Wst=11.85): LT=0.001, RR=1.5, SR=0.15 um

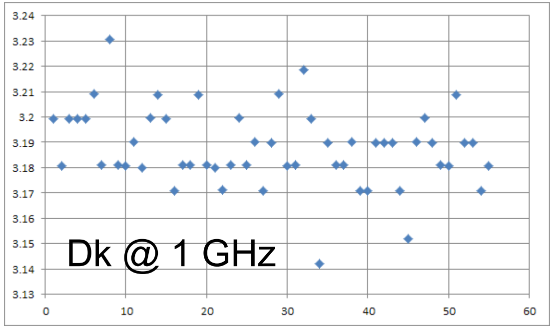
Relative Resistivity – RR=1.5, Roughness – SR=0.15 um, RF is adjusted
Wideband Debye model for dielectric – LT=0.001 @ 1 GHz, Dk is adjusted
Huray-Bracken model for roughness

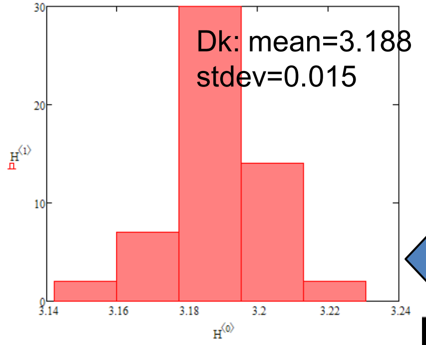




All conductor losses and some impedance variations are included in this parameter





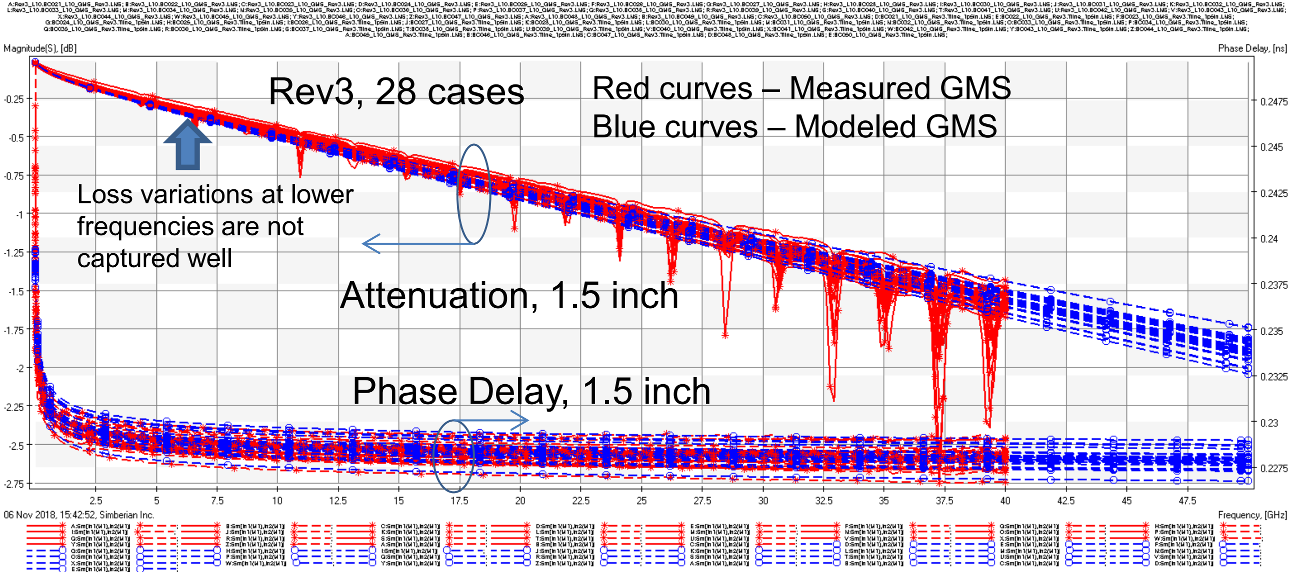


All phase delay variations and some impedance variations are included in this parameter

Statistical Model with Fixed Trace Thickness and Width

The model quality at lower frequencies can be further improved by taking into account the actual strip geometry variations

LT=0.001 @ 1 GHz, RR=1.5, SR=0.15 um, Dk, and RF are adjusted



Simplified model with fixed cross-section works reasonably well

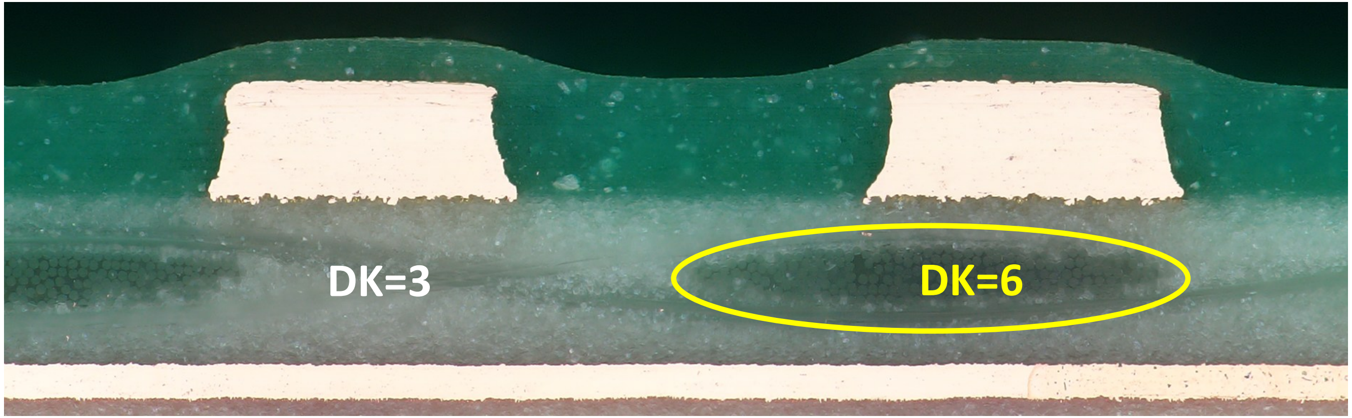
Summary on Statistical Trace Modeling

- This is important step toward building statistical models for the design of predictable interconnects for 448 Gbps signals
- Trace geometry and roughness causes most of the loss variations in this extremely low loss dielectric case
- Relatively small variations in identified dielectric constant and loss tangent
- In the simplest model, variations in interconnect impedance, losses and dispersion can be reduced to just two model variables with acceptable accuracy

More in A. Manukovsky, Y. Shlepnev, Effect of PCB Fabrication Variations on Interconnect Loss, Delay, Impedance & Identified Material Models for 56-Gbps Interconnect Designs, DesignCon 2019
A. Manukovsky, Y. Shlepnev, Measurement-assisted extraction of PCB interconnect model parameters with fabrication variations, EPEPS 2019.

Fiber Weave Effect – Another Obstacle

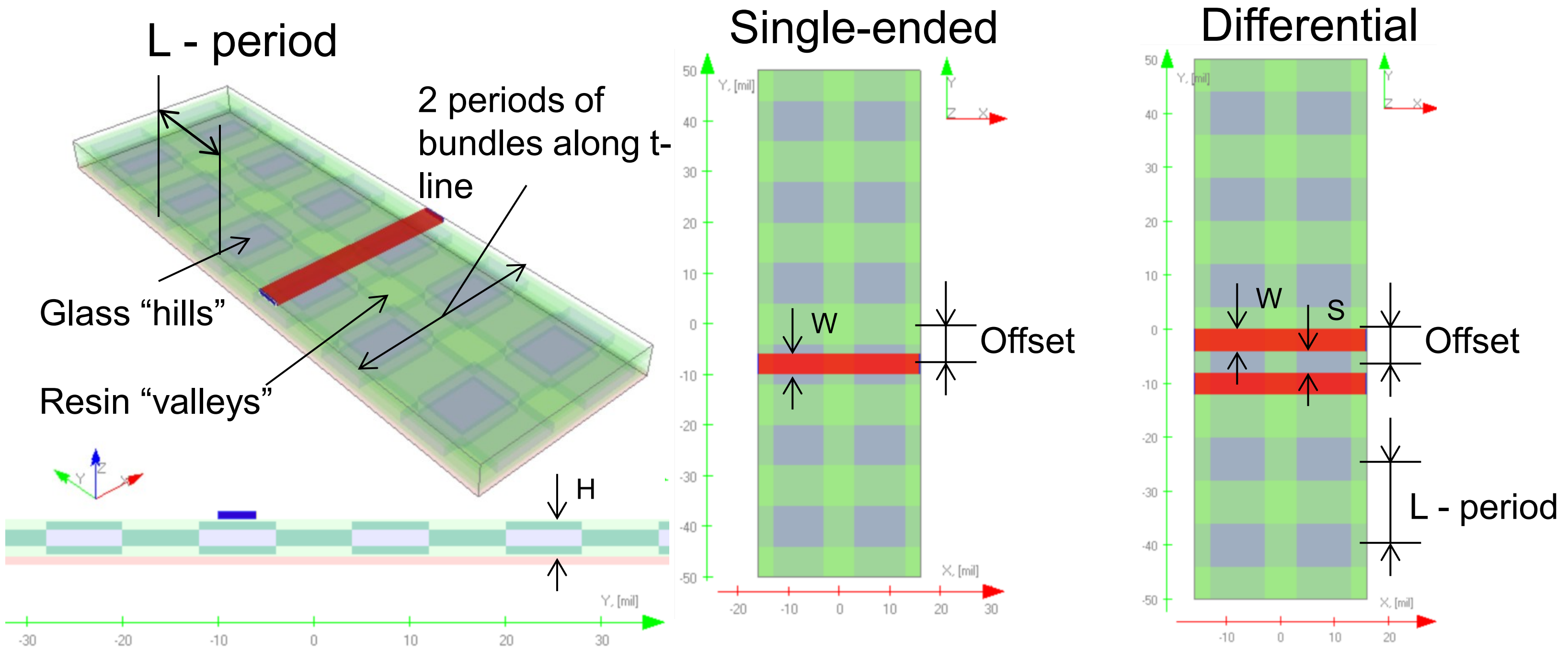
- Both fabric fiber and resin are composite materials with different dielectric constant (DK)
- For each trace effective Dk is deferent (relative position to glass bundles)
- *How to formalize laminate selection process for parallel (DDR) as well as for serial PCB (PCIe) interconnects?*



Typical Dielectric Material Property	DK
Glass Weave	4.4 - 6.1
Resin	3-3.5

Trace #1 Delay ≠ **Trace #2 Delay**

ELECTROMAGNETIC MODEL

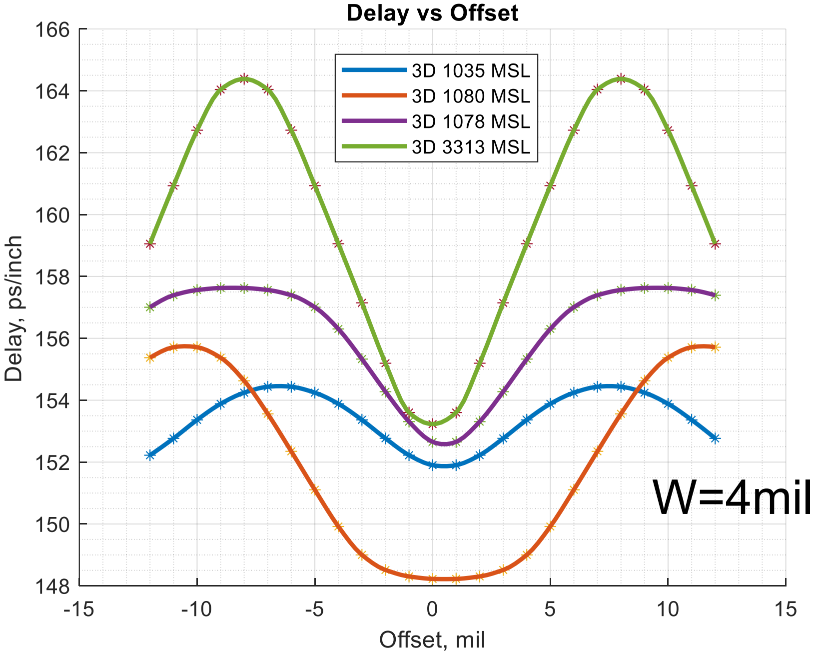


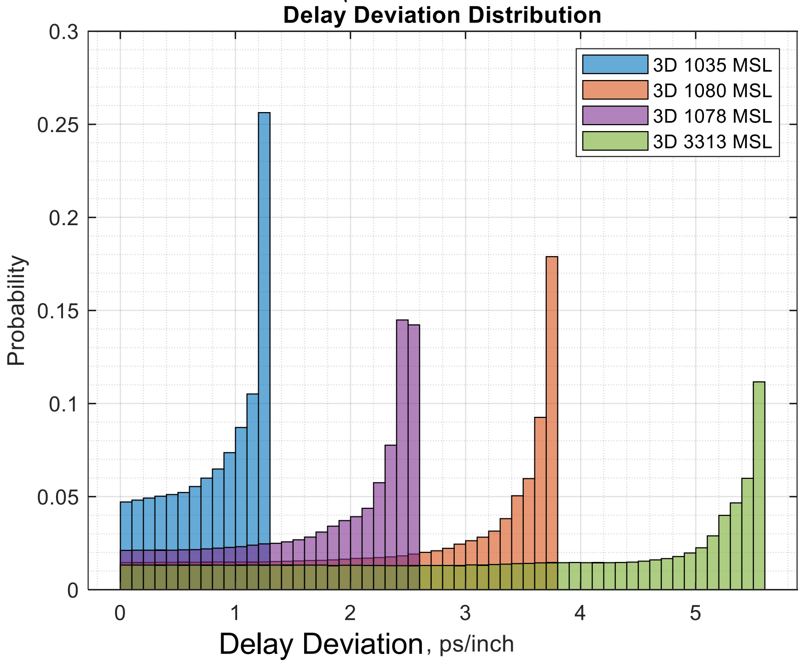
Details in A. Manukovsky, Y. Shlepnev, S. Mordooch, Impact Evaluation of Fiber-Weave Effect Induced Delay Uncertainty in DDR Data Links on DDR5 & Towards DDR6, February 2nd, DesignCon 2023

SINGLE-ENDED DELAY

$$t(x) = \Delta t \left| \sin\left(\frac{2\pi x}{L} + \alpha \right) \right|, \; x \in [-L/4, +L/4]$$

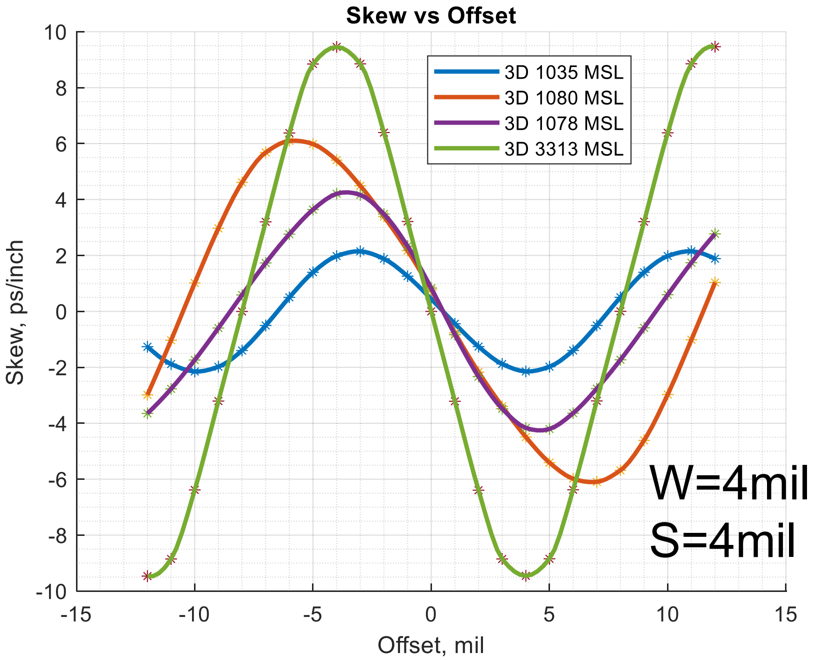
$$P(t) = \frac{4}{L} \cdot \frac{dx}{dt} = \frac{2}{\pi \cdot \Delta t \sqrt{1 - \left(\frac{t}{\Delta t} \right)^2}}, \; t \in [0, +\Delta t]$$

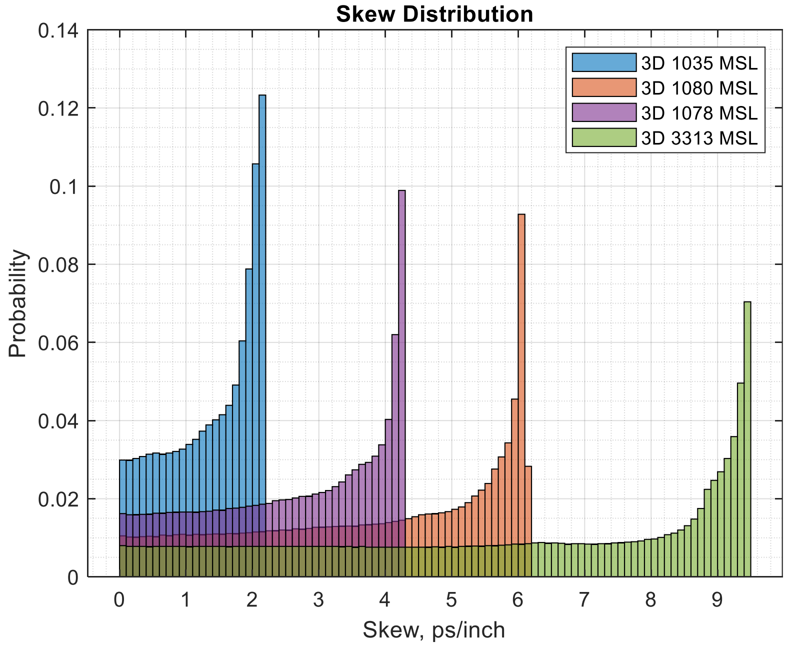




DIFFERENTIAL SKEW

$$t(x) = \Delta t \left| \sin\left(\frac{2\pi x}{L} + \alpha \right) \right|,\ x \in [-L/4, +L/4] \Rightarrow P(t) = \frac{4}{L} \cdot \frac{dx}{dt} = \frac{2}{\pi \cdot \Delta t \sqrt{1 - \left(\frac{t}{\Delta t} \right)^2}},\ t \in [0, +\Delta t]$$

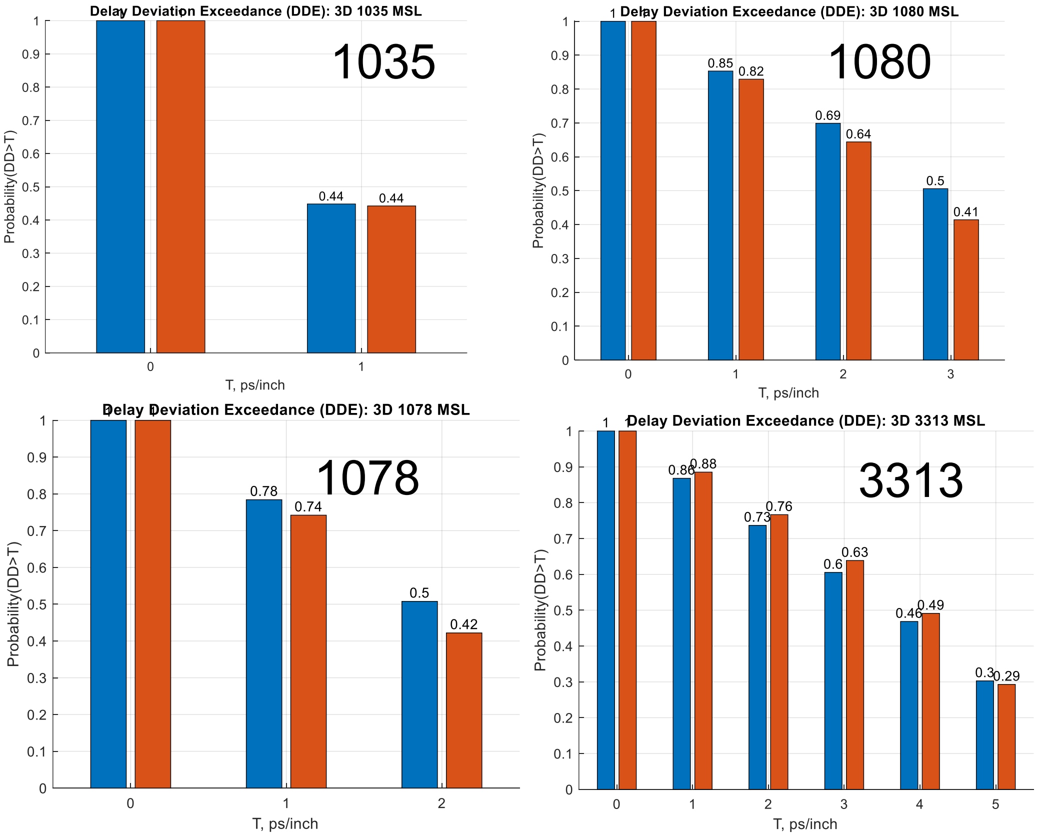




DELAY DEVIATION EXCEEDANCE

Blue bars: directly from numerical experiment

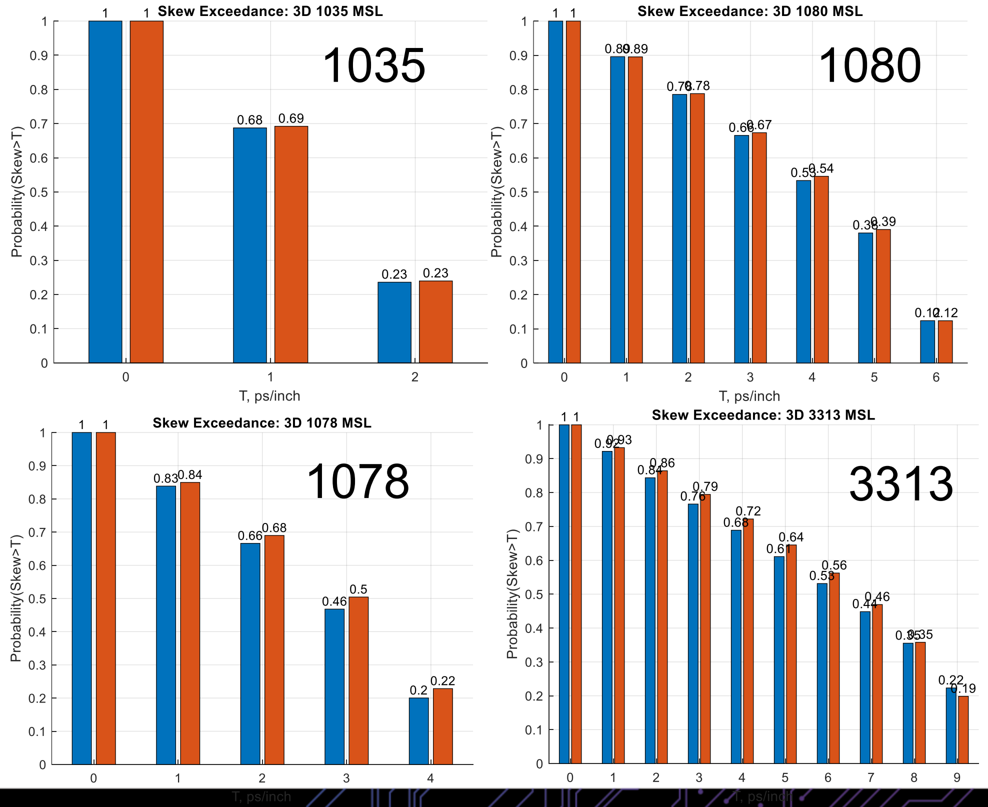
Brown bars: delay deviation from numerical experiment and Arcsine distribution for CCDF



DIFFERENTIAL SKEW EXCEDANCE

Blue bars: directly from numerical experiment

Brown bars: delay deviation from numerical experiment and Arcsine distribution for CCDF



Approximate Arcsine Model

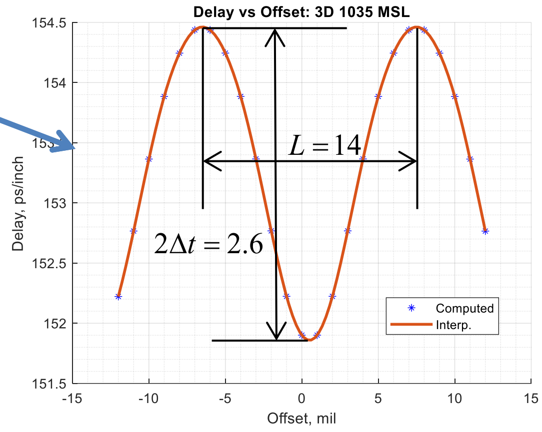
Delay Deviation: $$DD(x) = \Delta t \left| \sin\left(\frac{2\pi x}{L} + \alpha \right) \right|, \ x \in [-L/4, +L/4]$$

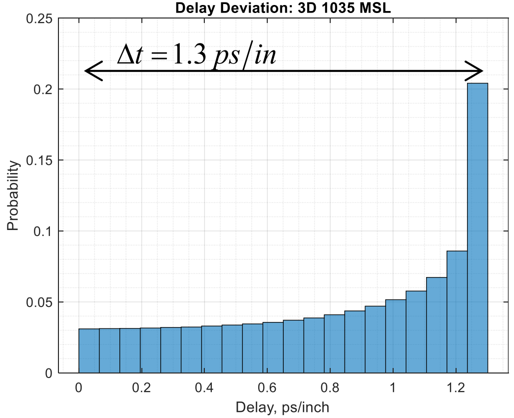
Probability Density Function (PDF): $$P(t) = \frac{2}{\pi \cdot \Delta t \sqrt{1 - \left(\frac{t}{\Delta t} \right)^2}}, \ t \in [0, +\Delta t]$$

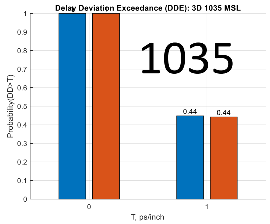
Cumulative Distribution Function (CDF): $$F(t) = P(T \le t) = \frac{2}{\pi} \arcsin\left(\frac{t}{\Delta t} \right), \ t \in [0, +\Delta t]$$

Complimentary CDF (Delay Deviation Exceedance): $$S(t) = P(T \ge t) = 1 - \frac{2}{\pi} \arcsin\left(\frac{t}{\Delta t} \right), \ t \in [0, +\Delta t]$$

Require just one parameter – maximal delay deviation!





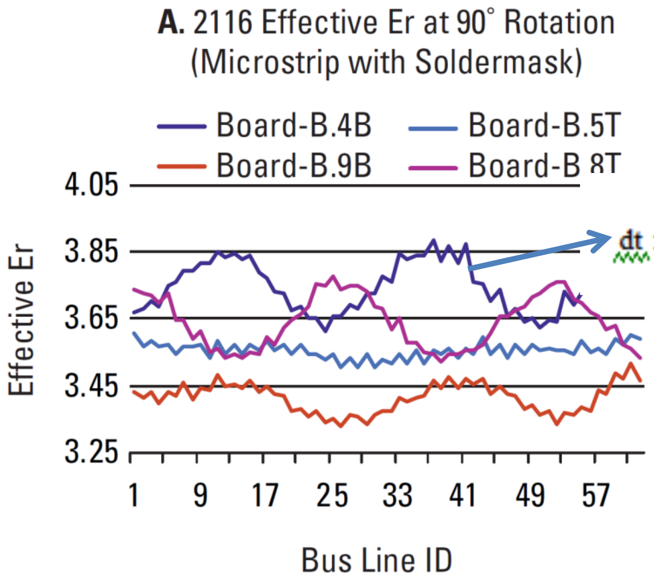


PRACTICAL EXAMPLE

G. Brist, B. Horine and G. Long, "Woven glass reinforcement patterns", Printed Circuit Design & Manufacture, pp. 28-33, Nov. 2004.

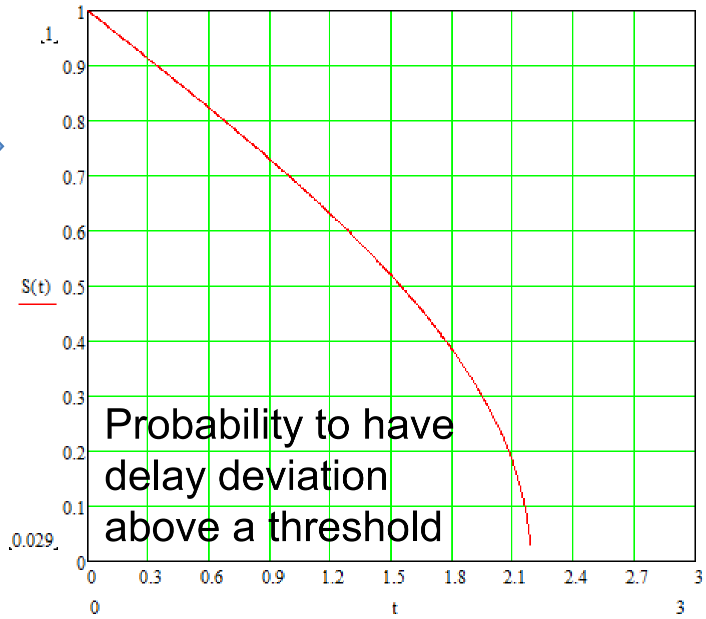
Delay Deviation Exceedance for 2116

$$S(t) = P(T \geq t) = 1 - \frac{2}{\pi}\arcsin\left(\frac{t}{\Delta t}\right), \; t \in [0, +\Delta t]$$

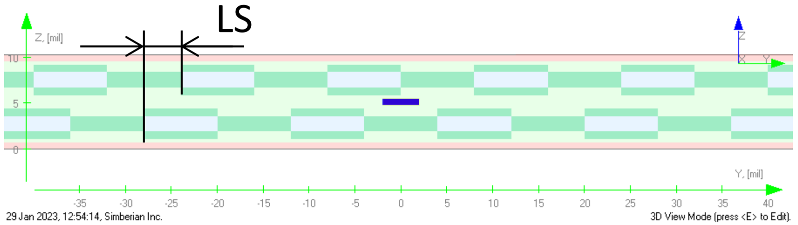


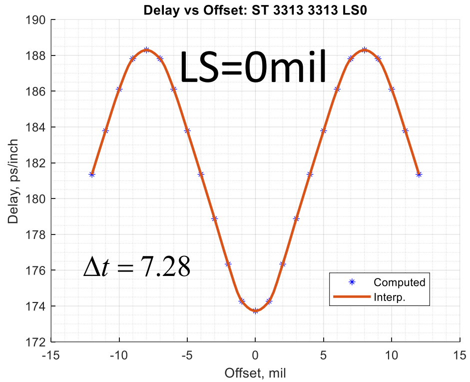
L=1 inch

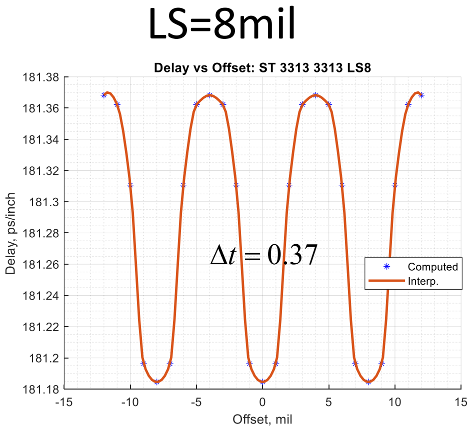
$$dt := \frac{L \cdot \left(\sqrt{\varepsilon max} - \sqrt{\varepsilon min}\right)}{2c0} \cdot 10^{12}$$

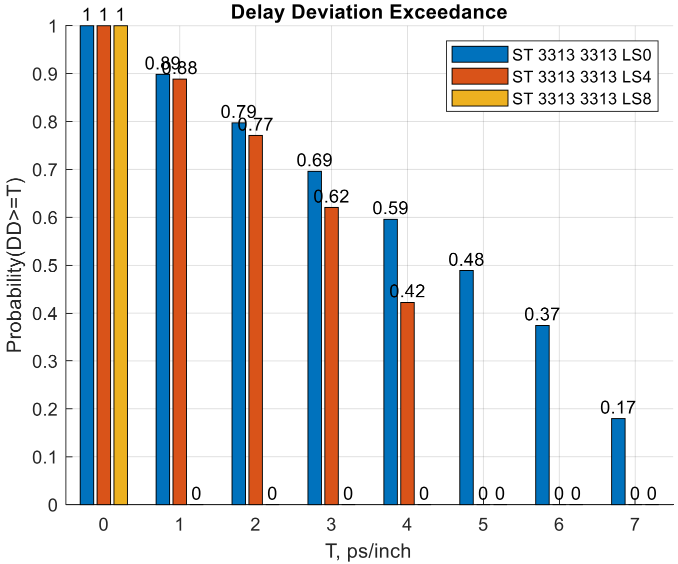


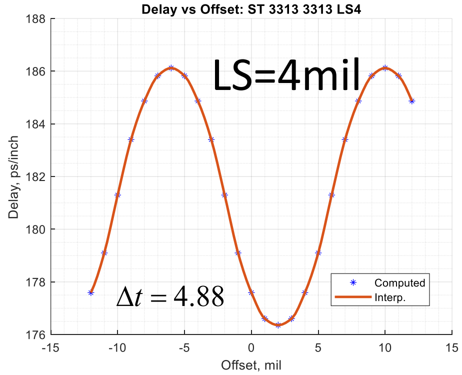
Mitigation Stripline: 3313 on 3313







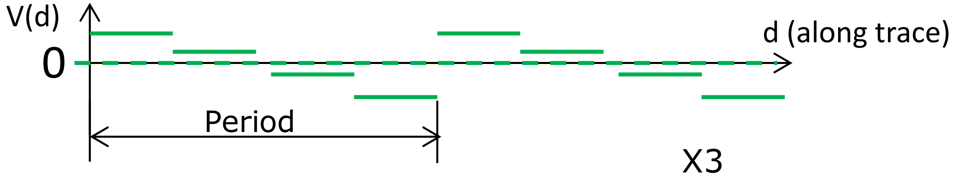




Possible way to mitigate FWE…

Effect of Small Variations in Trace Direction

Modulation Factor
= 1+V(d)

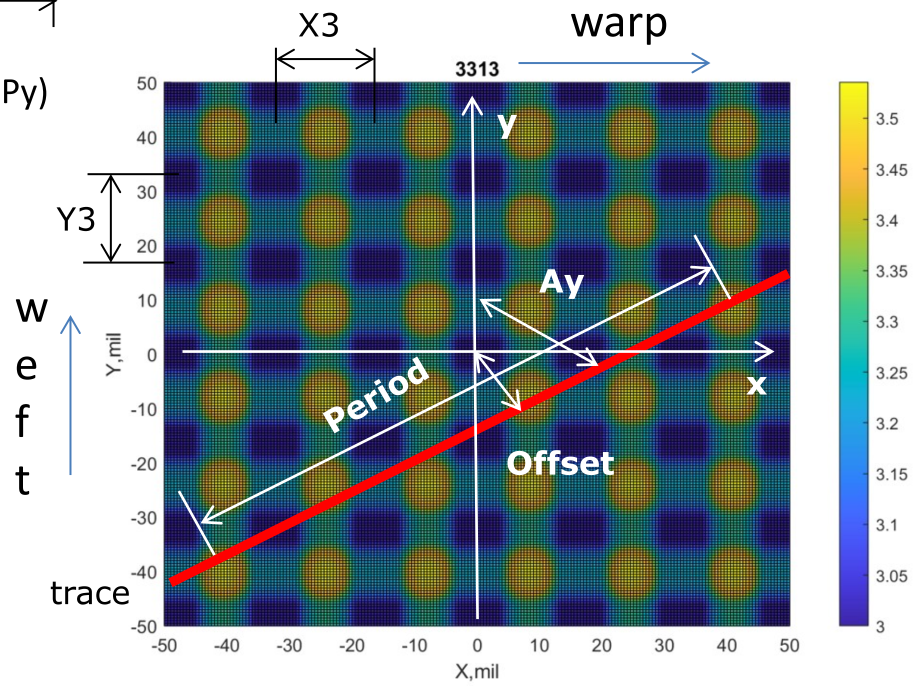


Simbeor NUTL model over 2D bump model of FWE is used to evaluate uncertainty related to angle

Periods from Weft(Py) and Warp(Px)

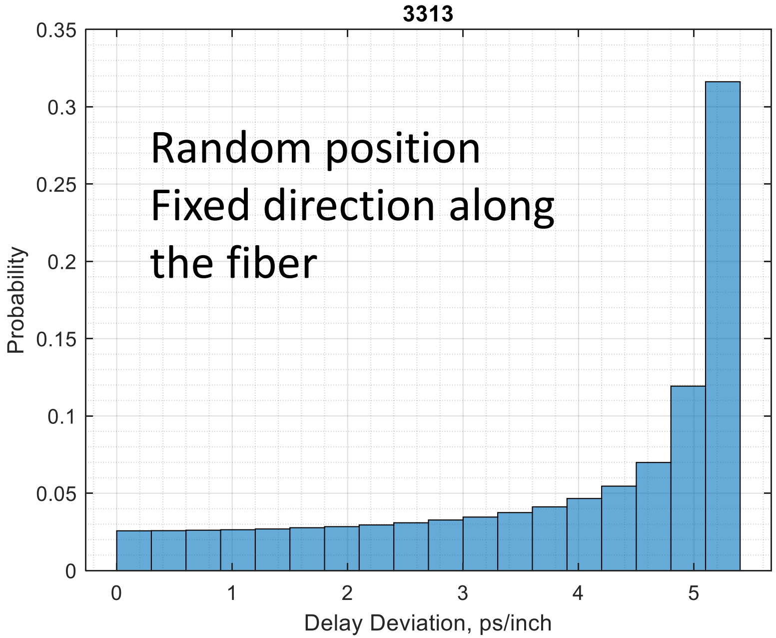
$$Py = \frac{X3}{\sin(Ay)}$$

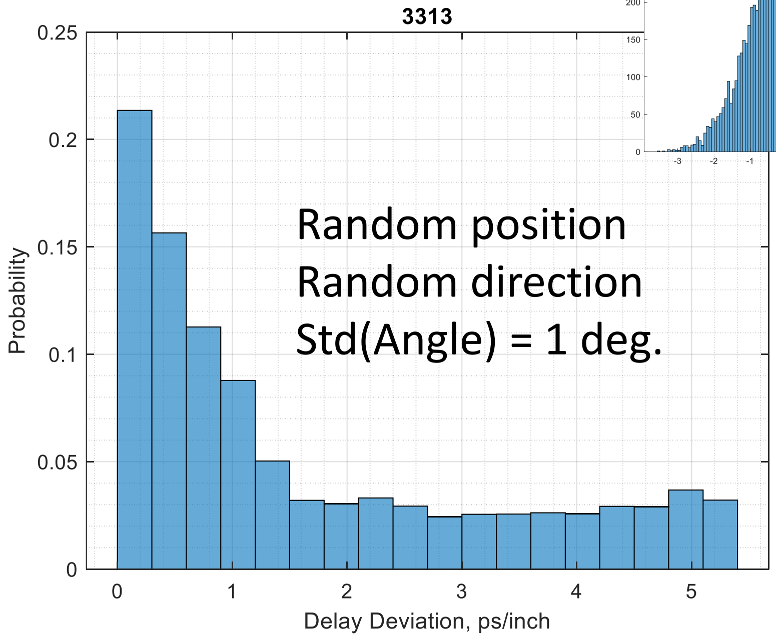
$$Px = \frac{Y3}{\cos(Ay)}$$

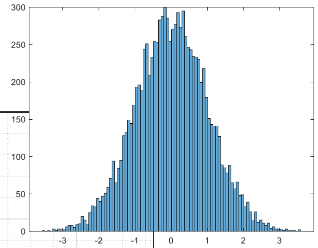


Y. Shlepnev and C. Nwachukwu, "Modelling jitter induced by fibre weave effect in PCB dielectrics," 2014 IEEE International Symposium on Electromagnetic Compatibility (EMC), 2014, pp. 803-808, doi: 10.1109/ISEMC.2014.6899078

Effect of Small Variations in Trace Direction







More in A. Manukovsky, Y. Shlepnev, S. Mordooch, Impact Evaluation of Fiber-Weave Effect Induced Delay Uncertainty in DDR Data Links on DDR5 & Towards DDR6, February 2nd, DesignCon 2023

Via Design and Predictability

- Designing PCB and packaging interconnects for 56-448 Gbps links presents multiple challenges
- Design of vertical transitions, or vias, being one of the most critical elements and **is the main roadblock for 448 Gbps links**
- Vias dissipate and reflect signals, contribute to crosstalk noise through both local and distant coupling
- How to approach the via analysis and design at these data rates?...

Y. Shlepnev, A. Manukovsky, ***Waveguiding Approach to Via Design with Bandwidth over 120 GHz****, EPEPS 2025.*
A. Manukovsky, Y. Shlepnev, J. Nutzati, A. Kuntsevych, I. Peleg, S. Mordooch ***Via Design for 112 Gbps and Beyond: Theory and Reality****, DesignCon 2025*

Waveguiding Approach to Via Design

- **Goals:**
  - Ensure localization and single-mode bandwidth up to 1.5x - 2× the Nyquist.
  - Maintain reflections below a defined threshold.
  - Reduce sensitivity to manufacturing variations.
  - Ensure usability across different layers.
- **Process:**
  - Divide via into middle and end sections.
  - Design middle section as substrate integrated waveguide with minimal sensitivity to antipads: **Substrate Integrated Coaxial Waveguide (SICW) and Twinax Waveguide (SITW)**
  - Design end sections as **TEM-to-TEM waveguiding transitions** as simple as possible (VVT and VHT).

Introduced in A. Manukovsky, Y. Shlepnev, J. Nutzati, A. Kuntsevych, I. Peleg, S. Mordooch Via Design for 112 Gbps and Beyond: Theory and Reality, DesignCon 2025

Localization: SE Via Dissipated Power

$$P_{dissipated} = \left(1 - \sum_k \left|S_{k,1}\right|^2\right) P_{in}$$

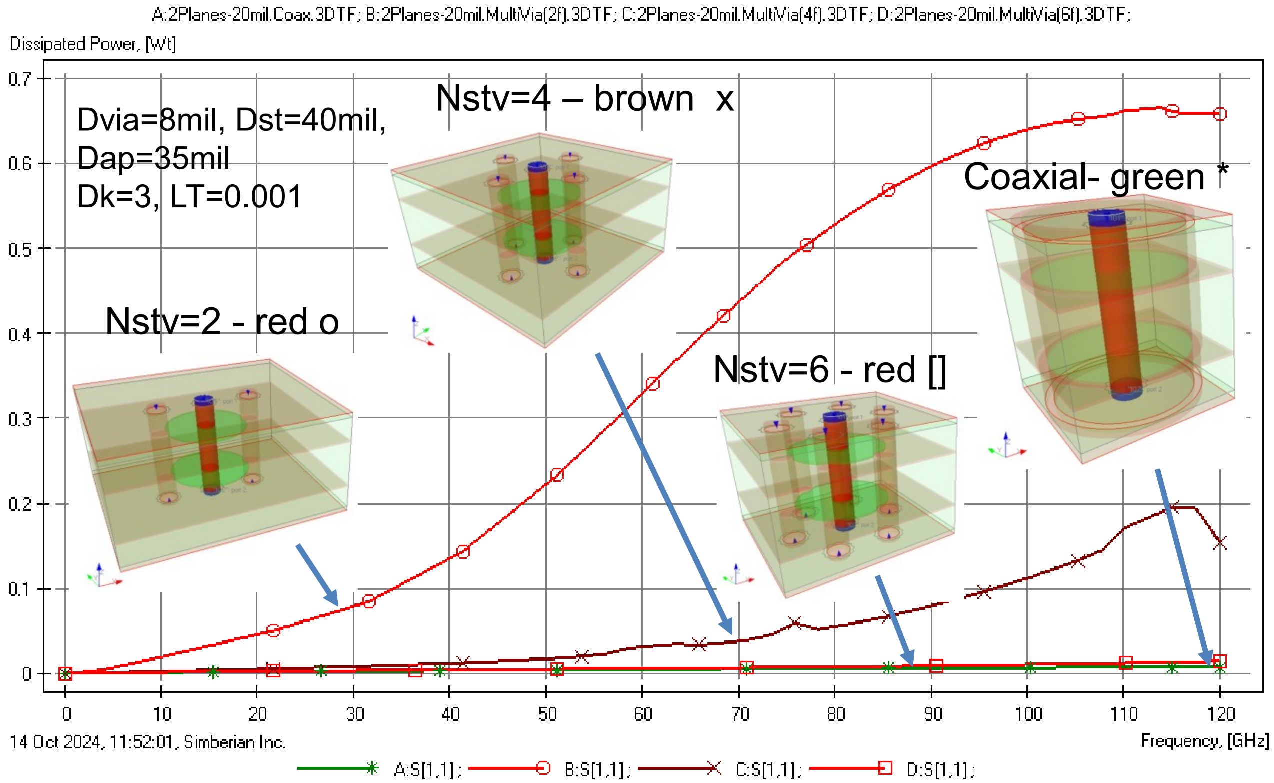
3D EM model for estimation of dissipated power and comparative analysis

2 Planes, H=20mil

Excitation: 1 Wt

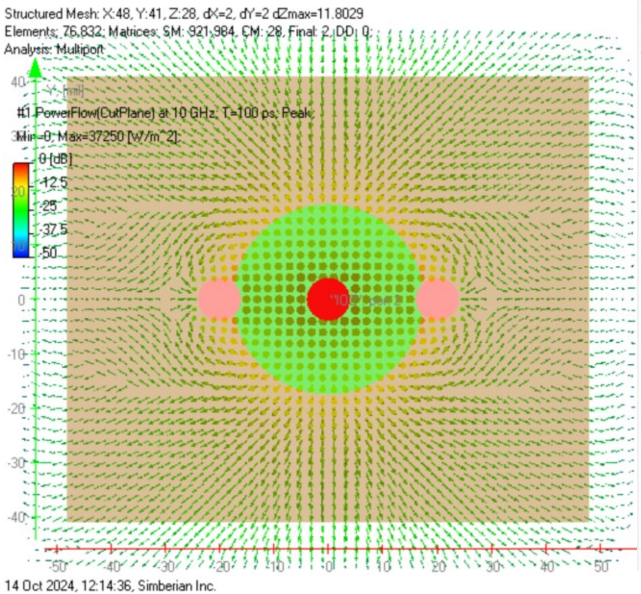
Stitching vias reduce dissipated power and potential coupling

Simbeor 3DTF, PML



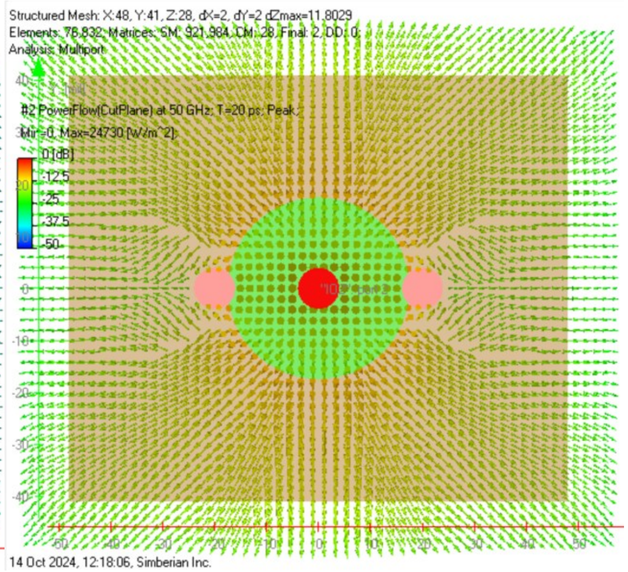
SE Via Power Flow Density, Nstv=2

10 GHz



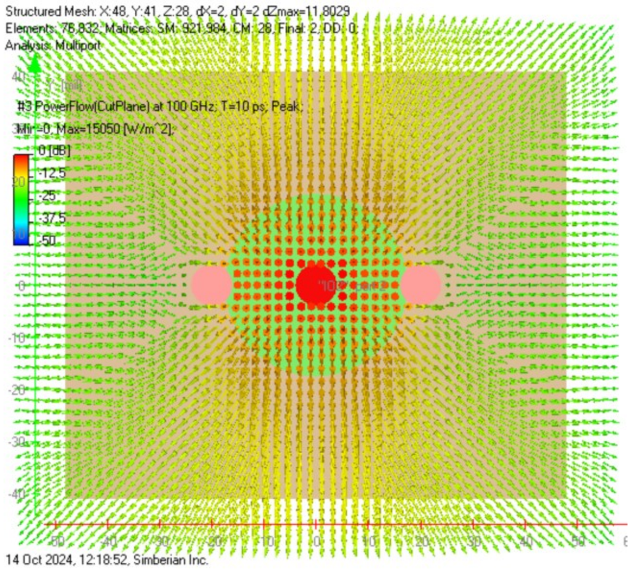
DP=2%

50 GHz



DP=22%

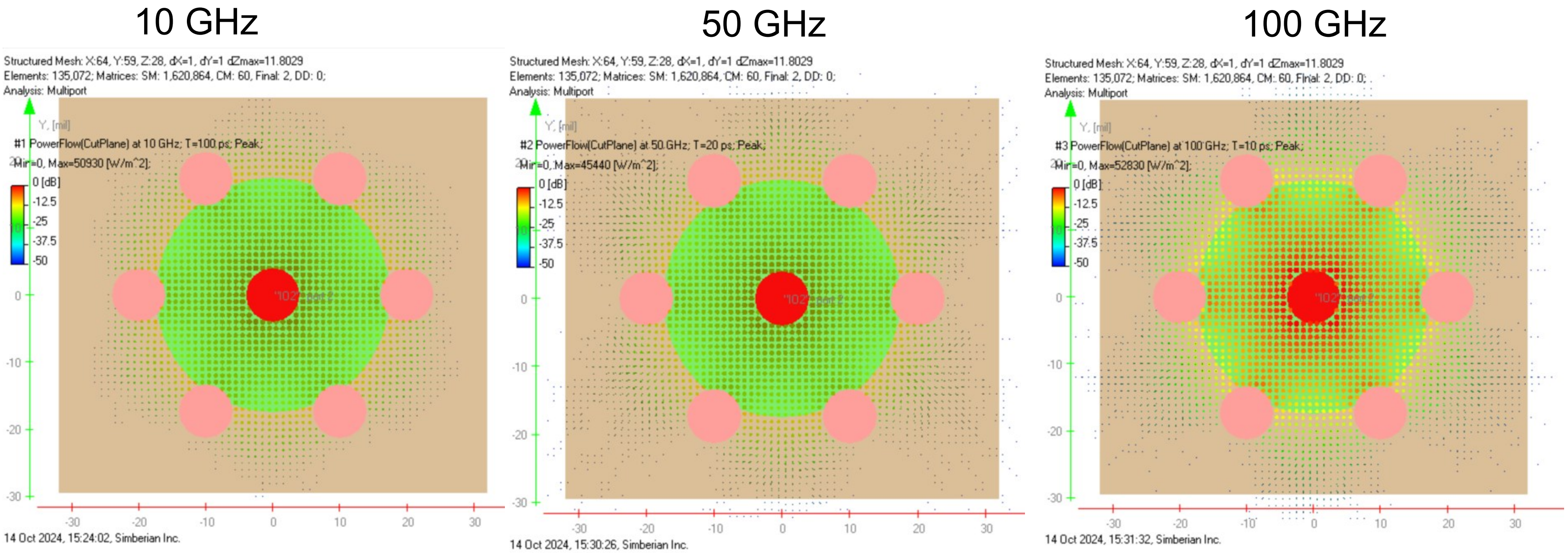
100 GHz



DP=64%

Peak PFD, Simbeor 3DTF, PML BC, Dvia=8mil, Dst=40mil, Dap=35mil, Dk=3, LT=0.001

SICW POWER FLOW DENSITY

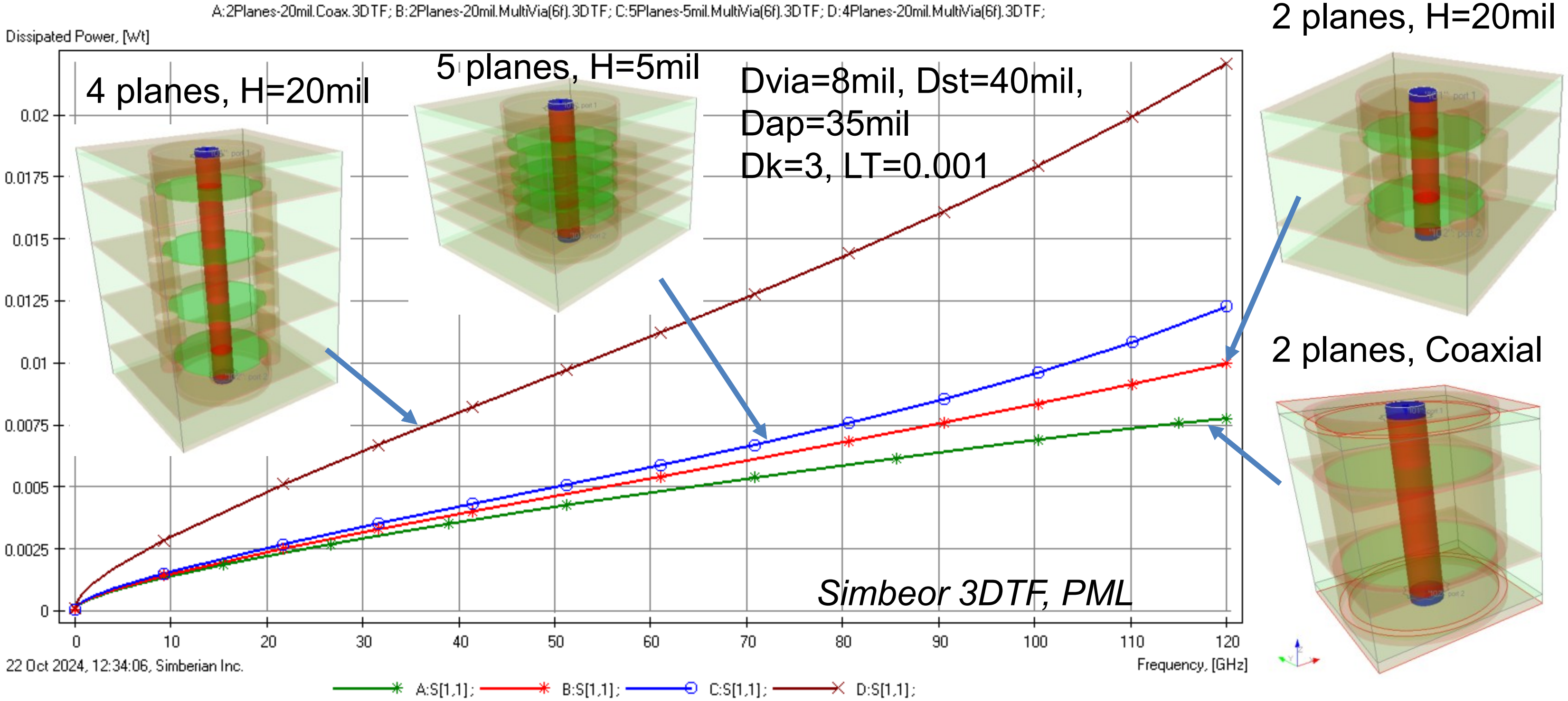


DP=0.15% DP=0.46% DP=0.8%

Peak PFD, Simbeor 3DTF, PML BC, Dvia=8mil, Dst=40mil, Dap=35mil, Dk=3, LT=0.001

SICW LOCALIZATION

$$P_{dissipated} = \left(1 - \sum_k |S_{k,1}|^2\right) P_{in}$$



DP increases with number of layers NL (proportional to NL) and decrease with smaller separation H

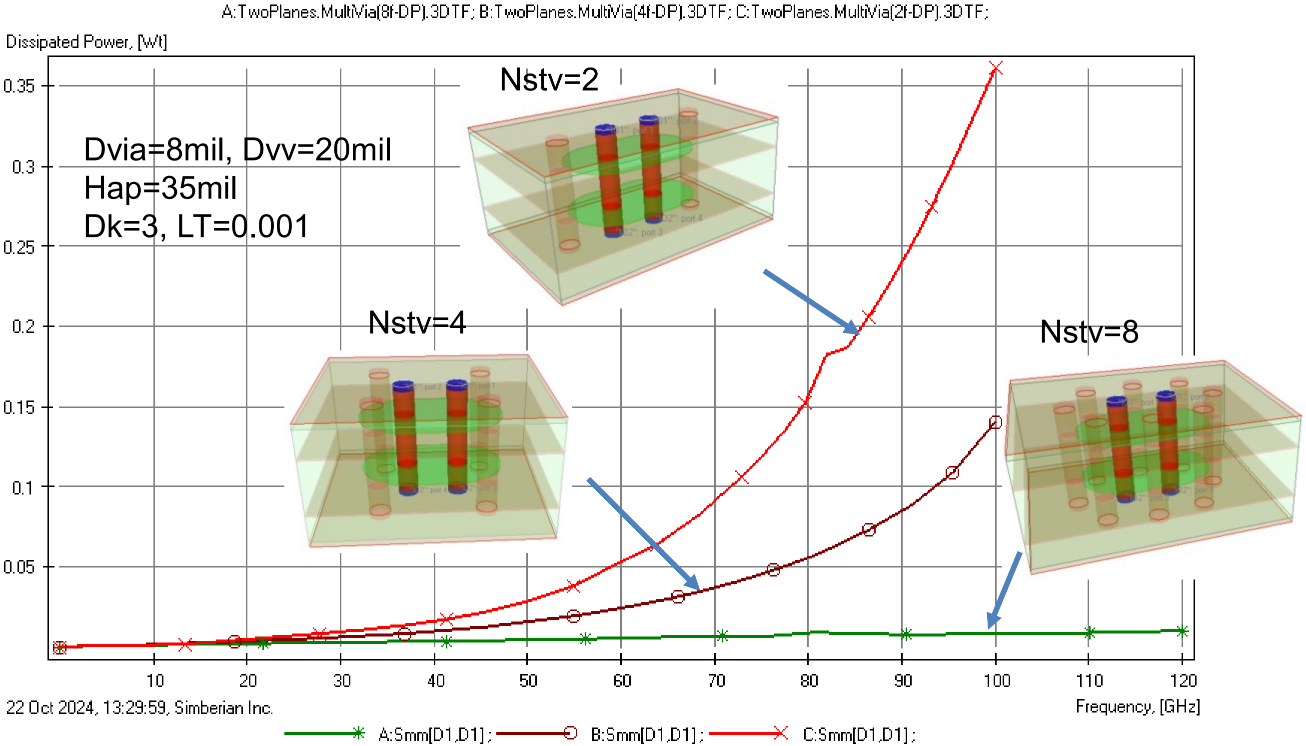
Localization: Diff. Vias Dissipated Power

$$P_{dissipated} = \left(1 - \sum_k \left|S_{k,1}\right|^2\right) P_{in}$$

Diff. Excitation 1 Wt

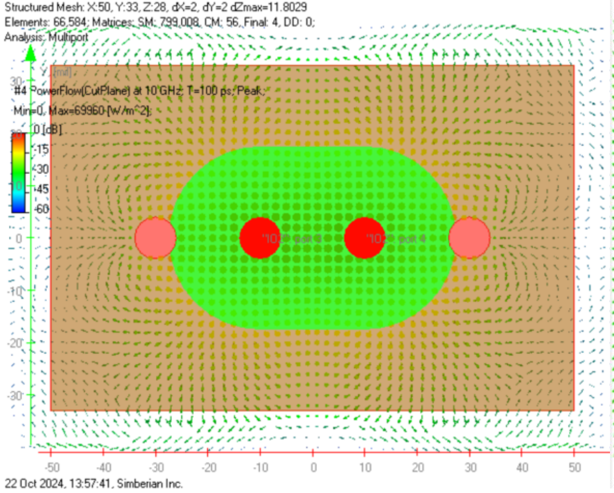
Stitching vias reduce dissipated power and possible leaks and coupling

Simbeor 3DTF, PML



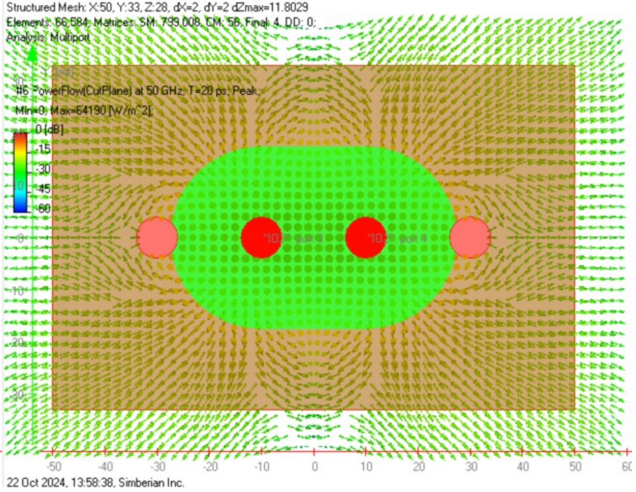
Diff. Vias Power Flow Density, Nstv=2

10 GHz



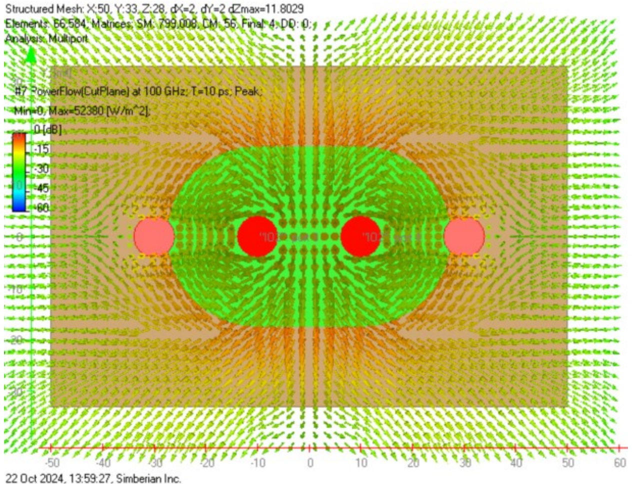
DP=0.12%

50 GHz



DP=2.9%

100 GHz

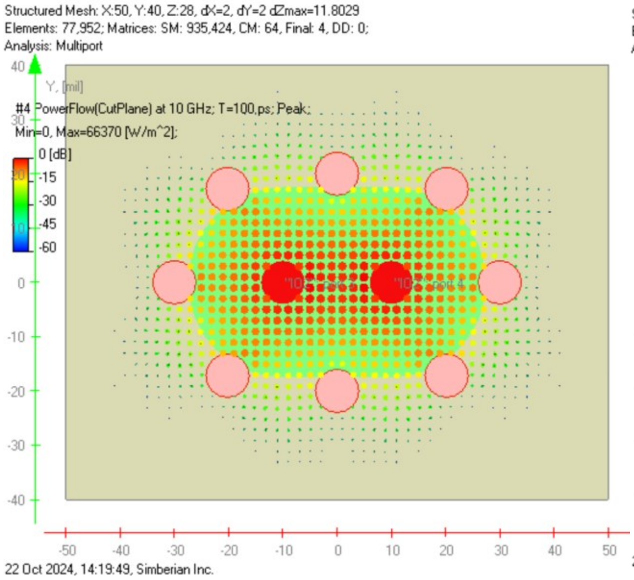


DP=36%

Peak PFD, Simbeor 3DTF, PML BC, Dvia=8mil, Dvv=20mil, Hap=35mil, Dk=3, LT=0.001

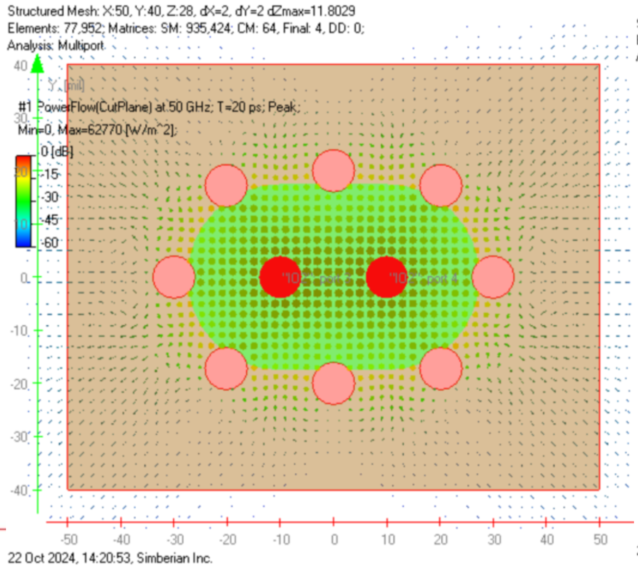
SITW POWER FLOW DENSITY

10 GHz



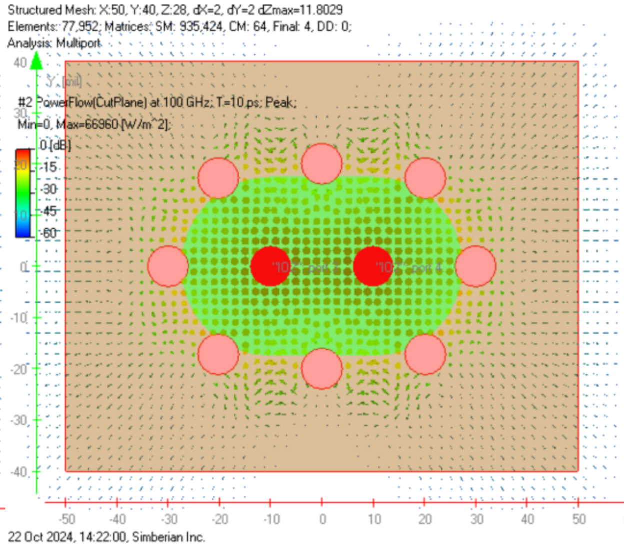
DP=0.13%

50 GHz



DP=0.45%

100 GHz



DP=0.84%

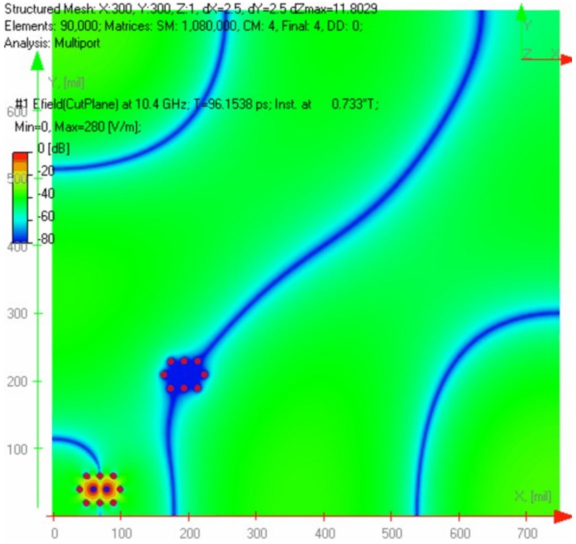
Peak PFD, Simbeor 3DTF, PML BC, Dvia=8mil, Dvv=20mil, Hstv=40mil, Hap=35mil, Dk=3, LT=0.001

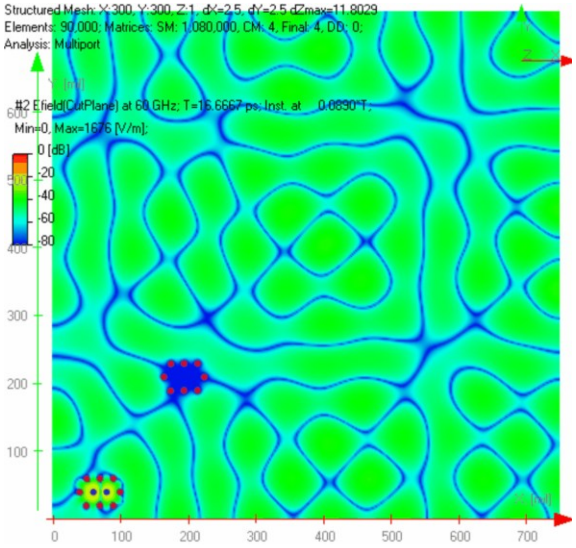
Coupling Reduction with Stitching Vias

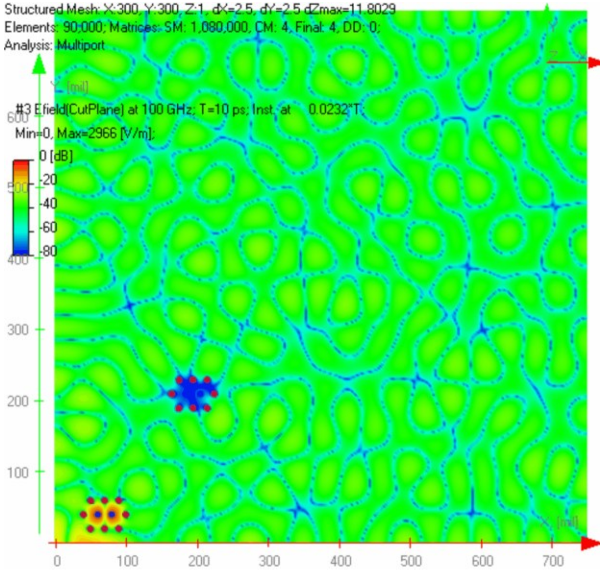
750mil x 750mil with PMC, Nstv=8

Electric field for 1V differential source at corner vias

Does not need 3D EM analysis of whole boards







(animated)

Takeouts – Localize or Face Uncertainties…

Localization Frequency

Frequency

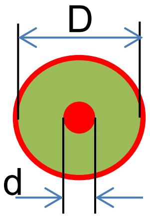
Localized	Non-Localized
Predictable with analysis in isolation	Requires analysis with PDNs
Any boundary conditions can be used for analysis in isolation	Low-impedance ABC are required for simulation in isolation
Local coupling can be included	Hybrid 2D+3D analysis is required
EASY	DIFFICULT

Localization of any via breaks as frequency grow…

Use Dissipated Power as the localization metric

*More on crosstalk between vias at Y. Shlepnev, **Tutorial: How Interconnects Work: Crosstalk Anatomy and Quantification**, DesignCon 2025 – Technical Presentation #2025_01*

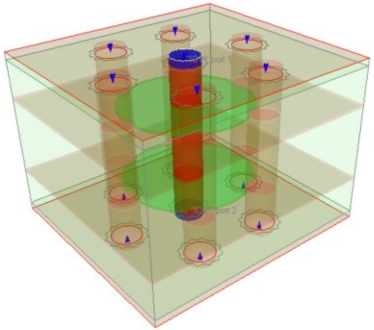
SE VIA MIDDLE SECTION: SICW



Coaxial -> **Substrate Integrated Coaxial Waveguide (SICW)**

Single-mode limit is defined by mode TE11:

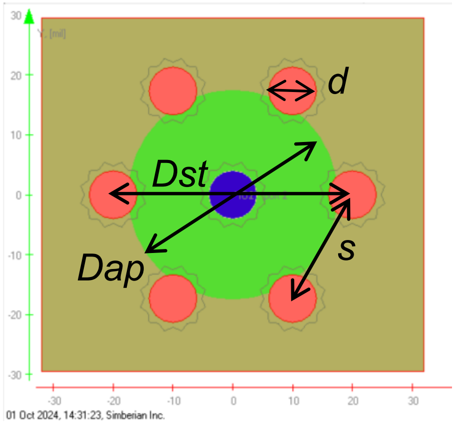
$$f_{cutoff} \approx \frac{2c}{\pi(d+D)\sqrt{\varepsilon}}$$



$$D = d \cdot e^{2\pi Z_o \sqrt{\frac{\varepsilon}{\mu}}}$$

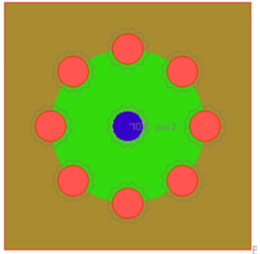
$$s < 0.4\lambda \quad D_{ap} \approx D$$

$$Dst = D + \frac{d^2}{0.95 * s}$$



Dk = 3, Dvia=8mil, Dst=40mil, s=21mil → $f_{cutoff} \approx 96.4\ GHz$ (<AWG30)

Dk = 3, Dvia=4mil, Dst=20mil, s=7.8mil → $f_{cutoff} \approx 199\ GHz$ (<AWG36)



E. R. Pillai, "Coax via technique to reduce crosstalk and enhance impedance match at vias in high-frequency multilayer packages verified by FDTD and MoM modeling," in IEEE Transactions on Microwave Theory and Techniques, vol. 45, no. 10, pp. 1981-1985, Oct. 1997.

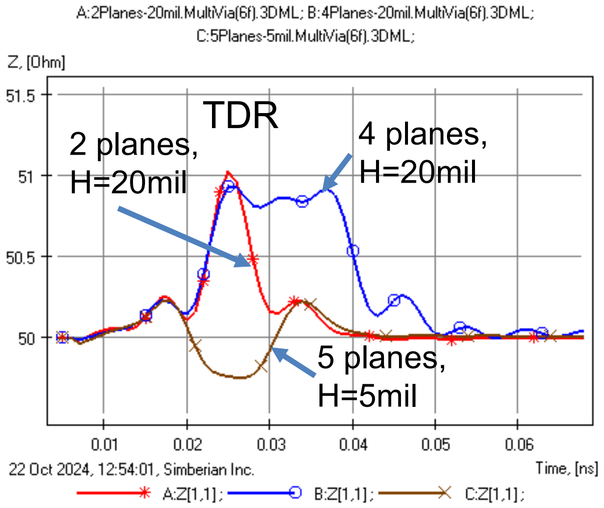
Bozzi, M.; Georgiadis, A.; Wu, K. "Review of substrate-integrated waveguide circuits and antennas". IET Microwaves, Antennas & Propagation, 2011 ***5*** *(8): 909.*

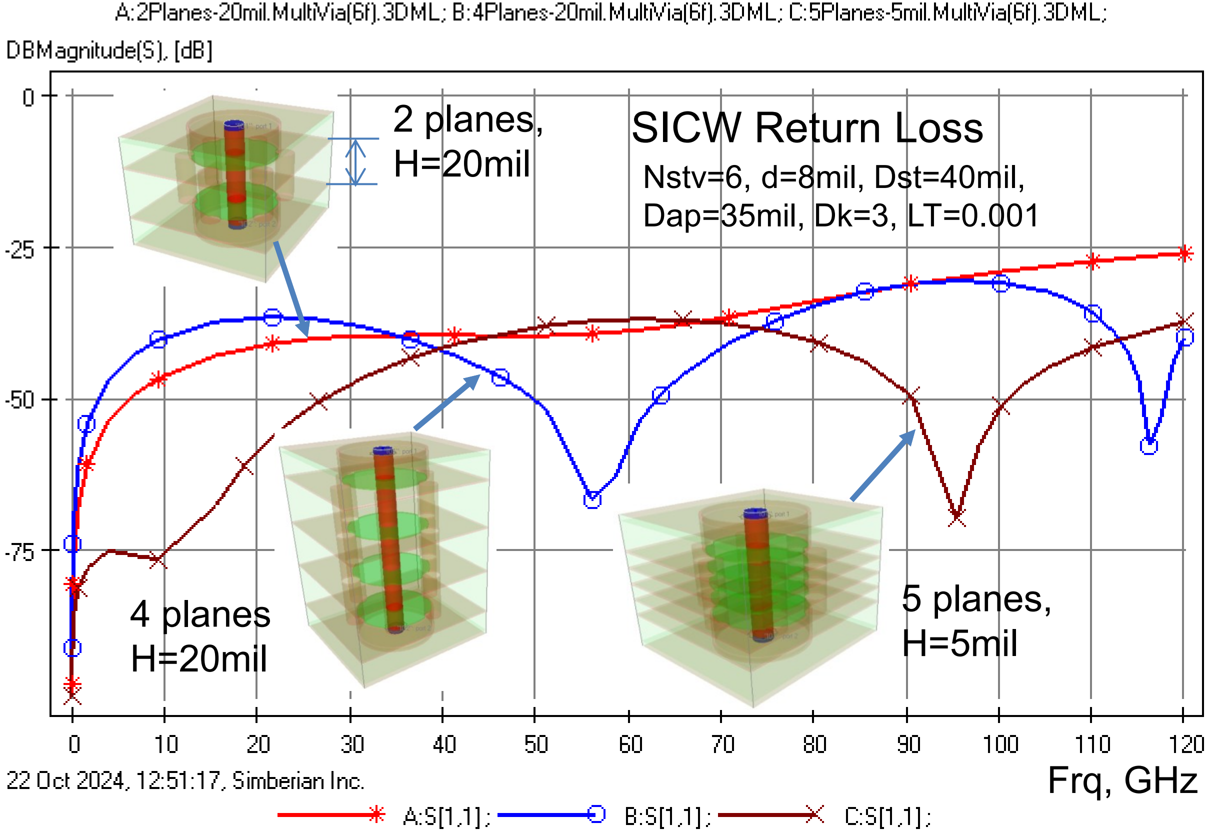
SICW: IMMUNITY TO STACKUP

SICW is immune to stackup structure changes

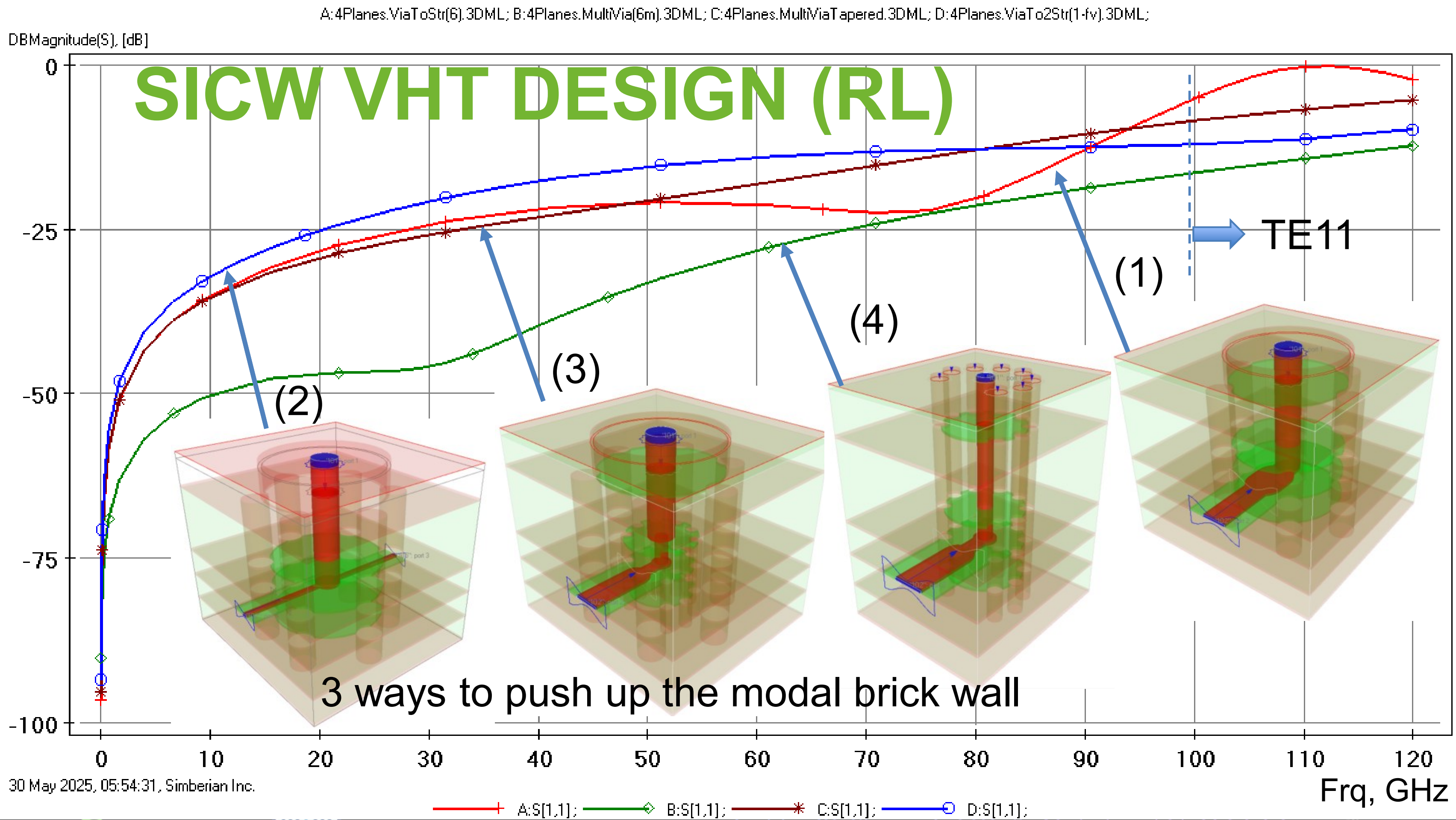
Same XY-plane geometry:

Nstv=6, Dvia=8mil, Dst=40mil, Dap=35mil, Dk=3, LT=0.001



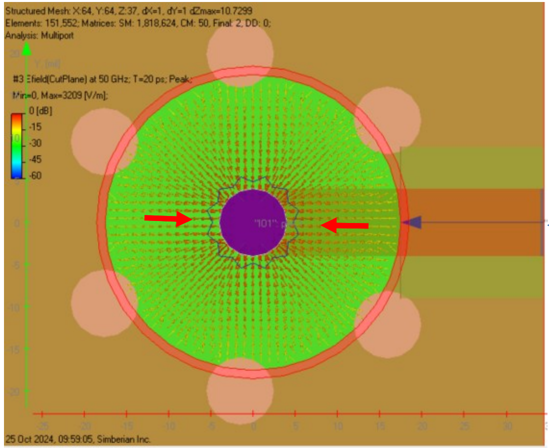


SICW VHT DESIGN (RL)

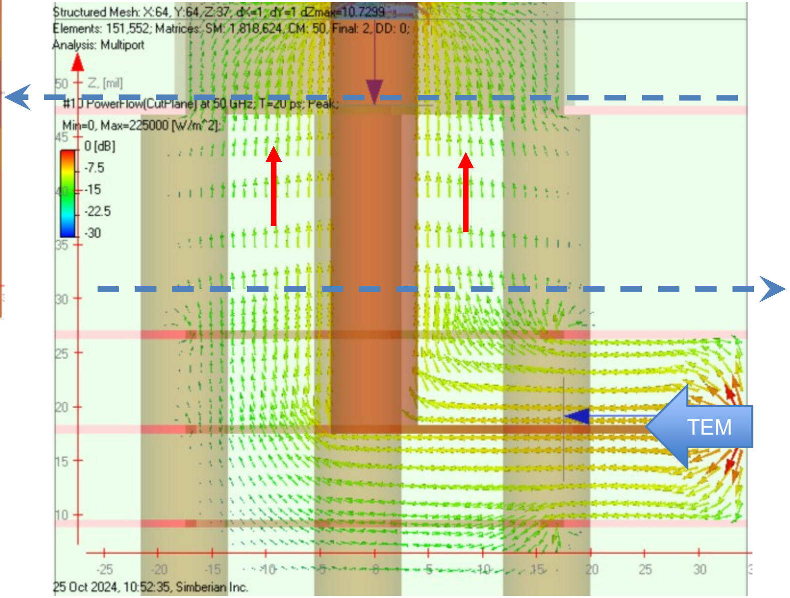


Mode Conversion at VHT: TEM to TEM

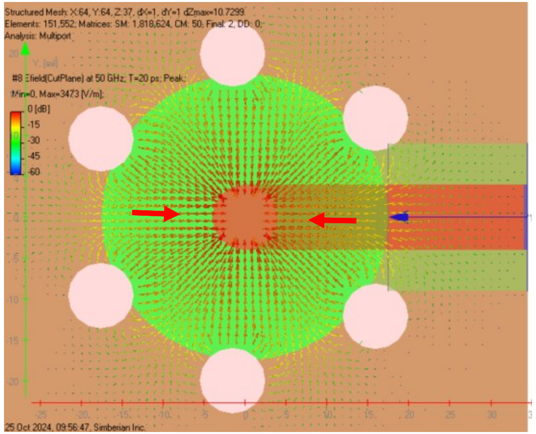
E-fields at 50 GHz - Coax. TEM



Peak PFD at 50 GHz

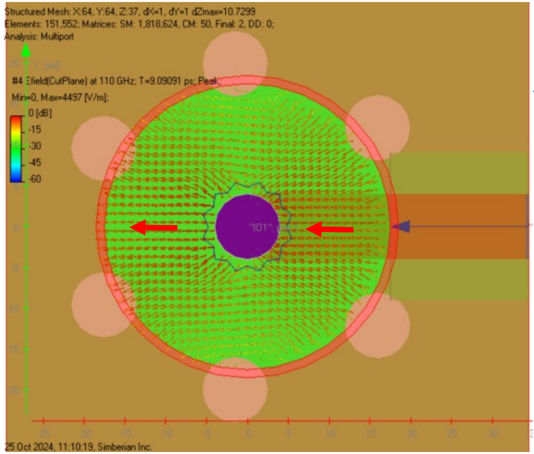


E-field at 50 GHz - SICW Quasi-TEM

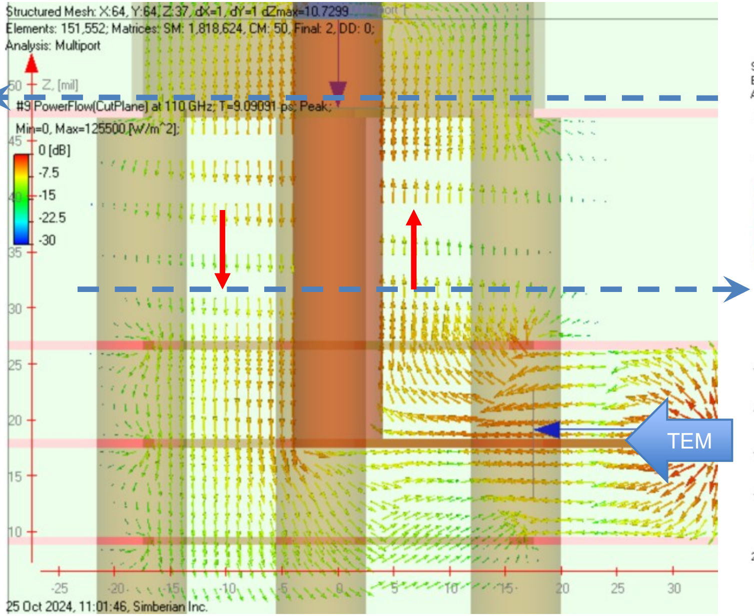


Mode Conversion at VHT: TEM to TE11

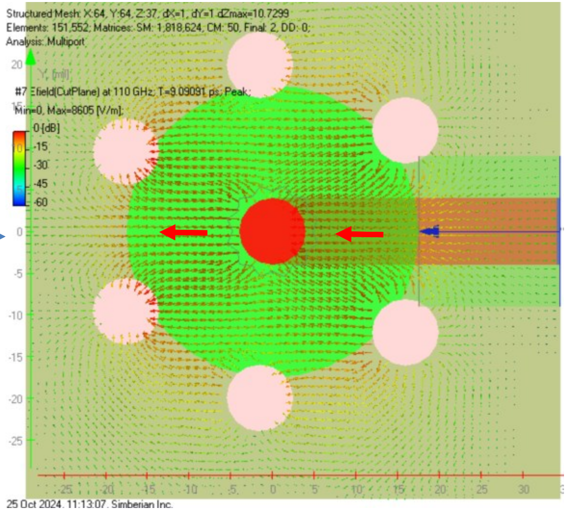
E-field at 110 GHz – Coax. TE11



Peak PFD at 110 GHz

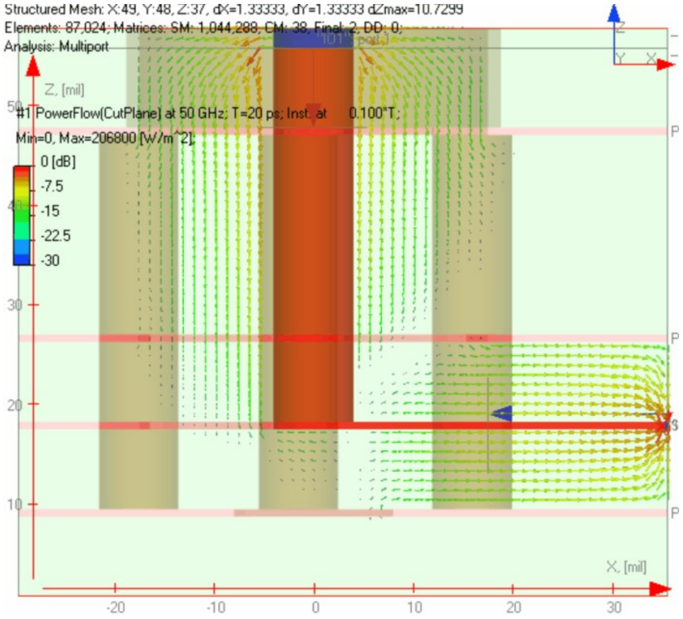


E-field at 110 GHz - SICW Quasi-TE11

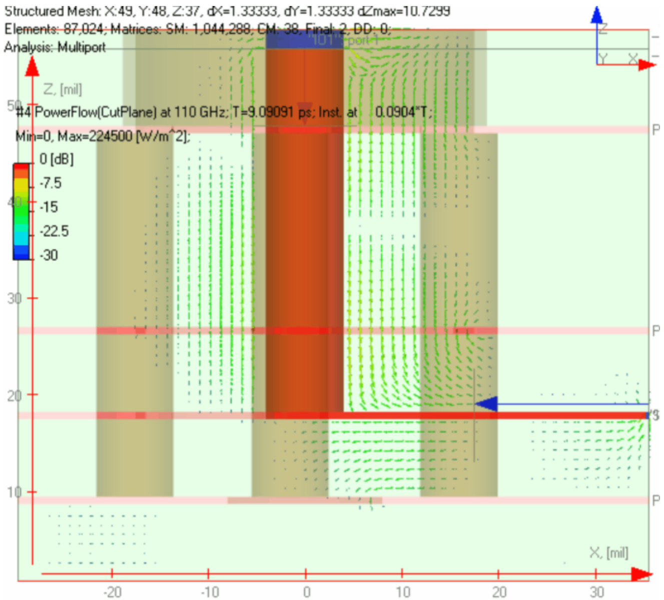


Mode Conversion at VHT (animated)

Peak PFD at 50 GHz: TEM -> TEM

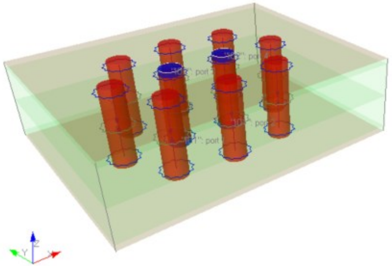


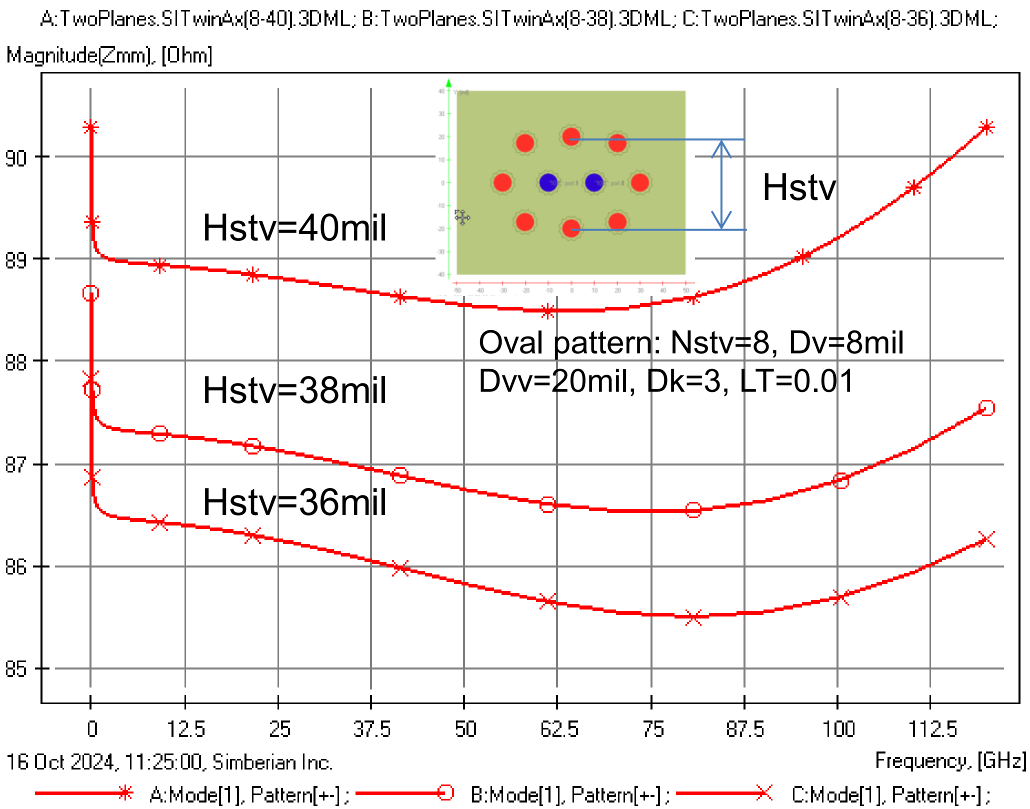
Peak PFD at 110 GHz: TEM ->TE11



TWINAX TO SITW

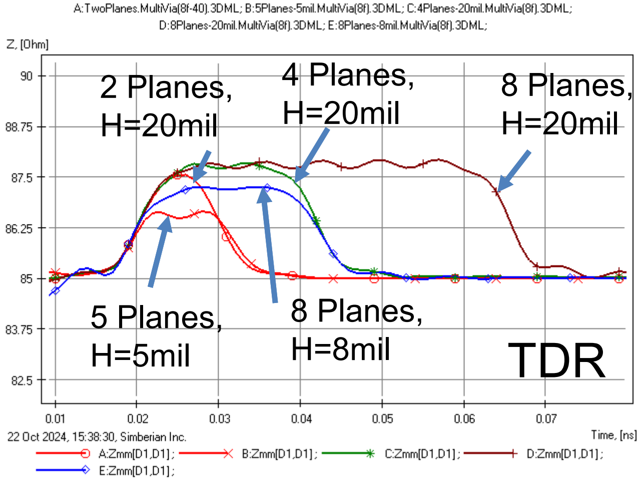
Oval pattern, Nstv=8
H=20mil, Dvv=20mil
Dk=3, LT=0.01

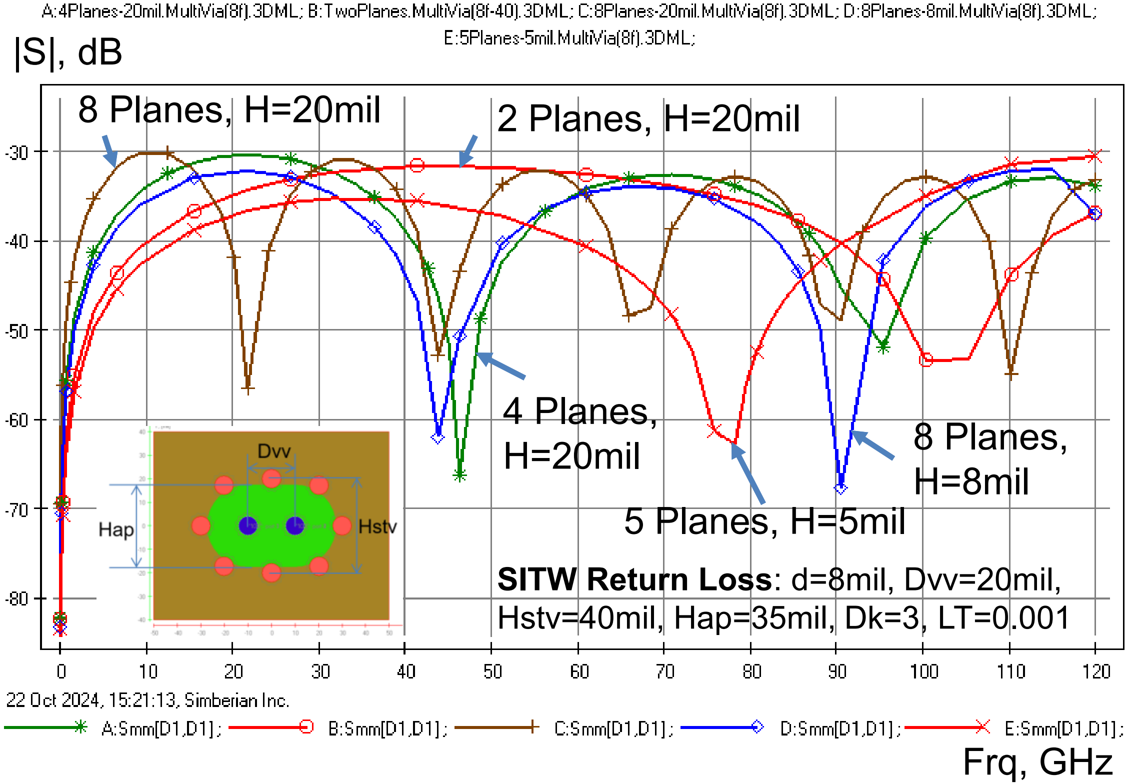




SITW: IMMUNITY TO STACKUP

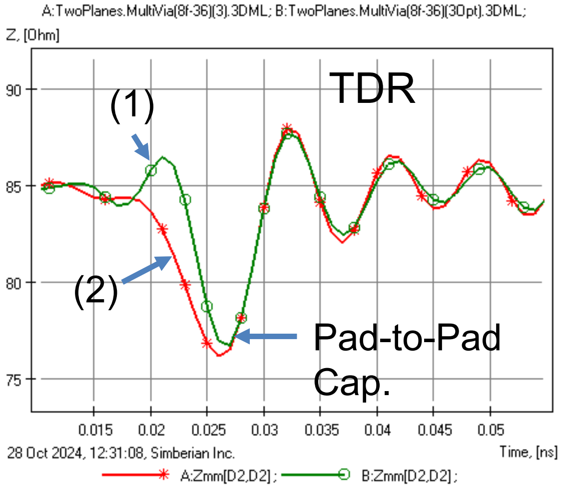
Same XY-plane geometry:
Dvia=8mil, Dvv=20mil, Hstv=40mil,
Hap=35mil, Dk=3, LT=0.001
Simbeor 3DML, ABC

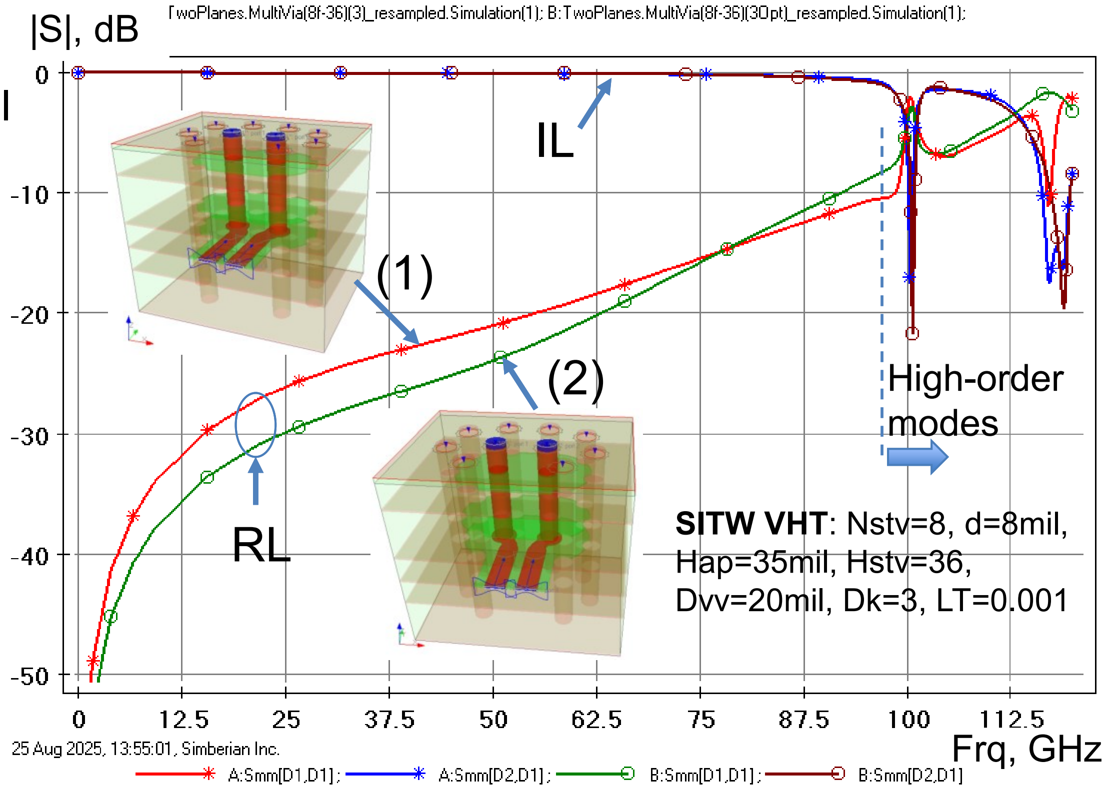




SITW VHT DESIGN (same modal brick wall)

Nstv=8, Dvia=8mil,
Hap=35mil, Hstv=36, Dvv=20mil
Dk=3, LT=0.001
Simbeor 3DML, PEC





Conclusion on Via Predictability & Design

1. The Dead End of Optimization

   Direct optimization of conventional padstacks fails. They are excessively sensitive to manufacturing variations and stackup changes.

2. The Localization Metric

   We established formal conditions for Localization up to 120 GHz.

   Rule: If the field leaks (non-local), the via is unpredictable.

3. The Solution: Waveguiding Approach

   Designing vias as Substrate Integrated Waveguides (SIW) (Coaxial/Twinax style).

   Benefit: Makes the via independent of the board stackup and robust against geometry variations.

4. The Path to 448 Gbps

   This is a verified theoretical framework that solves the "Design Brickwall," with practical hardware validation currently in progress.

More in A. Manukovsky, Y. Shlepnev, J. Nutzati, A. Kuntsevych, I. Peleg, S. Mordooch Via Design for 112 Gbps and Beyond: Theory and Reality, DesignCon 2025
Y. Shlepnev, A. Manukovsky, ***Waveguiding Approach to Via Design with Bandwidth over 120 GHz****, EPEPS 2025.*

Conclusion: The Path to 448 Gbps Predictability

1. The Foundation

Analysis-to-Measurement Correlation is non-negotiable.

Adopt the "Sink or Swim" philosophy: If it doesn't correlate, don't build it.

2. The Manufacturing Reality

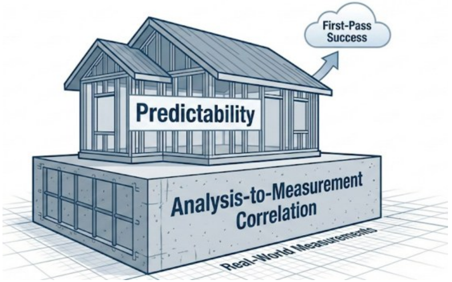
We cannot eliminate fabrication variations.

The Choice: We must either demand impossible manufacturing precision OR embrace Statistical Models.

3. The Design Paradigm Shift

Conventional vias are unpredictable at these frequencies.

The Waveguiding Approach (Localization) is not just an option—it is the required rethinking of interconnect design.



Thank you!

QUESTIONS?

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