Measurement Evaluation of PCB Electrical Performance 200 Gb/s PAM 4

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Acknowledgements: Rich Mellitz, Samtec and Adam Gregory, Samtec

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Supporters

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- ❑ Howard Heck, Intel Corp.

Purpose

PCB performance is a critical consideration for 200 Gb/s PAM4 signaling.

- ❑ Share recent electrical evaluation of emerging PCB material
- ❑ Discuss conductor width impact on performance
- ❑ Suggest temperature and humidity impacts be considered
- ❑ Focus of this presentation is single traces measurements
    - Differential traces measurements yielded similar results when adjusted for trace width

Measurement Setup for 110 GHz

Connectors

Test points: 1.0 mm Vertical Launch

Measurements

- Max frequency 110 GHz captured
  - Designed for 90 GHz
- VNA calibrated to test points
- Large number of measurements

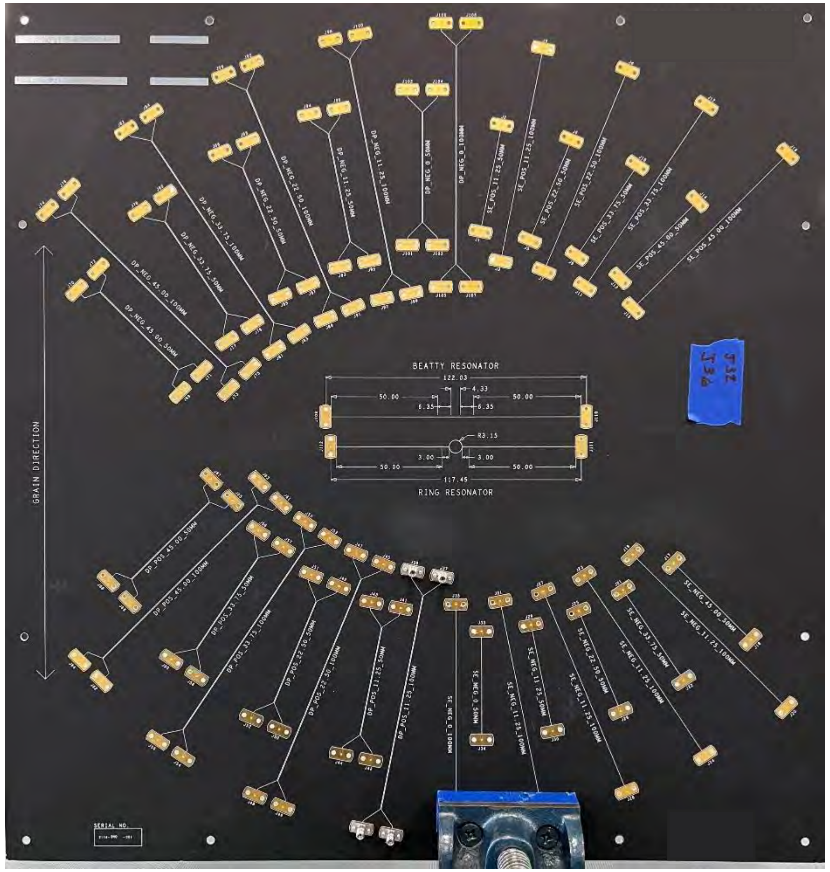
Goal:

Extract electrical characteristics for traces on **emerging*** dielectric and foil combinations for loss and fiber weave effect.

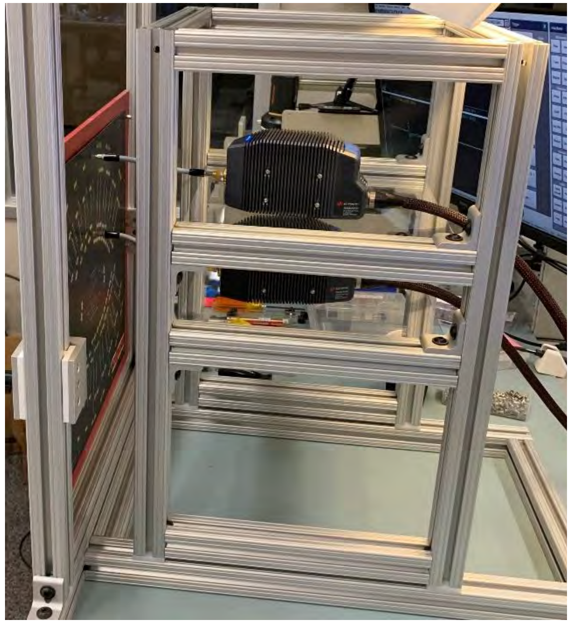
Constraint:

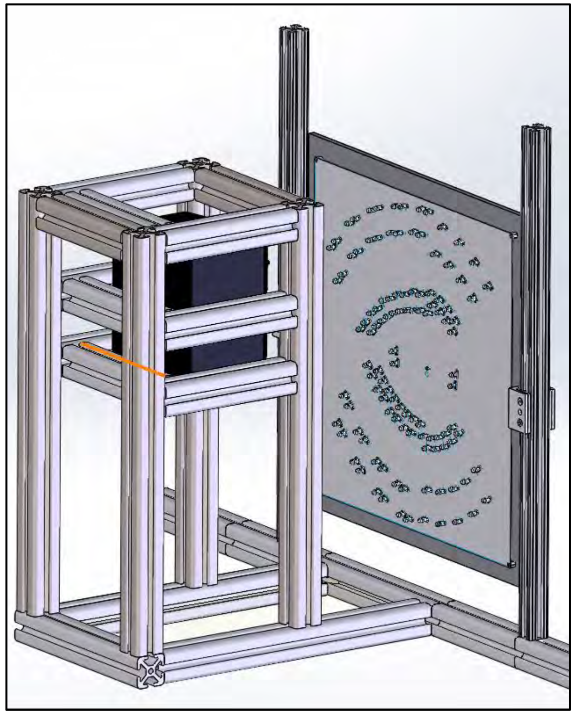
Same artwork, dielectric thickness and glass cloth (resin content). Figure on right was manufactured with a number of dielectric and foil combinations.

* Resin and foil combinations targeting mass production after 2024



Two lengths for each 9 routing angles





Material, Supplier, Fabricator Matrix

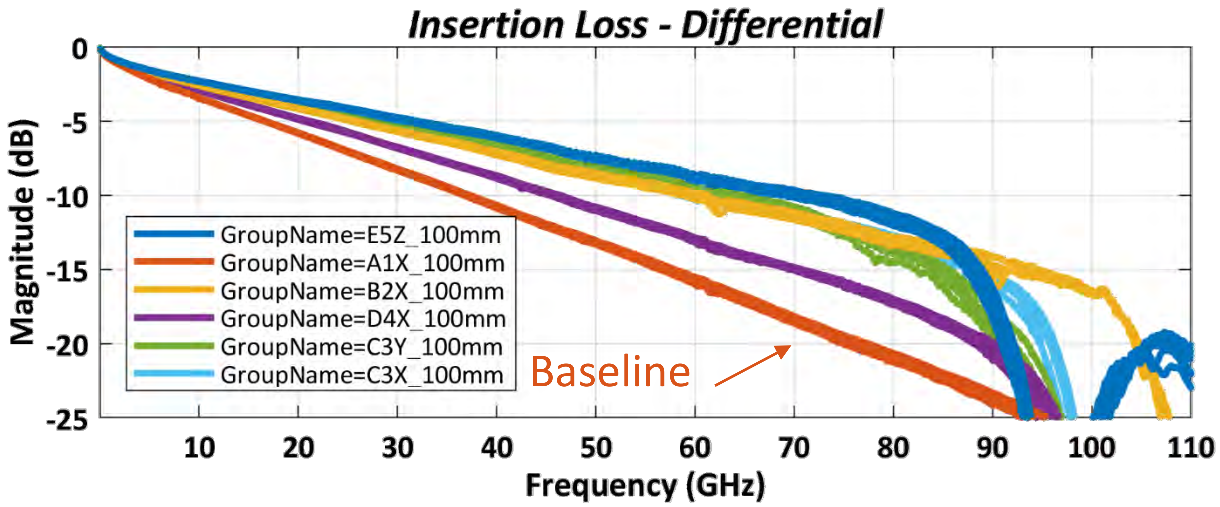
5 MATERIALS, 5 SUPPLIERS, 3 FABRICATORS

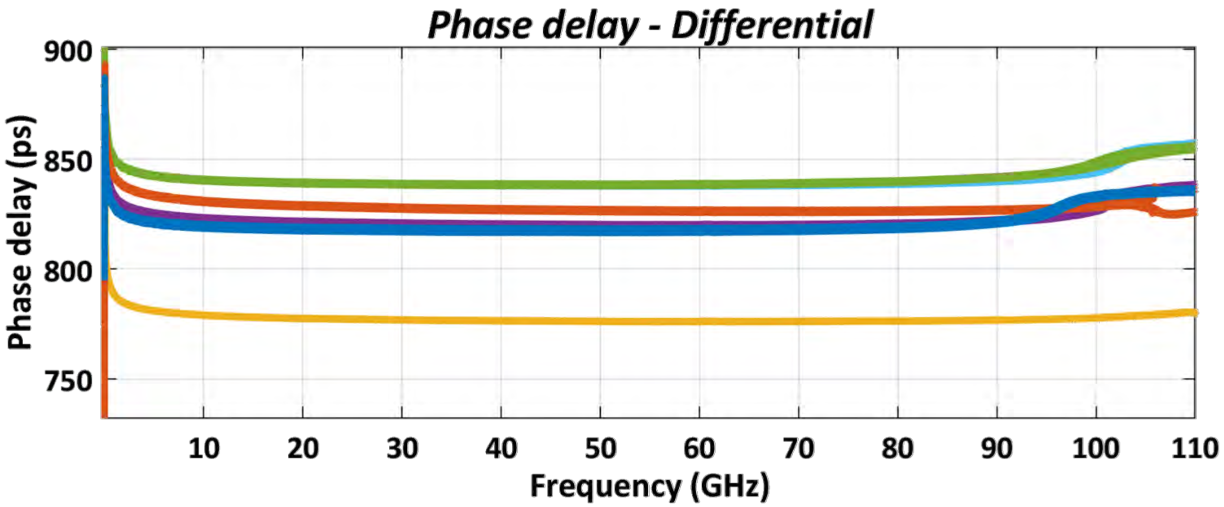
Material	Glass Style	Supplier	Factory	Resin System	$\varepsilon_r, tan\partial$ Datasheet (5 GHz)	Foil Type (Inner, Outer)	Oxide Etch	Rz (um) Datasheet	Conductivity 20º C (S/m) Datasheet
A	2x1067	1	X	PPO	3.05, 0.0021	VLP2, RTF	Multibond MP	< 2.0	_
B	1x1067	2	X	PTFE	2.77, 0.0014 **	UHLP, HTE6P	Multibond MP	_	_
C	2x1035	3	Y	PPO	3.2, 0.0012 *	SI-VSP, HVLP	Bondfilm HF 1000	< 0.8	5.739E+07
C	2x1035	3	X	PPO	3.2, 0.0012 *	SI-VSP, H-VLP	Multibond MP	< 0.8	5.739E+07
D	2x1035	4	X	PPO Halogen Free	3.1, 0.0019 **	H-VLP, H-VLP	Multibond MP	< 1.0	_
E	2x1035	5	Z	PPO Halogen Free	2.85, 0.0012 *	HVLP4, RTF-2	Atotech Bondfilm EX	< 0.5	5.75E+07

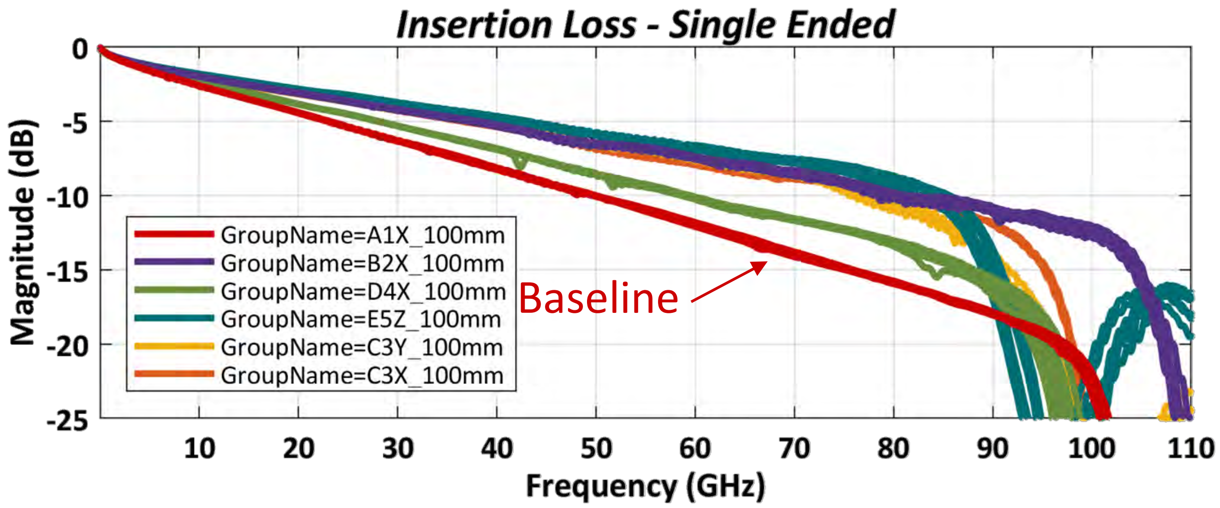
* IPC 650 TM 2.5.5.13
** IPC 650 TM 2.5.5.5c [4]

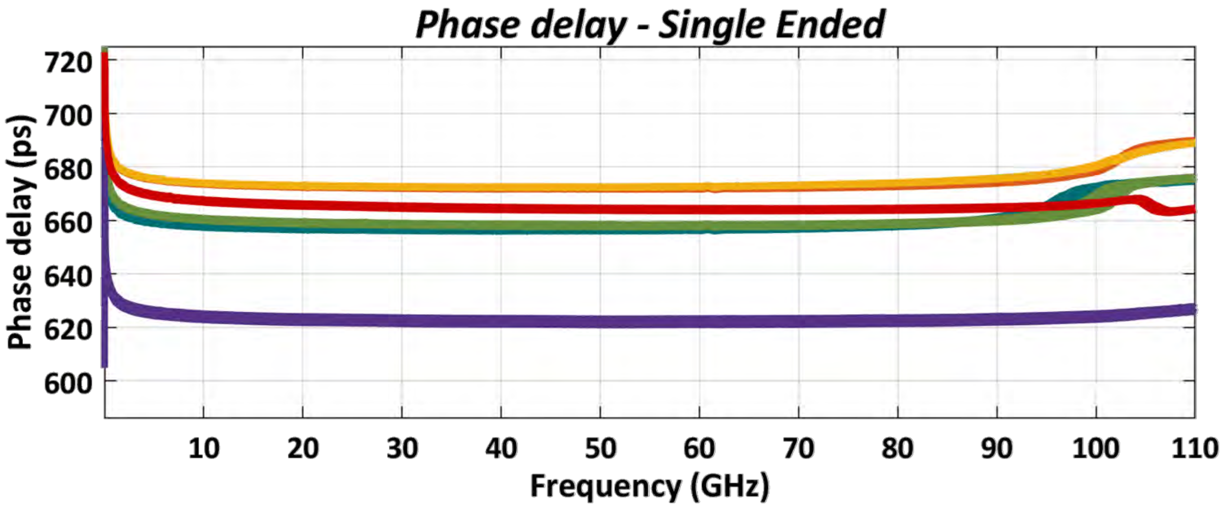
ε_r i.e. relative permittivity or dielectric constant (Dk)
$tan\partial$ i.e. loss tangent or dissipation factor (Df)
Rz is foil roughness profile
PPO is polyphenylene oxide

Example Raw Measurement Set





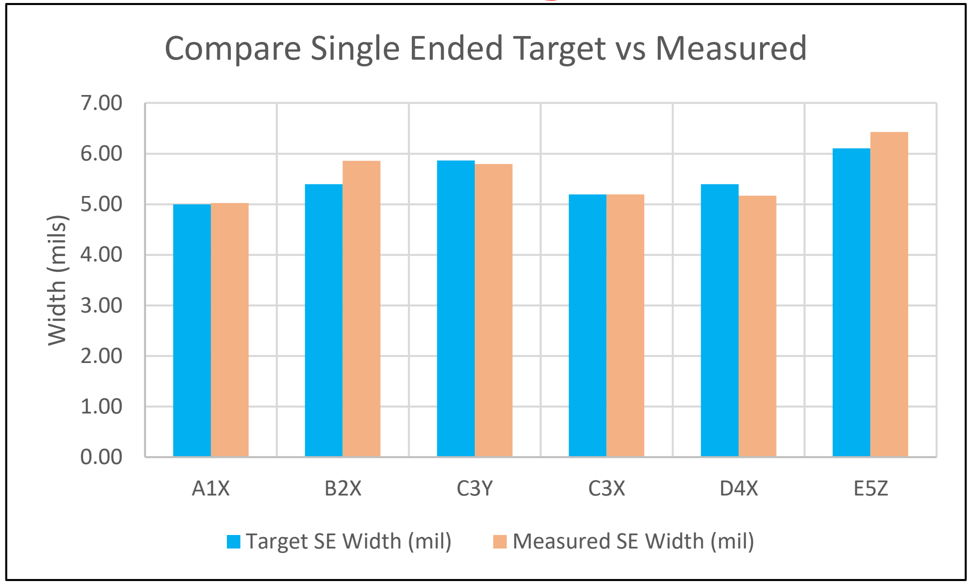


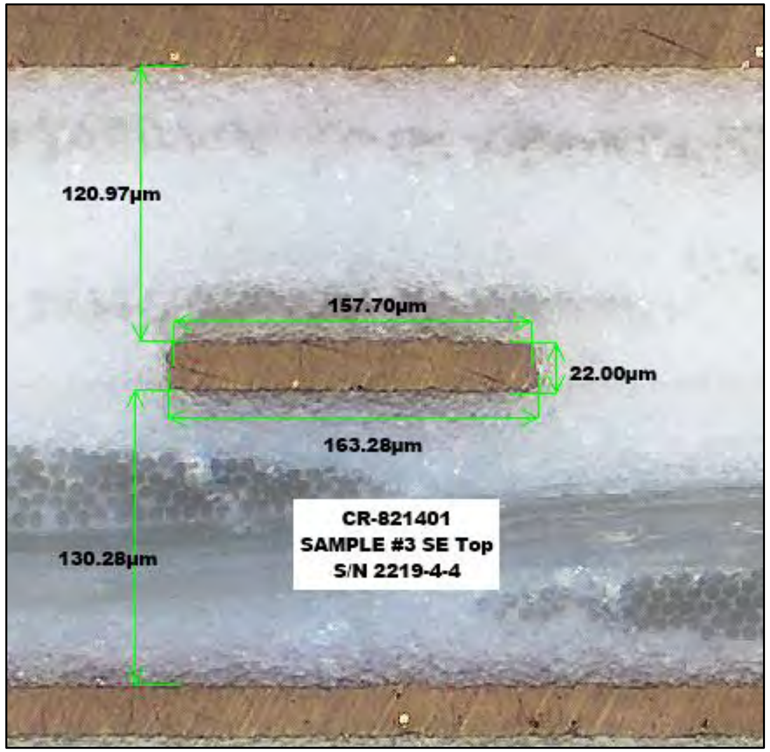


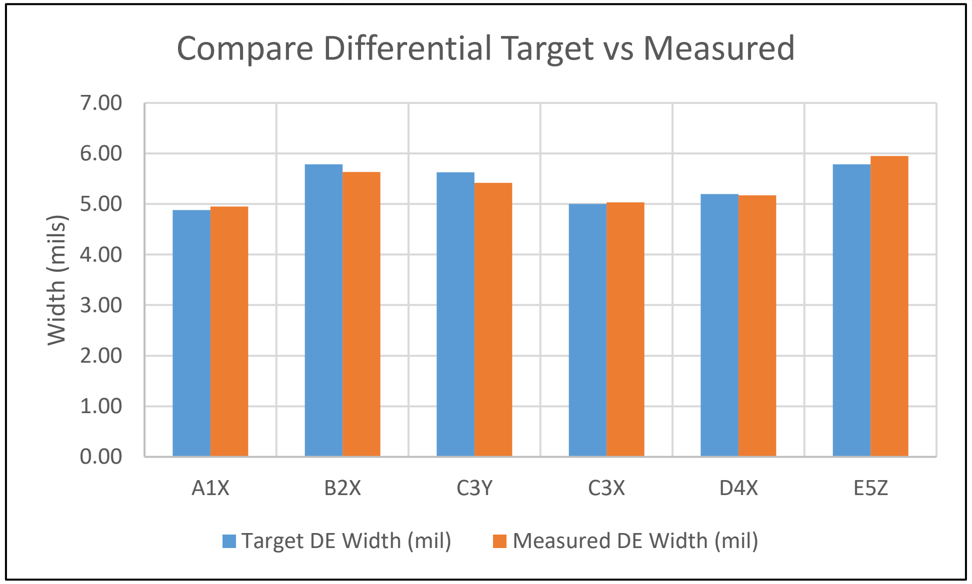
Phase delay or PD = $\frac{\theta_{unwrapped}}{\omega}$

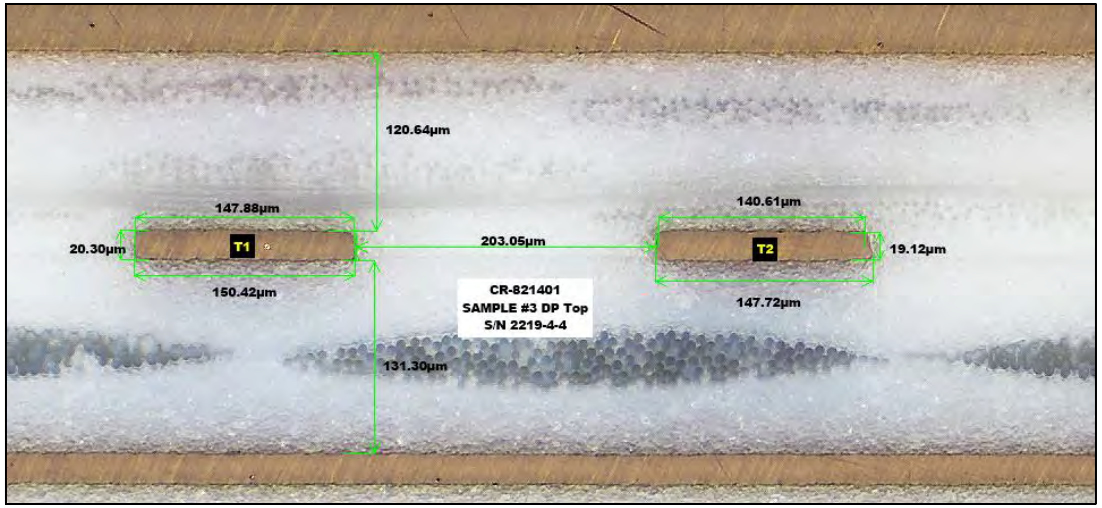
Confirming Trace Geometry

- Portions of the test panels were cross-sectioned and dimensioned with an optical microscope
- Measured values are used for characterization

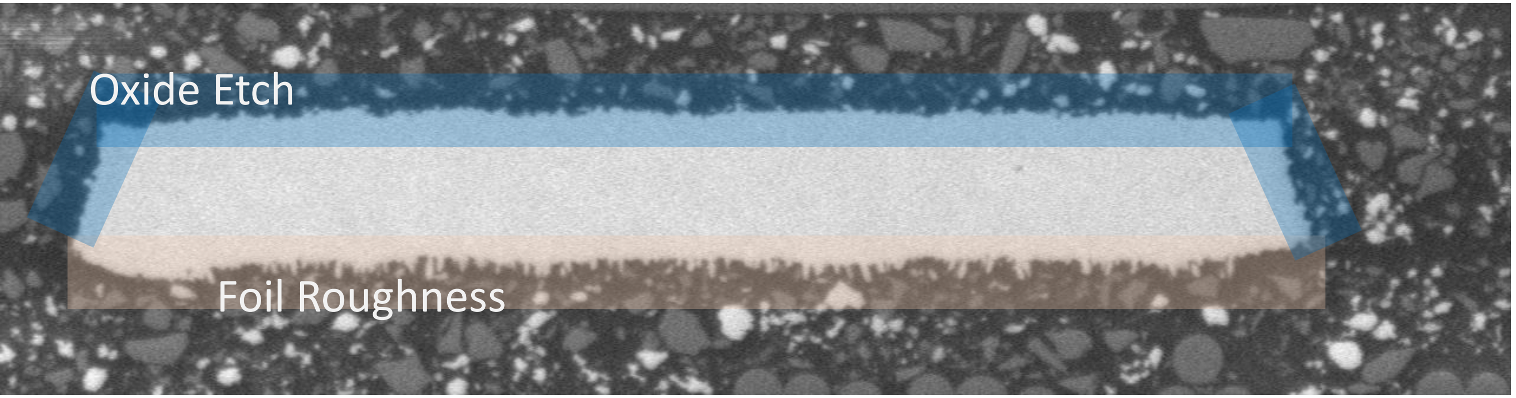




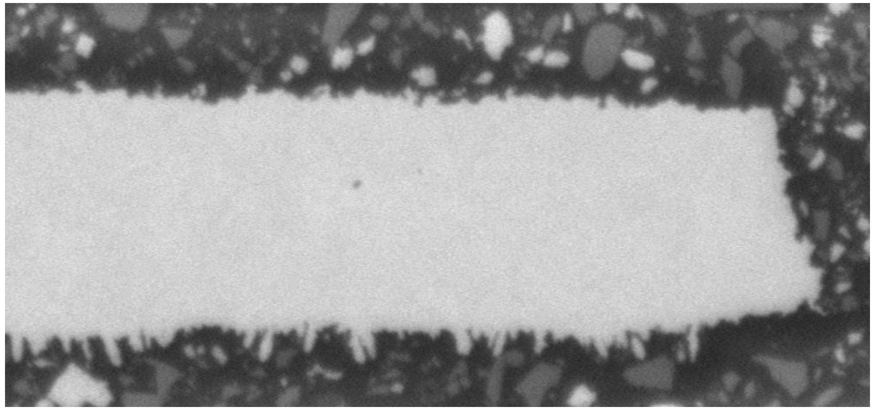


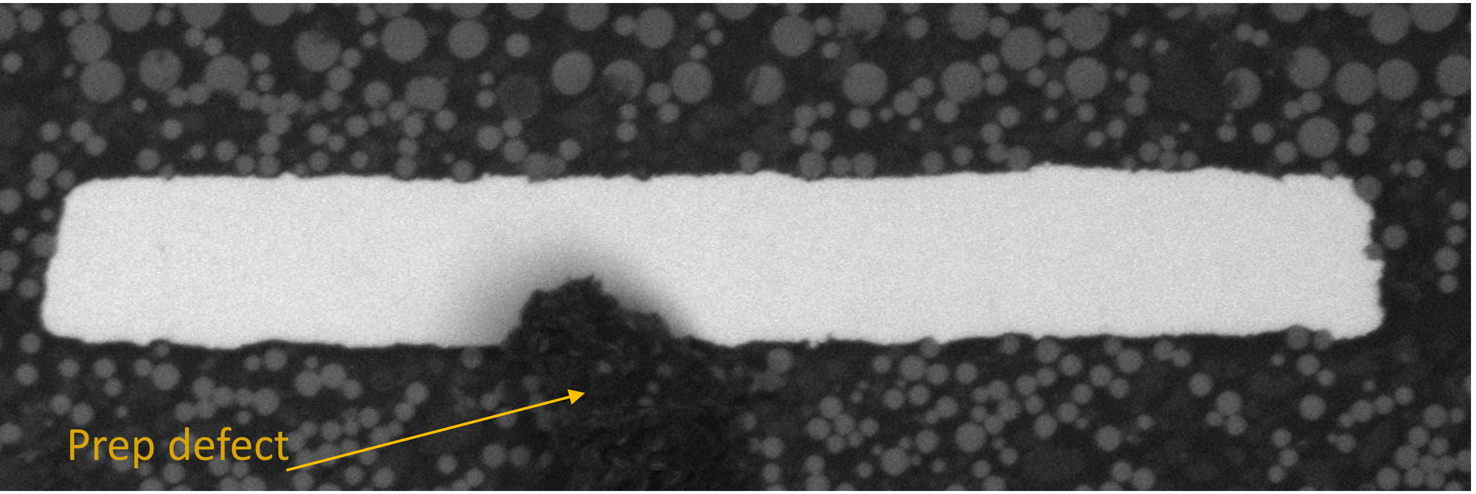


Examining Surface Roughness

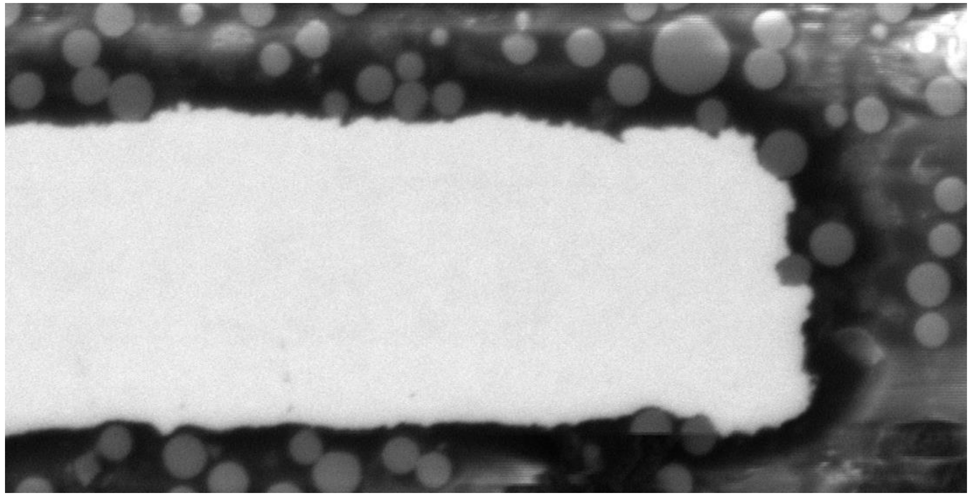


Baseline Loss A1X (VLP2)

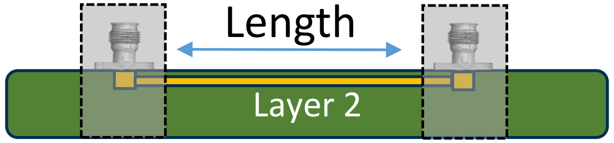

Zoomed in A1X



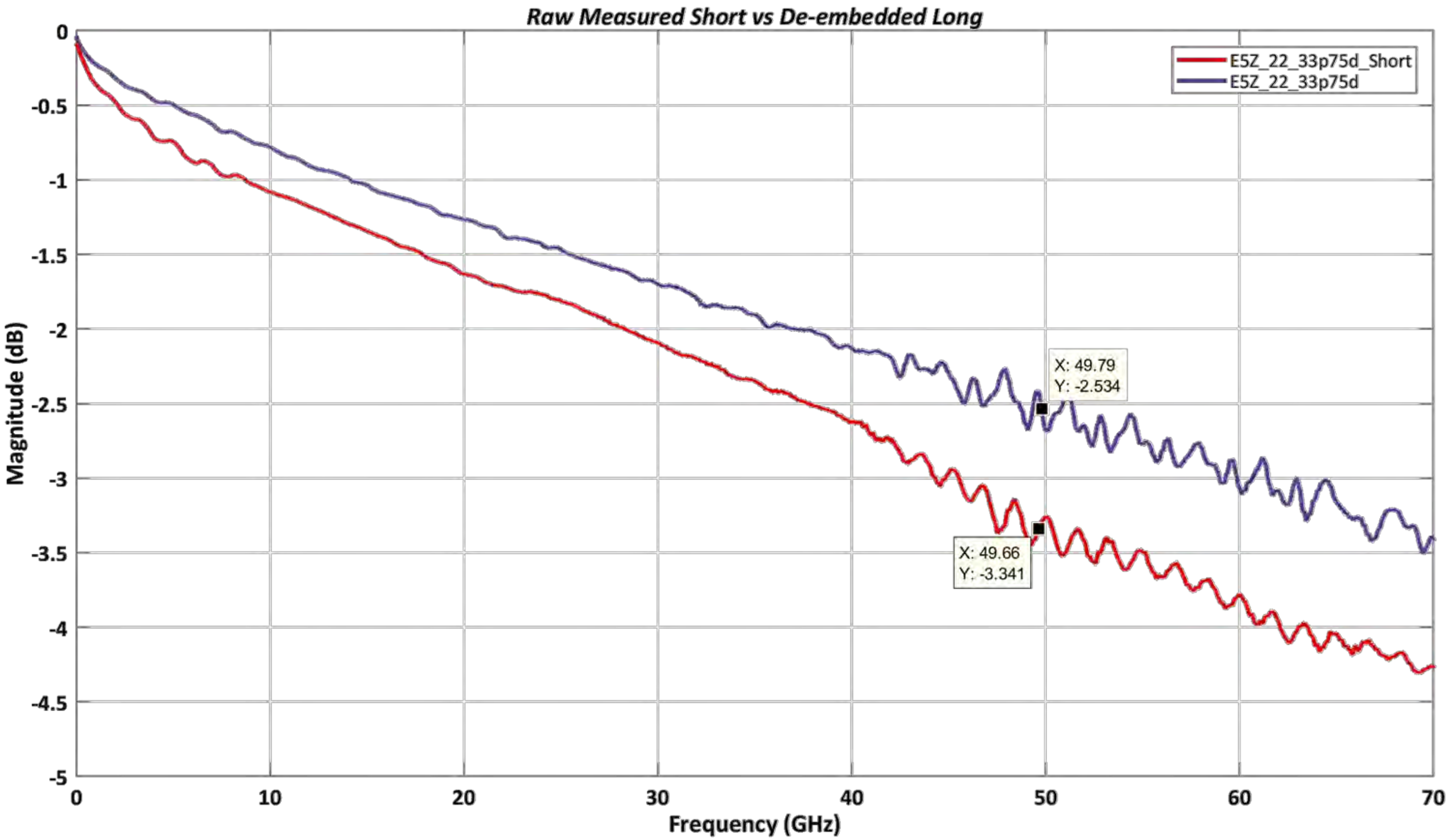
Lower Loss E5Z (HLVP4)


Zoomed in E5Z

Remove Test Point (De-embedding)

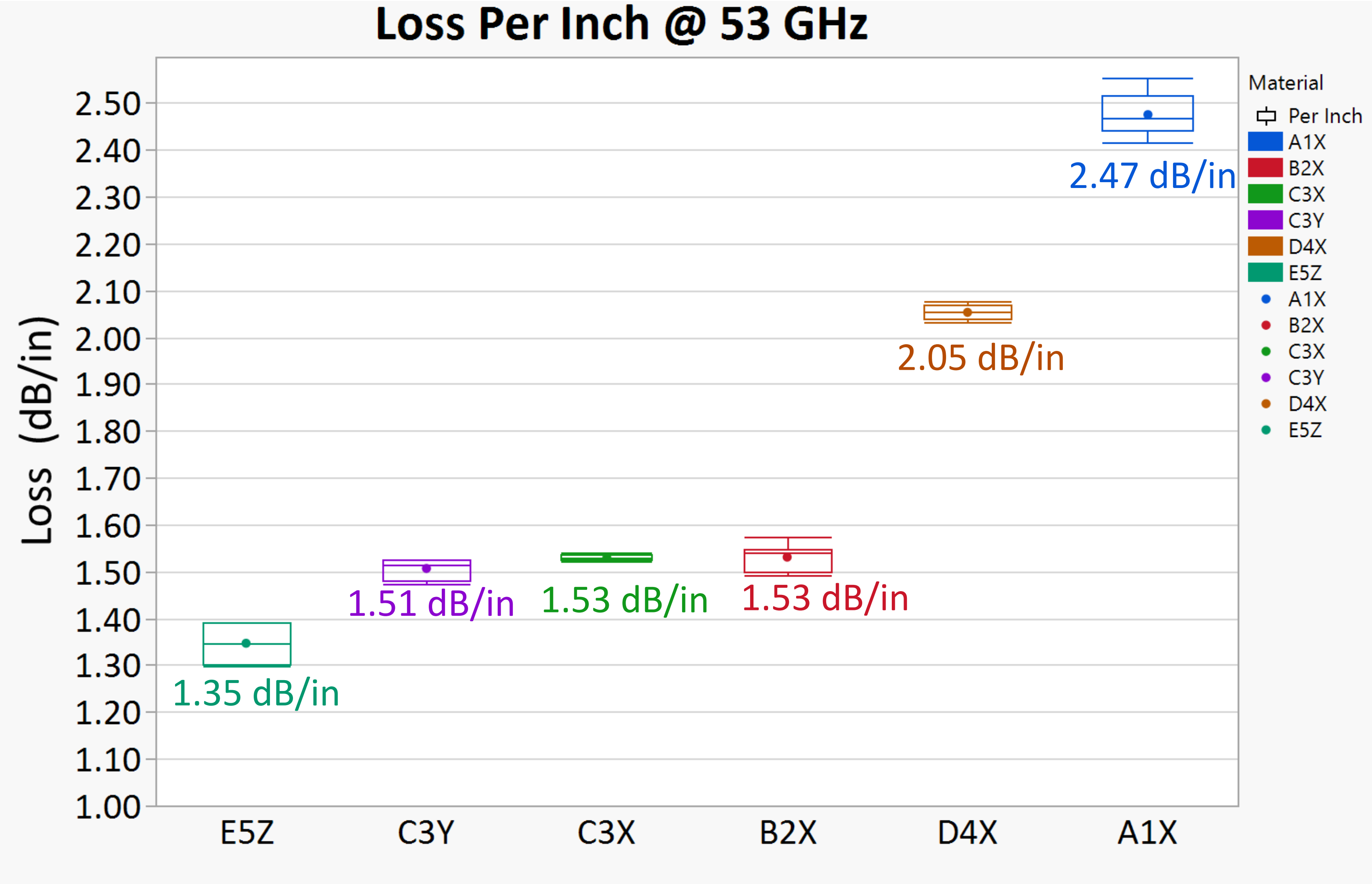


- An impedance corrected 2x Thru de-embedding algorithm used for post processing
- SMAs, Vias, and 2 mm of trace adds ~ 0.8 dB
- Purpose is to get the correct loss per unit length

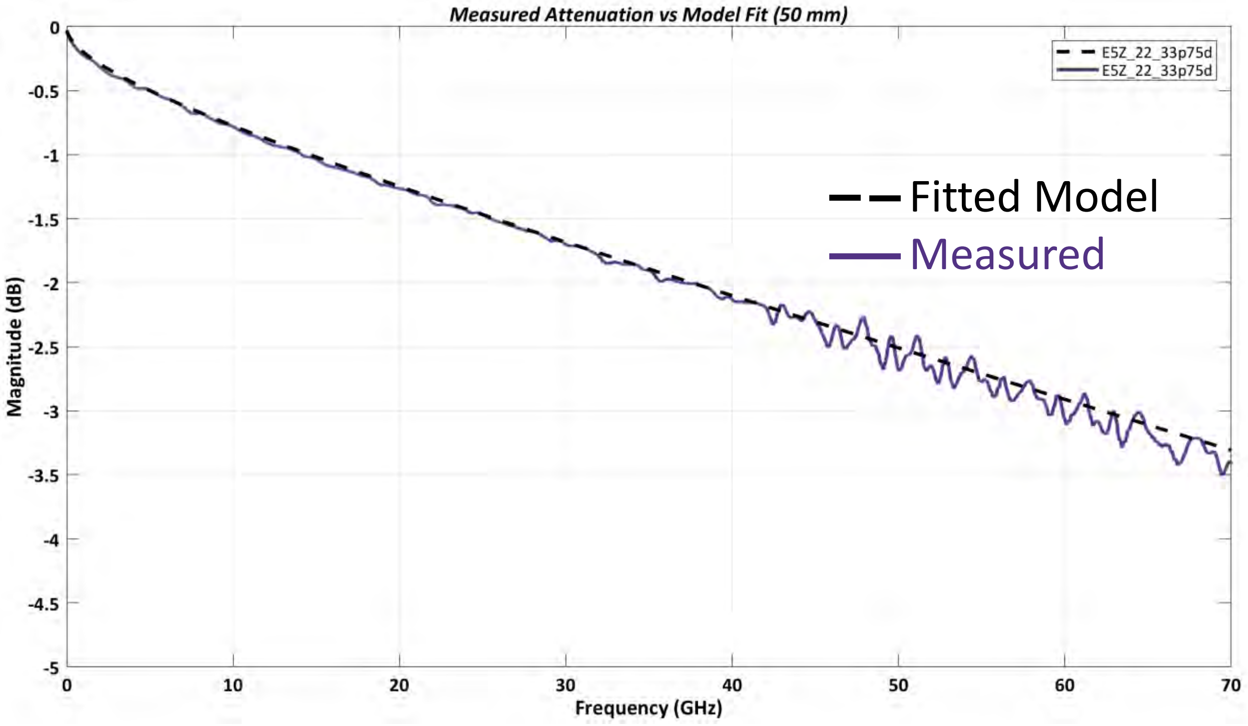


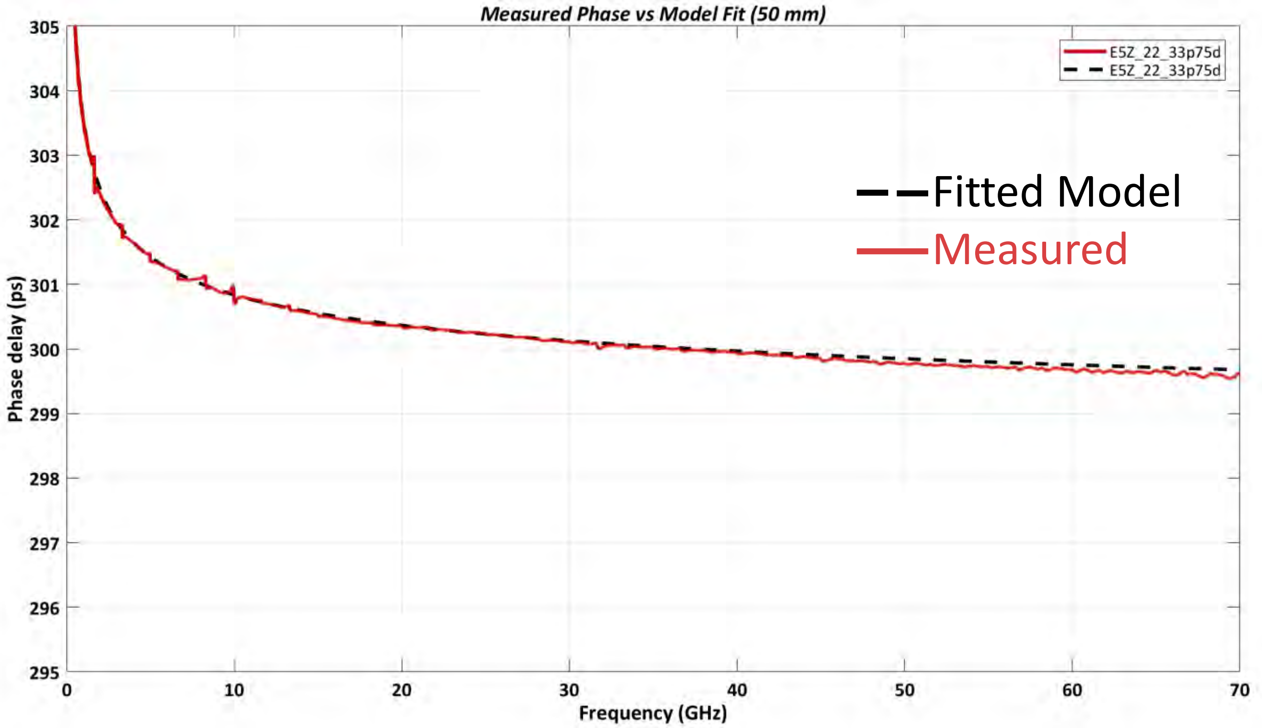
Loss / Inch 53 GHz De-embedded Fit

- Measured results as low as 1.3 dB/in
  - Mean of 1.35 dB/in
- Room Temperature 20°C



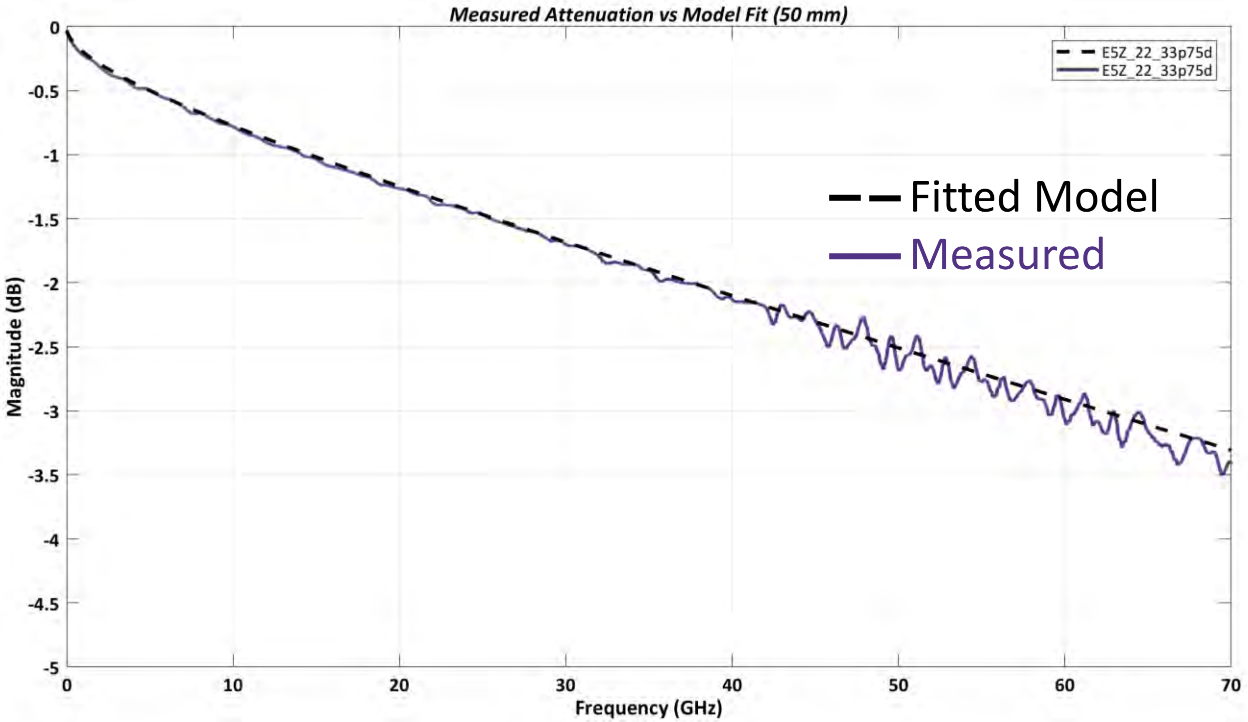
Creating an Extracted (Fitted) Transmission Line Model

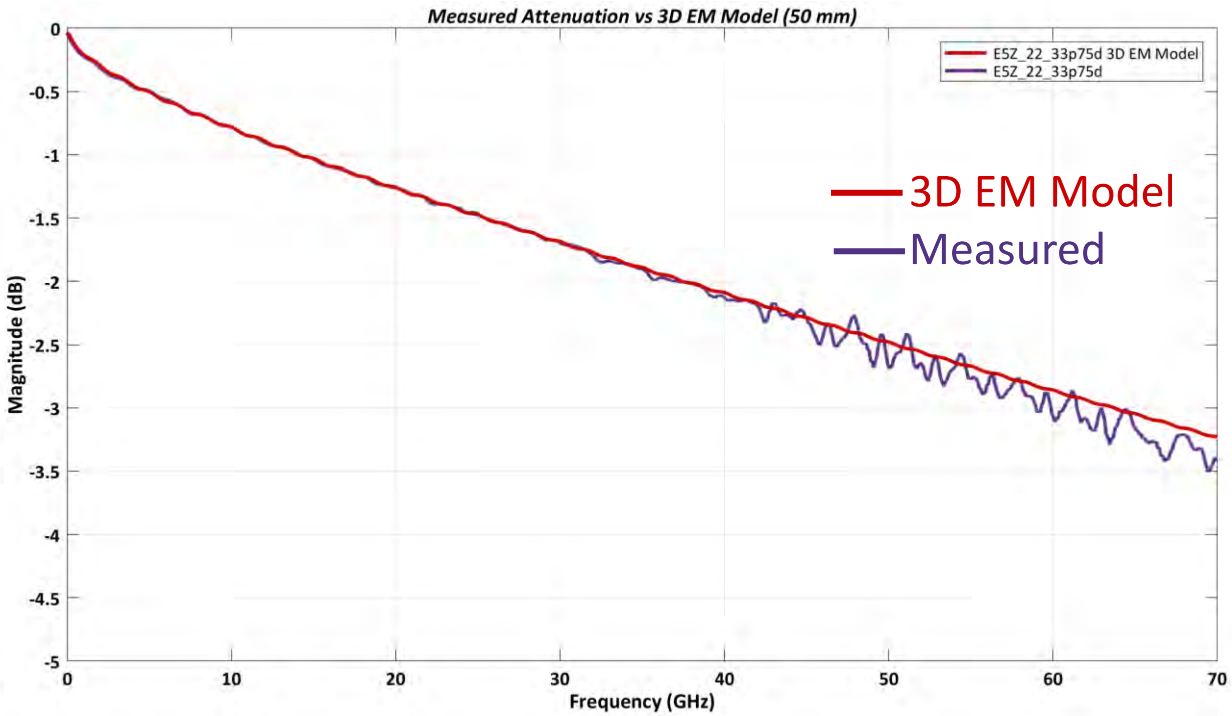




Fitted Transmission Line Model Matches very well to 70 GHz

Extracted (Fitted) Tline vs 3D EM Model





Fitted Transmission Line matches Extracted Parameters fed into a 3D EM modeling tool.

Parameters Used for Tline Modeling

LOWEST LOSS MEASUREMENTS

Material	Supplier	Factory	$\varepsilon_r / tan\partial$ Extracted (5 GHz)	Sphere Radius (um)	Hall-Huray Ratio	Conductivity 20º C (S/m)
C	3	Y	3.35, 0.0019	0.06	4.8869	5.739E+07
C	3	X	3.35, 0.0017	0.057	4.8869	5.739E+07
E	5	Z	3.21, 0.0017	0.06	4.8869	5.75E+07

* Cannon Ball – Huray [1],[2]
** Frequency dependent Djordjevic Sarkar [3]

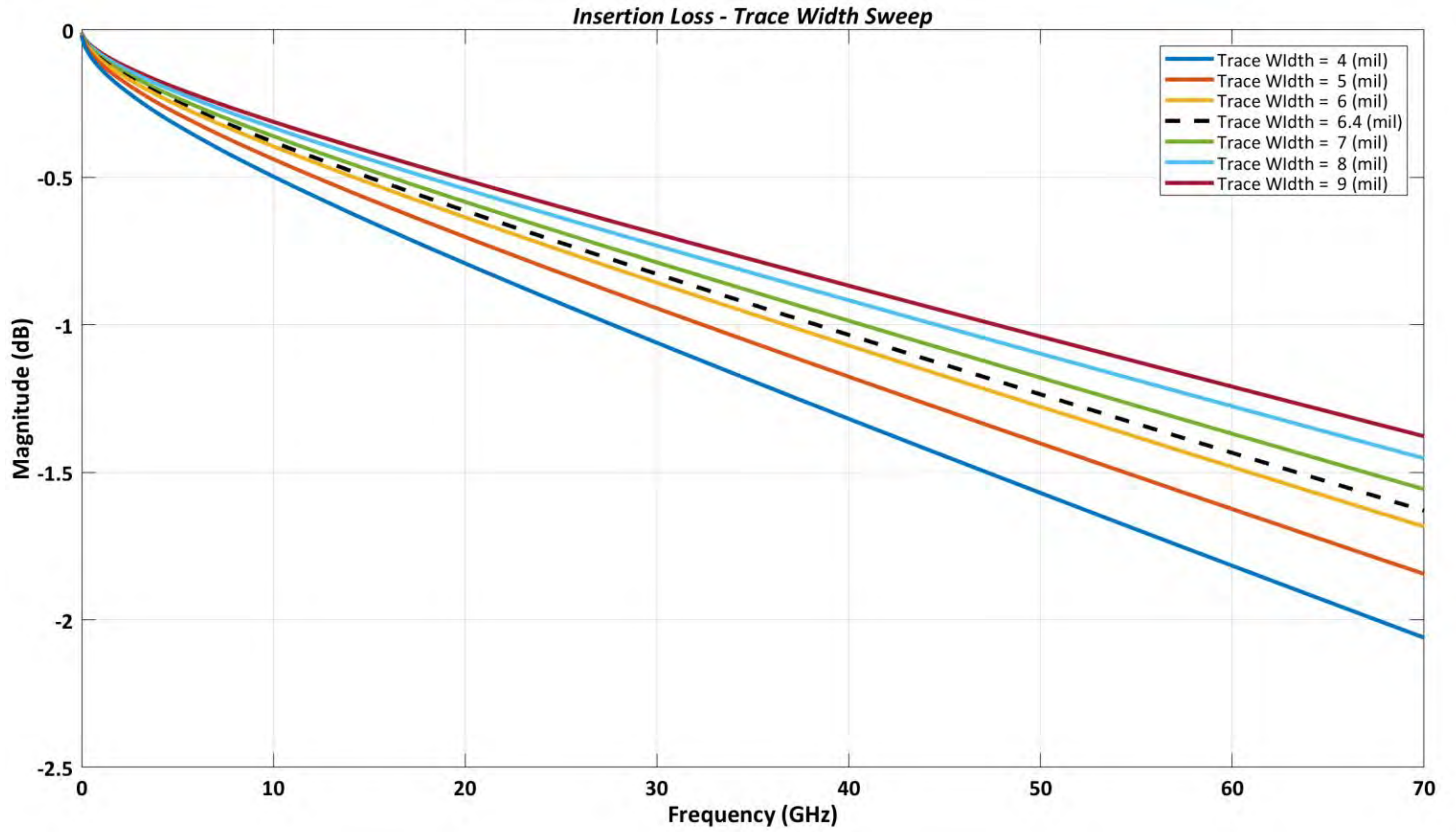
Predicting Trace Width vs Loss

USING THE LOWEST LOSS MODEL FITTED TO MEASUREMENT

Decreasing conductor width is a loss adder

What is the sweep spot trace width for design?

Insertion Loss Per Inch at 53 GHz		
ModelName	Width (mil)	IL (dB)
Synth_Tline_width4p0_length1in	**4**	-1.64419
Synth_Tline_width5p0_length1in	**5**	-1.46907
Synth_Tline_width6p0_length1in	**6**	-1.33903
Synth_Tline_width6p4_length1in	**6.4**	-1.29532
Synth_Tline_width7p0_length1in	**7**	-1.23631
Synth_Tline_width8p0_length1in	**8**	-1.15139
Synth_Tline_width9p0_length1in	**9**	-1.09071

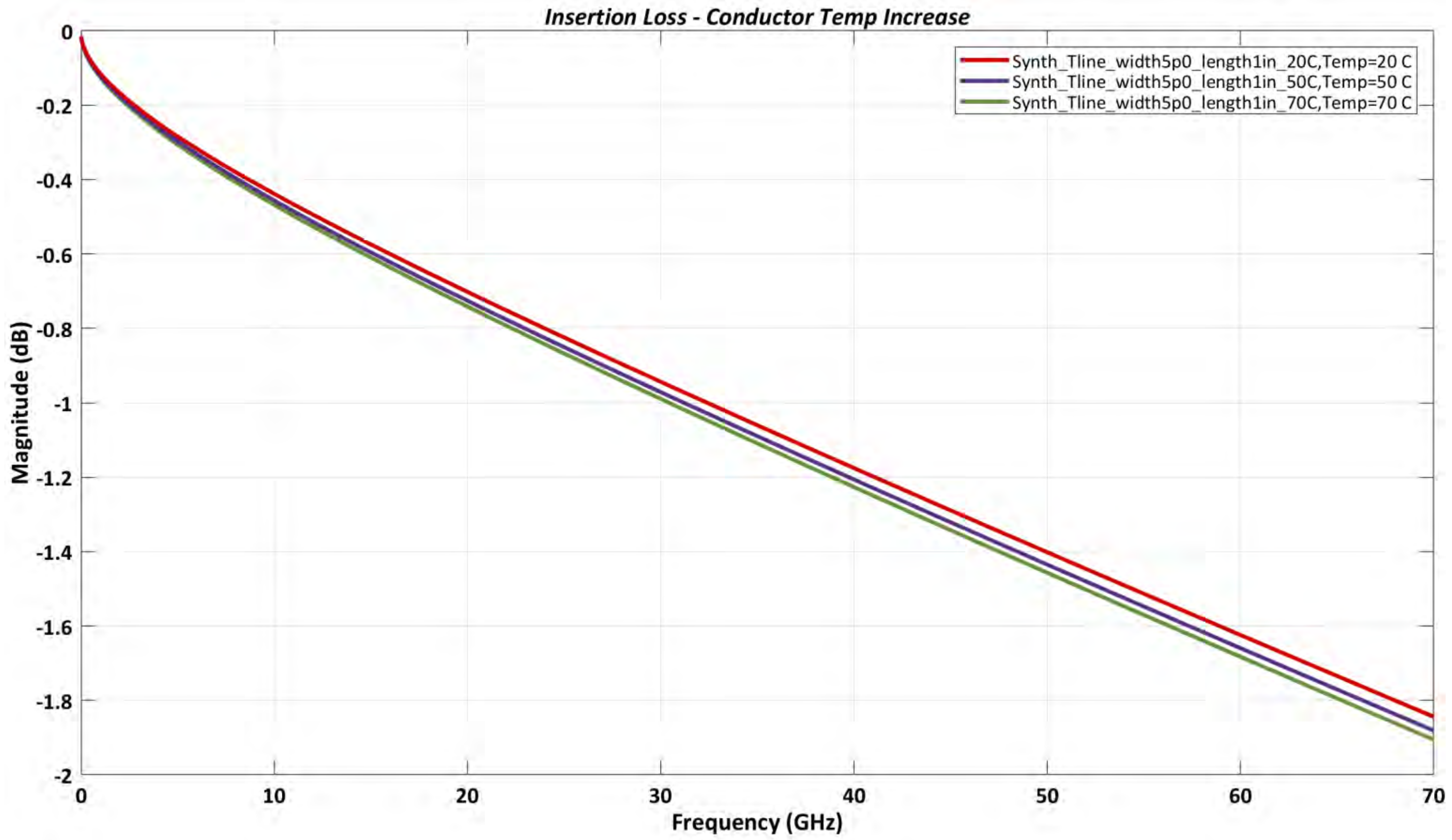


Predicting Temperature Impact to Loss

USING THE 5 MIL WIDTH MODEL

Assuming resistivity increases 0.393%/^{o}C
Conductivity 20^{o}C = 5.7e7 (S/m)
Conductivity 50^{o}C = 5.1e7 (S/m)
Conductivity 70^{o}C = 4.76e7 (S/m)

Temperature and humidity effects on the resin are *not* considered



Insertion Loss - Conductor Temp at 53 GHz		
Model	Temp (C)	IL (dB)
Synth_Tline_width5p0_length1in_20C	**20**	-1.46907
Synth_Tline_width5p0_length1in_50C	**50**	-1.50295
Synth_Tline_width5p0_length1in_70C	**70**	-1.5253

Summary

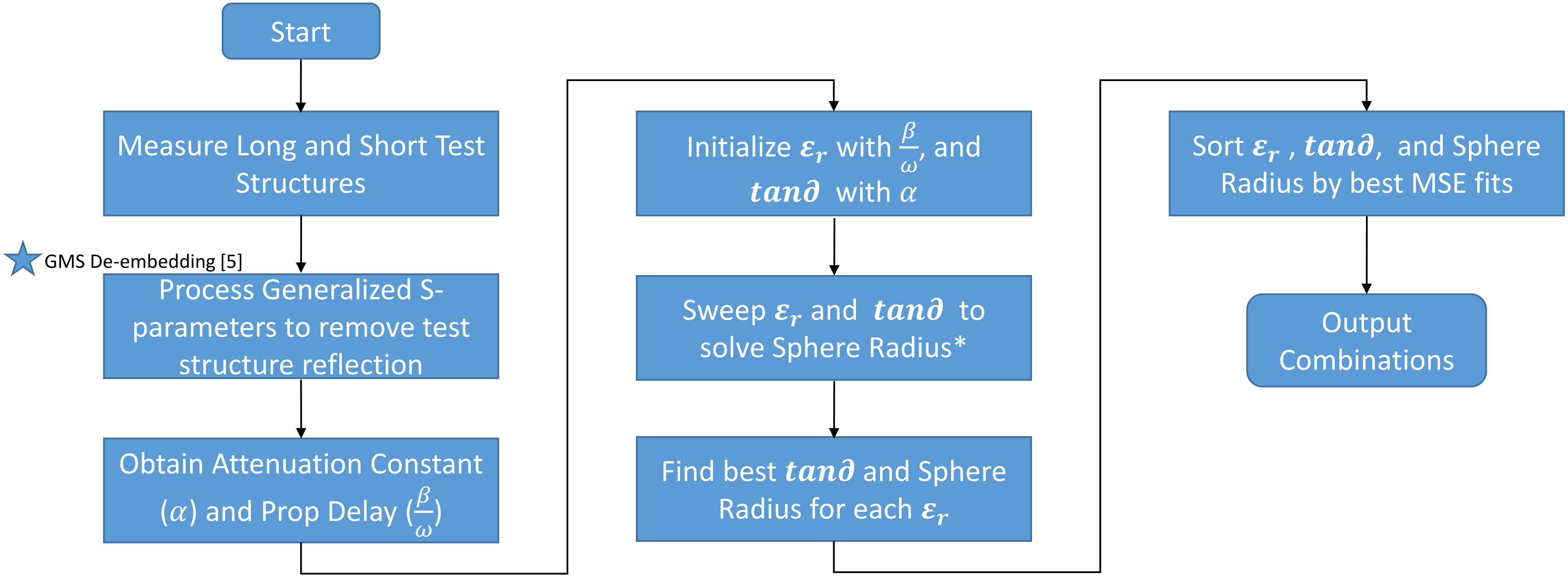
- ❑ Measurement based loss/in data at 53 GHz shown
  - A range of 1.3 dB/in to 1.4 dB/in at 20^{o}C and 6.4 mil wide trace
- ❑ Material parameters for modeling measured data provided for 3D EM
- ❑ Design trace width is impactful to achievable loss/in
- ❑ Conductor temperature increases loss.
- ❑ Loss increase from temperature and humidity should be further studied

Thank You!

Backup Reference

1. Simonovich, Bert, “Practical Method for Modeling Conductor Surface Roughness Using Close Packing of Equal Spheres”, DesignCon 2015 Proceedings, Santa Clara, CA, 2015, URL: http://lamsimenterprises.com/Copyright2.html
2. Huray, P. G. (2009) "The Foundations of Signal Integrity", John Wiley & Sons, Inc., Hoboken, NJ, USA., 2009
3. A. R. Djordjevic, R. M. Biljic, V. D. Likar-Smiljanic, and T. K. Sarkar, "Wideband Frequency-Domain Characterization of FR-4 and Time-Domain
Causality," IEEE Trans. Electromagnetic Compatibility, Vol. 43, No.4, November 2001
4. IPC-TM-650, 2.5.5.5, Rev C, Test Methods Manual, "Stripline Test for Permittivity and Loss Tangent (Dielectric Constant and Dissipation Factor) at X-Band", 1998
5. Shlepnev, Yuriy, et. al, “Practical Identification of Dispersive Dielectric Models with Generalized Modal S-parameters for Analysis of Interconnects in 6 – 100 Gb/s Applications”, DesignCon 2010 Proceedings, Santa Clara, CA, 2010, URL: https://www.simberian.com/AppNotes/DesignCon2010_Paper2807.pdf

Dk, Df, Surface Roughness Extraction Algorithm (Solver-less)



* Cannon Ball – Huray [1],[2]

** Frequency dependent Djordjevic Sarkar [3]

Creating an Extracted Transmission Line Model

- Imperfections in the measurement are not part of the transmission line
- Lower loss test structures are more sensitive to reflections
- Return loss > -15 dB is noticeable in the insertion loss.
    - This limits the max frequency of the fitting and modeling algorithm.
- Fmax for parameter extraction is set to 45 GHz
- Ideal transmission line log linear physics are not likely to change at higher frequencies