Model Development for Flexible Hybrid Electronics Process Design Kit (FHE-PDK)

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Dr. Sitaraman and Dr. Swaminathan

Acknowledgements

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- This work is also supported in part by Semiconductor Research Corporation (SRC) and the Texas Analog Center of Excellence (TxACE) under task 2712.024.

FHE Design Flow and Components Included in PDK 1.0

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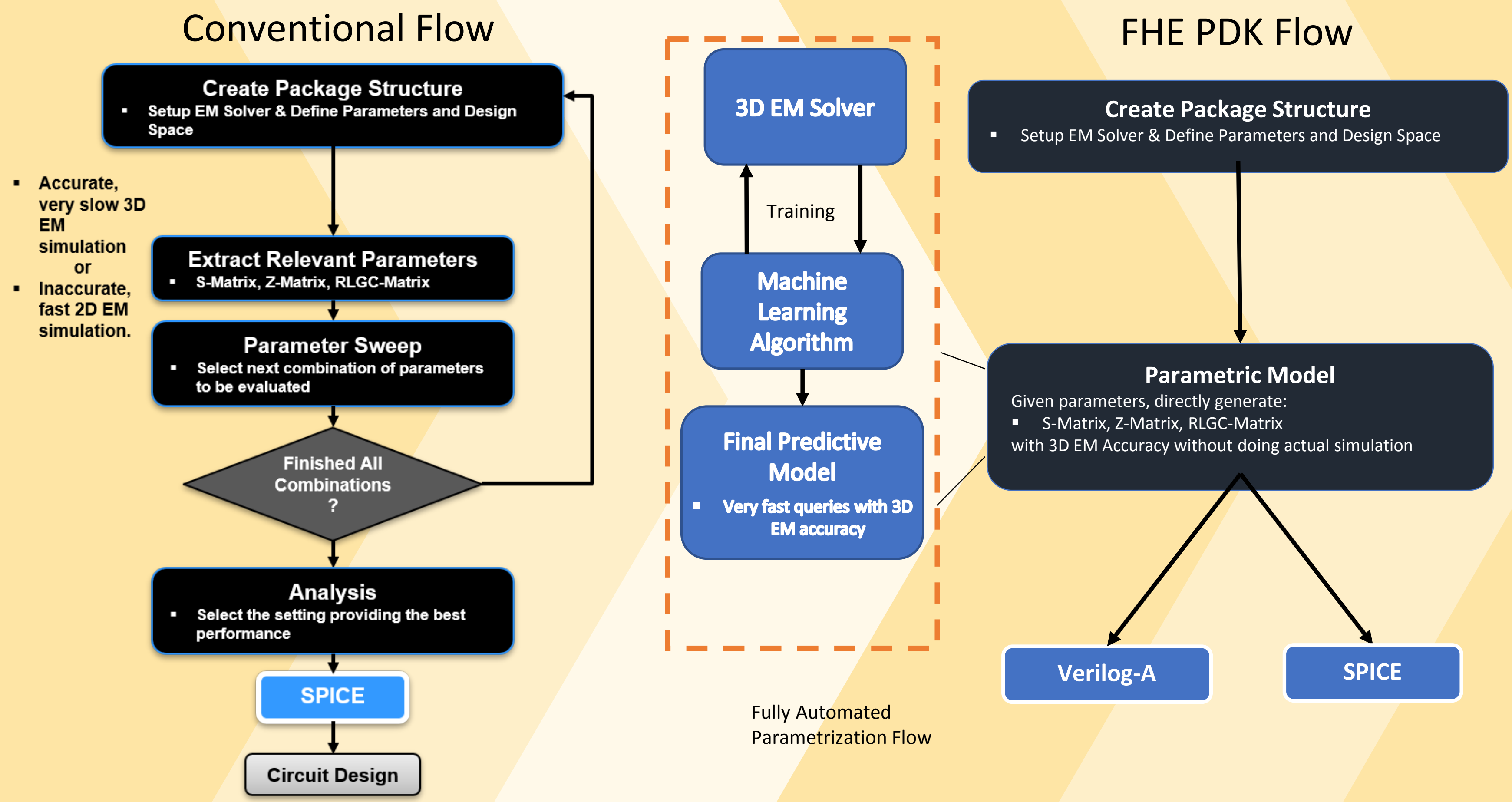
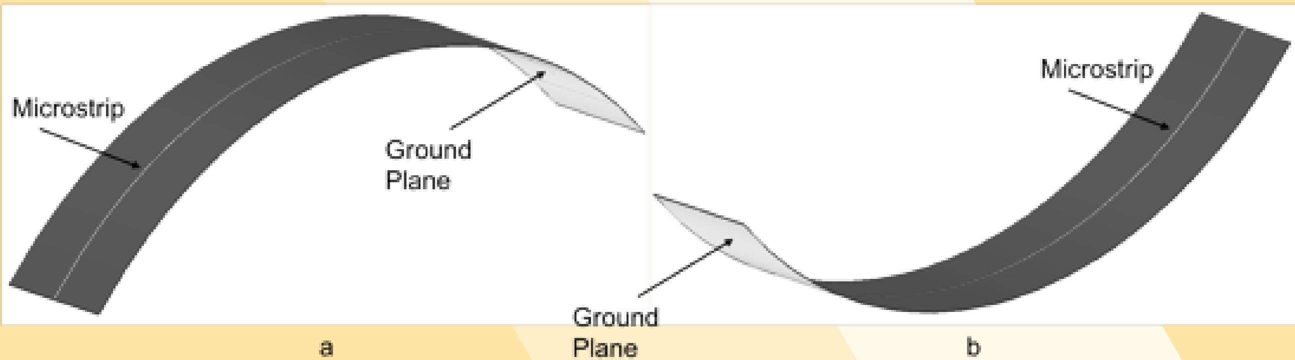
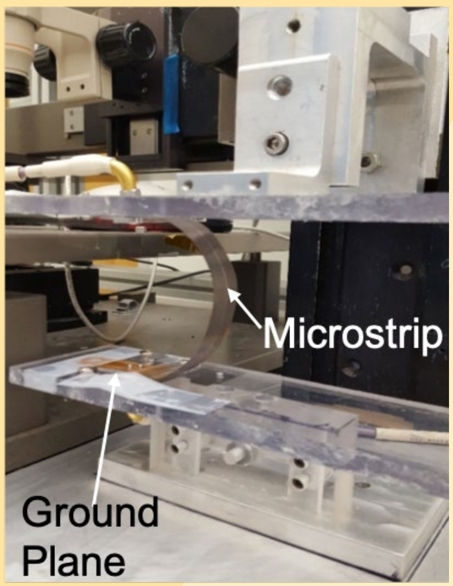
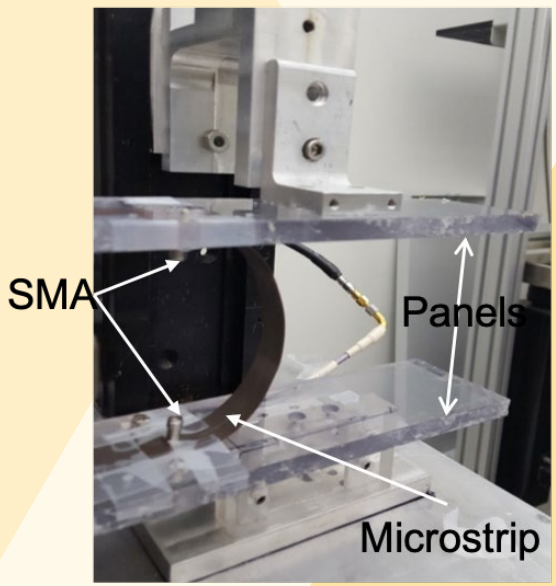


Bending Test Setup





Tensile



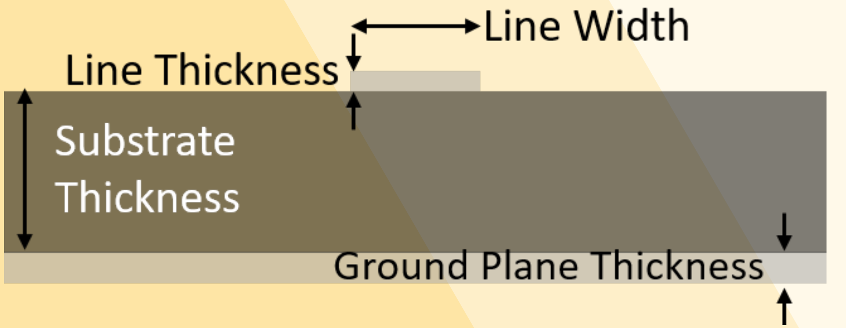
Compressive

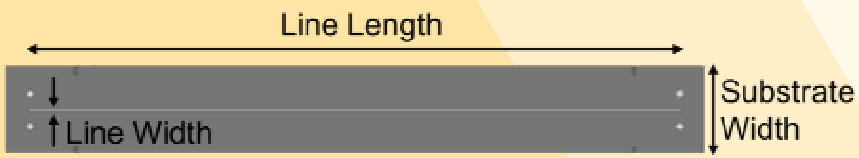
- All components underwent either tensile bending (a), compressive bending (b), or both
- An example of a component (microstrip transmission line) undergoing both compressive (left) and tensile (right) bending using adaptive curvature bending

*S. Sivapurapu, R. Chen, C. Mehta, Y. Zhou, X. Jia, M. L. F. Bellaredj, P. Kohl, T. Huang, S. K. Sitaraman, M. Swaminathan, "Multi-physics Modeling Characterization of Aerosol Jet Printed Transmission Lines," *2018 IEEE MTT-S International Conference on Numerical Electromagnetic and Multiphysics Modeling and Optimization (NEMO)*, Reykjavik, 2018, pp. 1-4.

Microstrip Transmission Line Dimensions

Fabricated and Model Dimensions





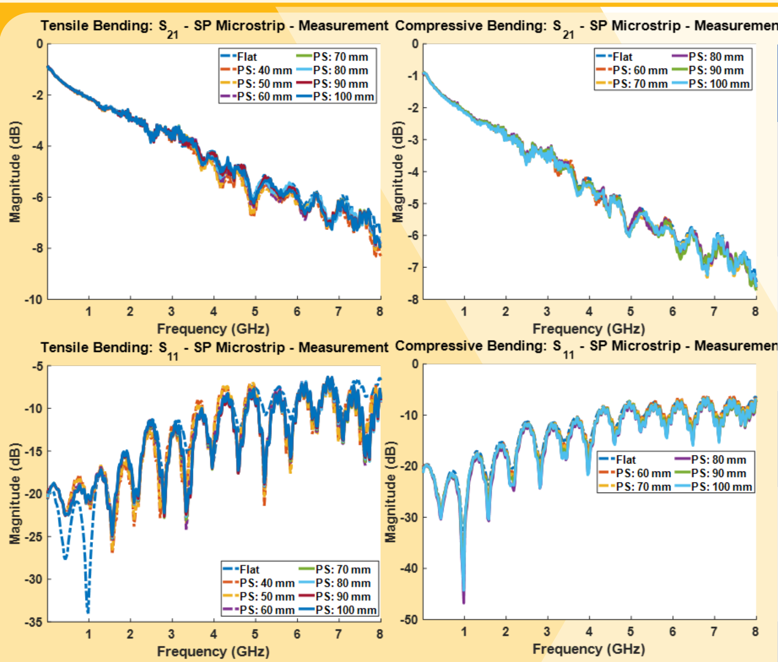
Parameter	Designed	Fabricated	Model Minimum	Model Maximum
Line Length (mm)	152.28	152.28	N/A	
Line Width (μm)	284.148	336.7	100	900
Line Thickness (μm)	10	12.53	5	30
Surface Roughness (μm)	1.2	5	1	4
σ (10^6 S/m)	3.57		1	60
Substrate Thickness (mils)	5 mil (127 μm)		.5	6.5
Ground Plane Thickness (μm)	38			
Substrate Width (mm)	15			

Conductor: Dupont 5025
Substrate: Kapton Polyimide
Ground Plane: Copper

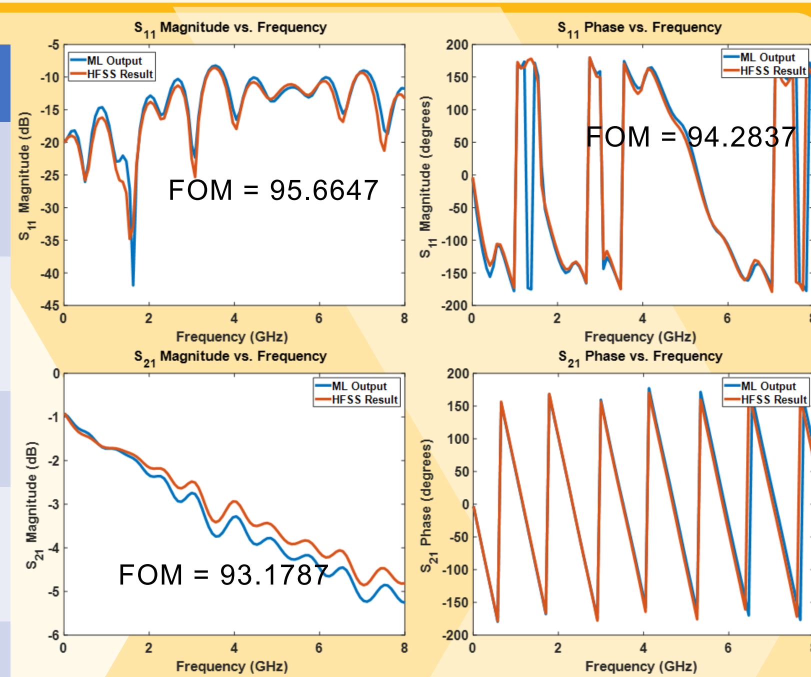
- The SP ML model was developed using a Gaussian Process Regression (GPR)
- The data was collected using Latin Hypercube Sampling (LHS)
- The data is trained to the RLGC parameters of the line, which are then converted to S-Parameters
    - The length can be set by the user since the RLGC parameters are length independent

Measurement Results

Fabricated Samples and Model



Parameter	Value
Conductor Width (µm)	274-377
Conductor Thickness (µm)	12.53
σ (10^6 S/m)	3.57
Substrate Height (mils)	5
Line Length (mm)	152.28
Frequency Range (GHz)	.01-8



- No significant change in both the insertion loss (S_{21}) and return loss (S_{11}) was found when the transmission line underwent tensile and compressive bending when compared against a flat transmission line

- To further quantify the quality of the model, the following FOM is used:

$$FOM = \left[1 - \frac{\sum_{i=1}^{N} |X_i(golden) - X_i(DUT)|}{\Delta X \times N}\right]$$

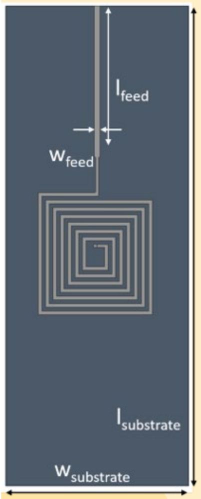
- The comparison is for a line that is split into 18 sections of widths inside of the range listed in the table

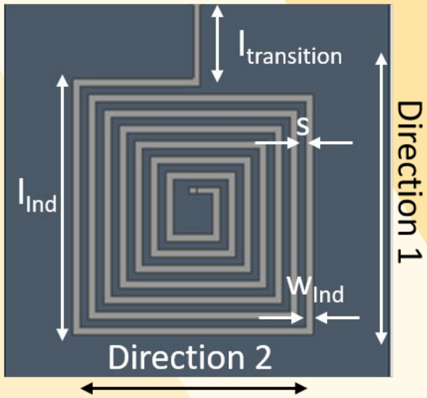
S. Sivapurapu, C. Mehta, R. Chen, Y. Zhou, X. Jia, M. L. F. Bellaredj, P. A. Kohl, S. K. Sitaraman, and M. Swaminathan, "Multi-physics Modeling Characterization of Aerosol Jet Printed Transmission Lines," *2018 IEEE MTT-S International Conference on Numerical Electromagnetic and Multiphysics Modeling and Optimization (NEMO)*, Reykjavik, 2018, pp. 1-4.

Power Inductor Dimensions

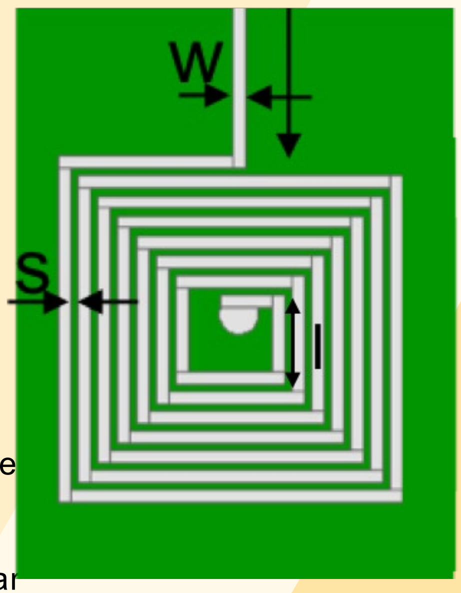
Fabricated and Model Dimensions

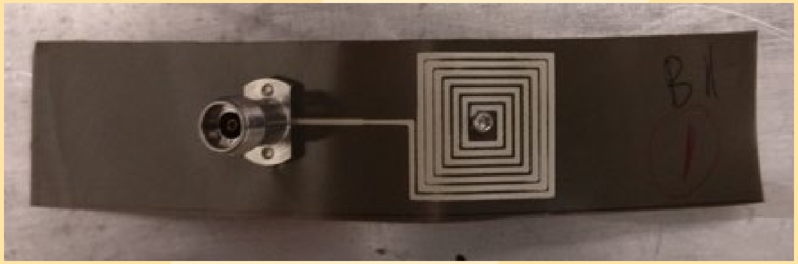
Parameter	Value
Substrate Length ($l_{substrate}$)	65 mm
Substrate Width ($w_{substrate}$)	25 mm
Inductor Side Length (l_{Ind})	16.6 mm
Inductor Line Width (w_{Ind})	500 µm
Inductor Line Spacing (s)	500 µm
Feed Length (l_{feed})	20.75 mm
Feed Width (w_{feed})	760 µm
Transition Length ($l_{transition}$)	4.8 mm
Number of Turns	7





Parameter	Range	
	Minimum	Maximum
Frequency (MHz)	1	100
Inner Turn Side Length (mm)	2	6
Trace Width (µm)	250	750
Trace Spacing (µm)	250	750
σ (S/m)	5×10^5	3×10^7
Trace Thickness (µm)	5	20
Number of Turns	4	7
Panel Separation (mm)	15	30

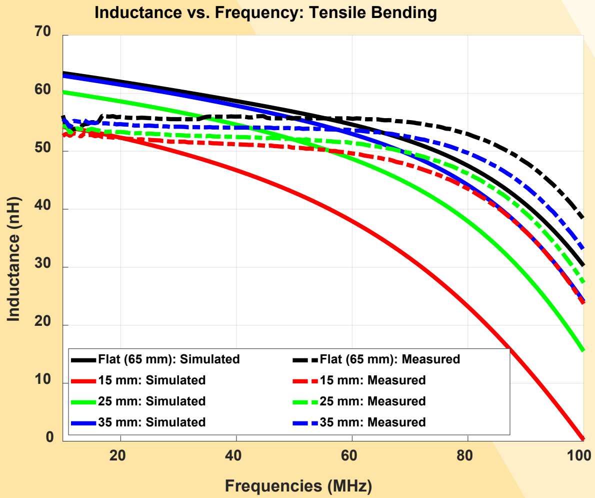


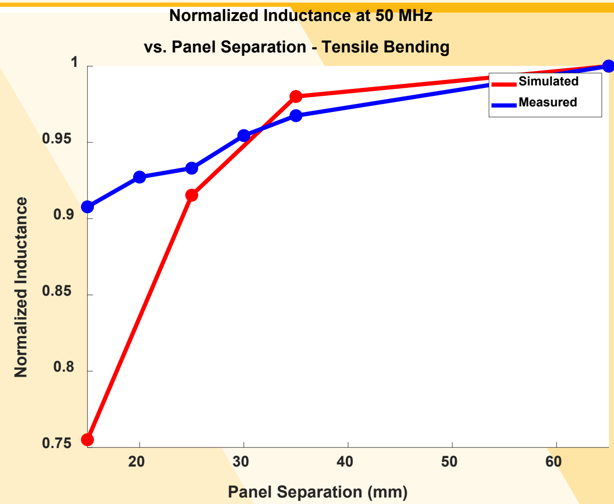


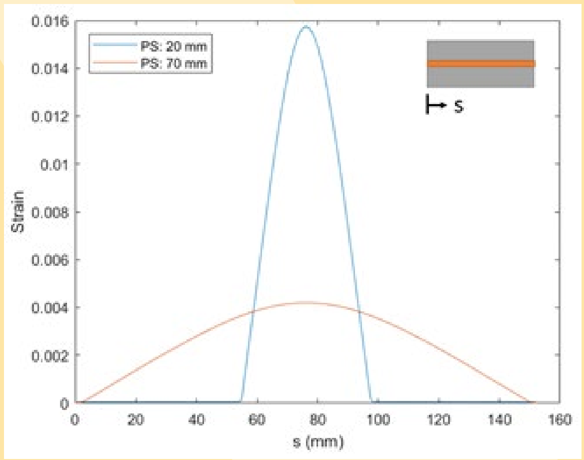
- The same Kapton polyimide substrate and copper ground plane used for the microstrip transmission line are used for the planar spiral inductor
- The conductor is Dupont 5025 (same as the SP microstrip transmission line)
- The model is built using GPR (similar to transmission line)

Measured Results

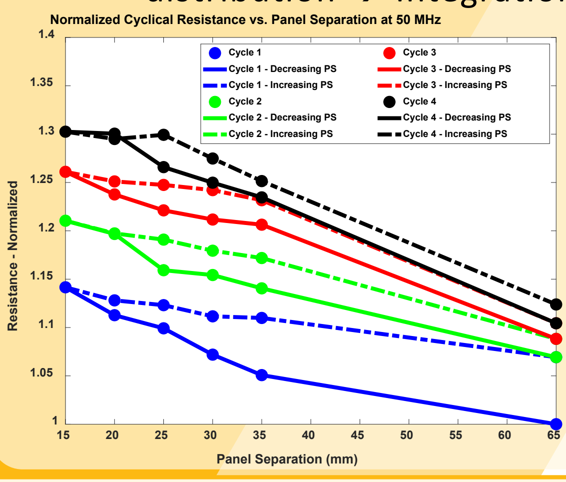
Fabricated Samples – Single and Multi-cycle

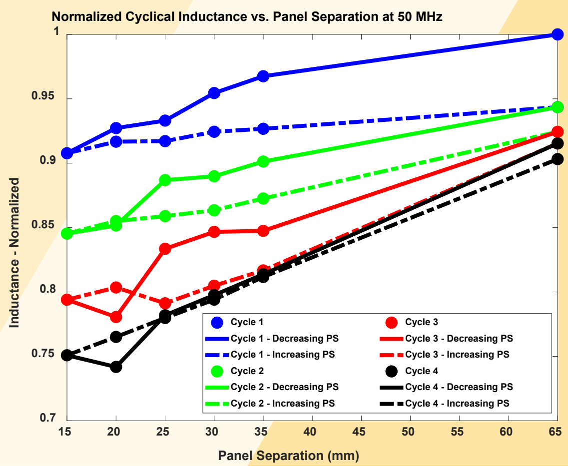






- Good correlation is found with between the simulation and measurement when the panel separation is large
- When the panel separation reaches the minimum measured value, the difference is more noticeable due to the nonlinear strain distribution along the length of the conductor
    - The impact increases more with the inductor due to more paths experiencing the nonlinear strain distribution → Integration between mechanical and electrical simulations is critical





- Cyclical bending has a large impact on the performance of these inductors (inductance decreases while resistance increases)
- The normalized resistance is ~28 Ω and the normalized inductance is ~55 nH

*S. Sivapurapu, R. Chen, C. Mehta, Y. Zhou, M. L. F. Bellaredj, X. Jia, P. Kohl, T. Huang, S. K. Sitaraman, M. Swaminathan, "Multi-physics Modeling & Characterization of Components on Flexible Substrates," in *IEEE Transactions on Components, Packaging and Manufacturing Technology*, vol. 9, no. 9, pp. 1730-1740, Sept. 2019.

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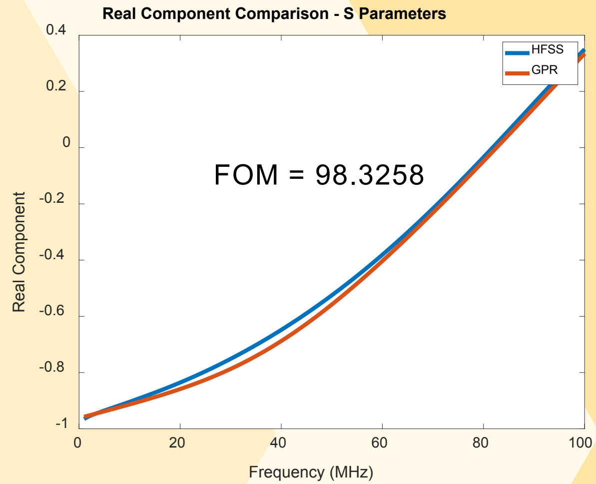
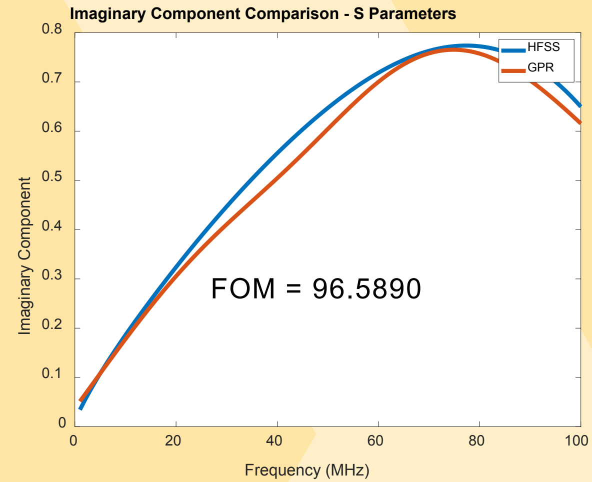
Model Results

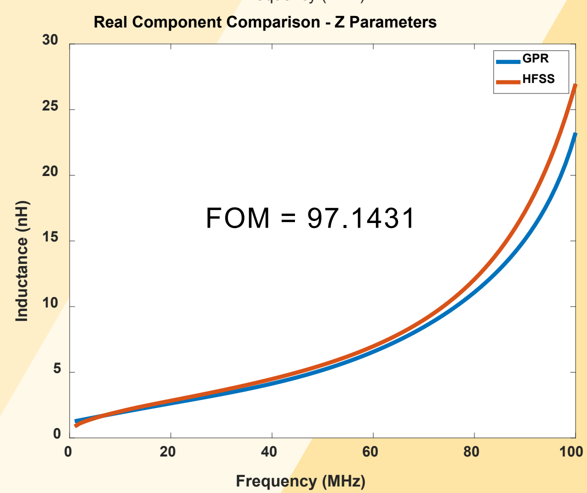
Tensile Bending for Power Inductor

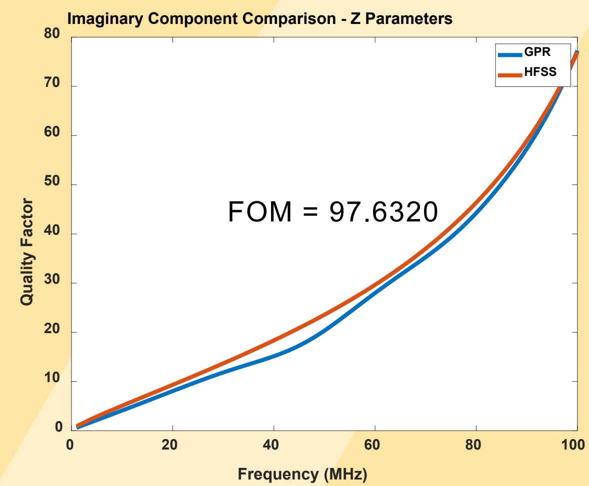
Parameter	Value
Frequency	1-100 MHz
Inner Turn Side Length	3.1 mm
Trace Width	500 µm
Trace Spacing	500 µm
Trace Conductivity	$1.8x\ 10^{6}$ S/m
Trace Thickness	10 µm
Number of Turns	7
Panel Separation	25 mm

- The dimensions used for this model are the same dimensions as the measured inductor with a panel separation of 25 mm



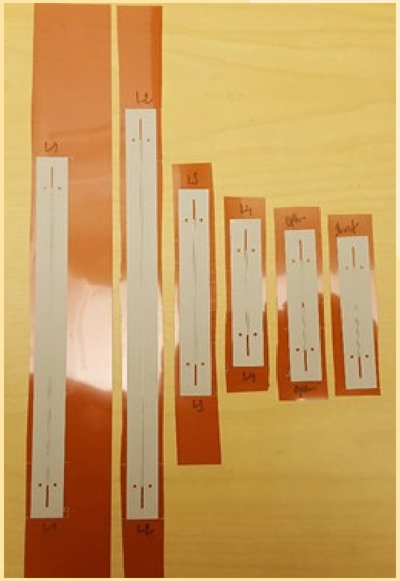




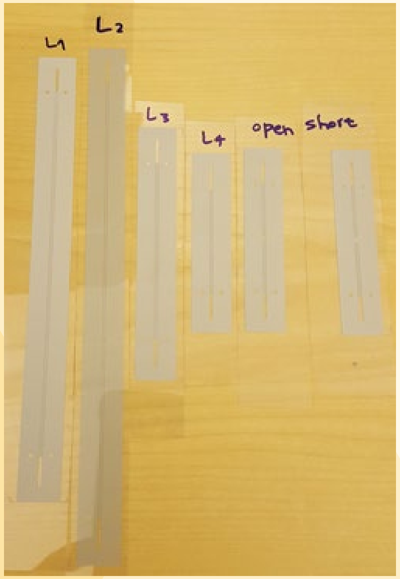


Coplanar Waveguide Dimensions

Fabricated and Model Dimensions

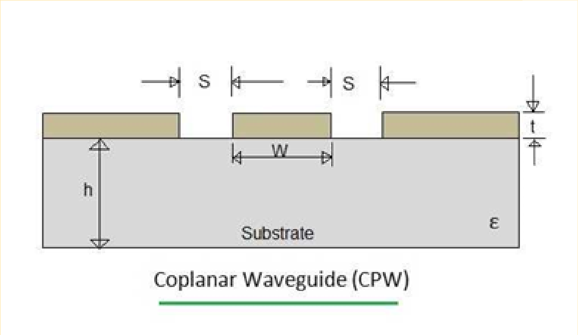


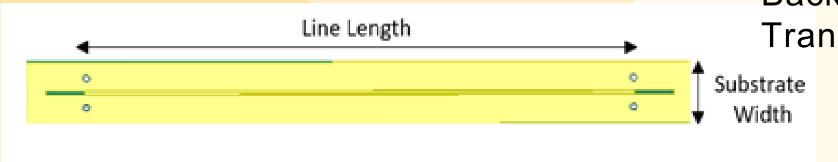
Kapton



PET

Dimension	Kapton Fabricated/Designed	PET Fabricated/Designed
Substrate Thickness (h)	5 mil	
Substrate Length	196.418 mm	
Substrate Width	14.82 mm/15 mm	
Trace Width (W)	762.07 µm/750 µm	805.41 µm/750 µm
Separation (S)	106.68 µm/125 µm	42.03 µm/125 µm
Trace Thickness (t)	11 µm/10 µm	11 µm/10 µm
Surface Roughness	1 µm/2 µm	1 µm/2 µm
Characteristic Impedance (L2)	62.99 Ω/66.89 Ω	49.64 Ω/70.82 Ω
Length (L2)	166.37 mm/166.63 mm	166.37 mm/166.63 mm





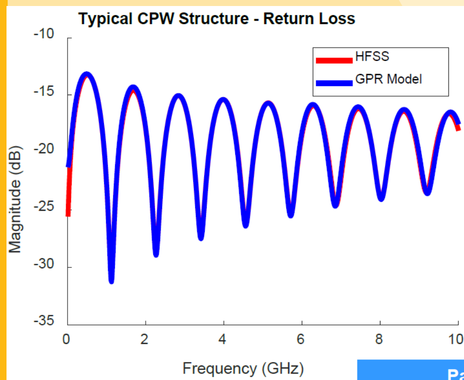
Conductor: Dupont 5028 Silver Conductor

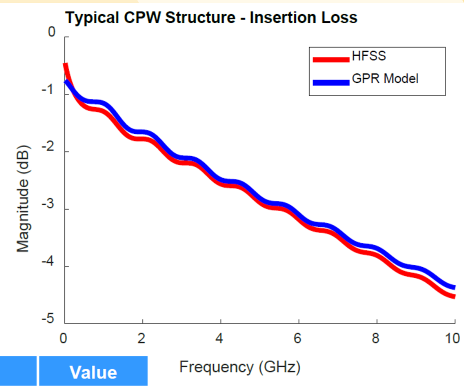
- Similar to the previous models, a GPR is used to create the CPW model
  - Model created in 2 sections: Backside Ground Plane and Transmission Line

Parameter	Range	
	Minimum	Maximum
Conductor Width (w)	150 µm	900 µm
Conductor Thickness (t)	500 nm	20 µm
Gap (g)	10 µm	250 µm
Substrate Height (h)	0.5 mils	6.5 mils
ϵ_r	1	5
$tan\delta$	0.001	0.1
σ (S/m)	5×10^5	6×10^7
Frequency	10 MHz	8 GHz

Coplanar Waveguide Results

Measured and ML Model

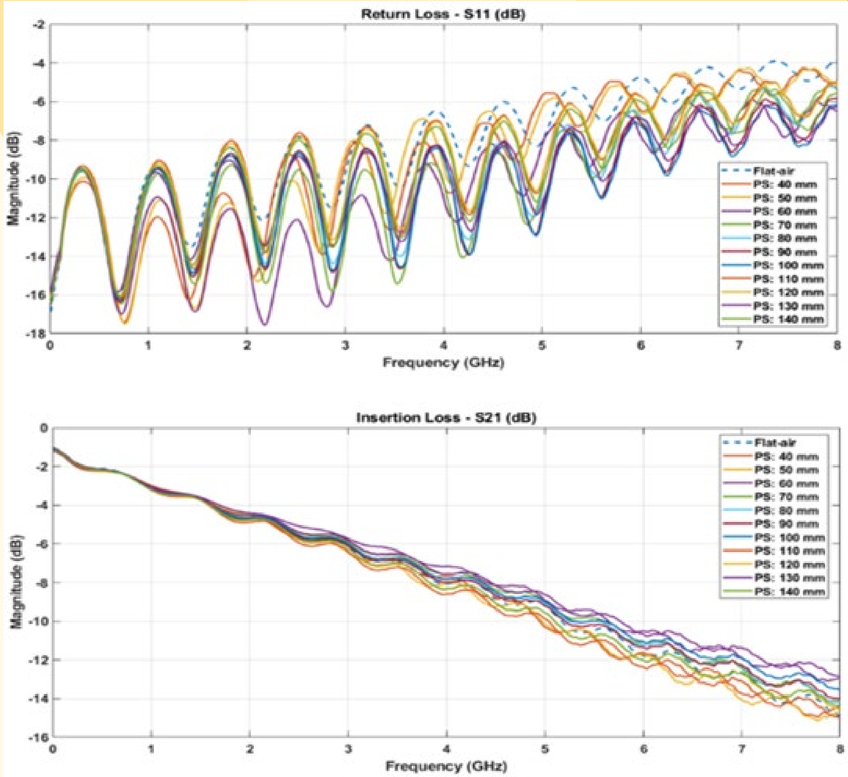




Frequency Sweep from 10 MHz to 10 GHz in increments of 10 MHz

Parameter	Value
Conductor Width	750 μm
Conductor Thickness	10 μm
Gap	100 μm
Substrate Height	5 mils
Substrate Relative Permittivity	3.5
Substrate Loss Tangent	0.026
Conductor Conductivity	10^7 S/m

Typical CPW Line Length is 100 mm



Tensile Bending

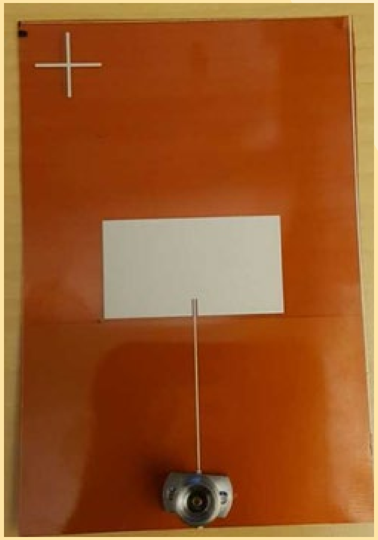
- The measurement were completed with panel separations between 40 mm and 140 mm
- The dashed line represents the flat measurement

N. Aslani-Amoli, S. Sivapurapu, R. Chen, Y. Zhou, M. L. F. Bellaredj, F. A. Soul, S. K. Sitaraman, and M. Swaminathan "Screen-Printed Flexible Coplanar Waveguide Transmission Lines: Multi-physics Modeling and Measurement," *2019 IEEE 69th Electronic Components and Technology Conference (ECTC)*, Las Vegas, NV, USA, 2019, pp. 249-257.

Patch Antenna Dimensions

Fabricated Sample and Model

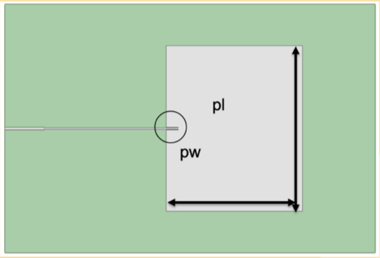
Small Patch



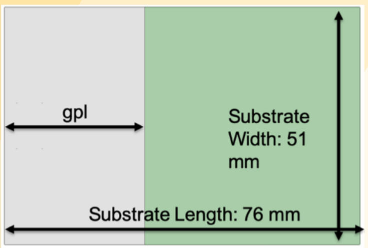
Big Patch

Measured σ: 2.647e6 S/m

Measured σ: 2.715e6 S/m



a



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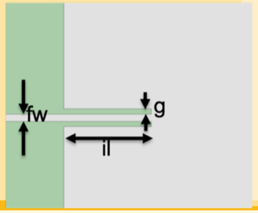
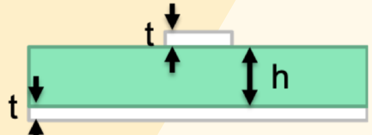


c



d

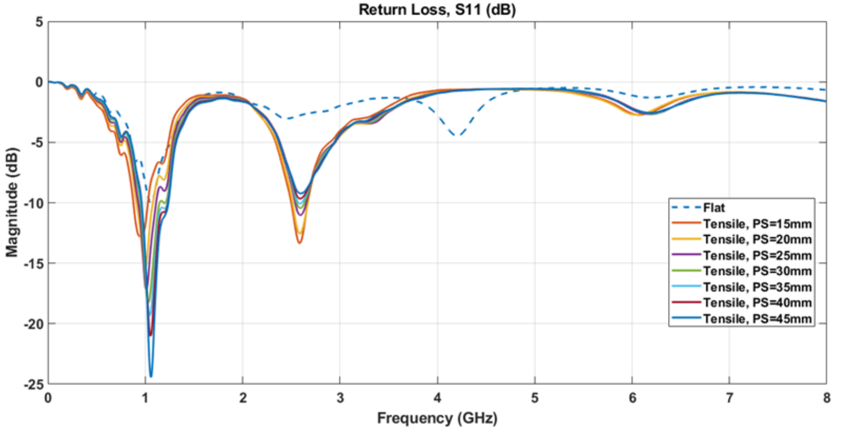
Dimension	Small Patch Fabricated/Designed	Big Patch Fabricated/Designed
Antenna Length	15 mm	28 mm
Antenna Width	27 mm	34 mm
Ground Plane Length	30 mm	
Substrate Length	76.2 mm	76 mm/76.2 mm
Substrate Width	50.8 mm	51 mm/50.8 mm
Feed Width	201.42 µm/240 µm	209.0131 µm/240 µm
Connector Width	597.41 µm/760 µm	588.05 µm/760 µm
Gap (left)	292.7467 µm/240 µm	153.353 µm/110 µm
Gap (right)	293.74 µm/240 µm	144.59 µm/110 µm
Surface Roughness	0.81936 µm/1 µm	0.10519 µm/1 µm
Ground Plane Thickness	38 µm/6.7558 µm	38 µm/6.855 µm
Substrate Thickness	5 mil	
Trace Thickness	15 µm/6.2789 µm	15 µm/5.9226 µm

Substrate: 5 mil Kapton Polyimide (DuPont Kapton HN)
Conductor: Ag-800 Silver ink (printed on both sides)

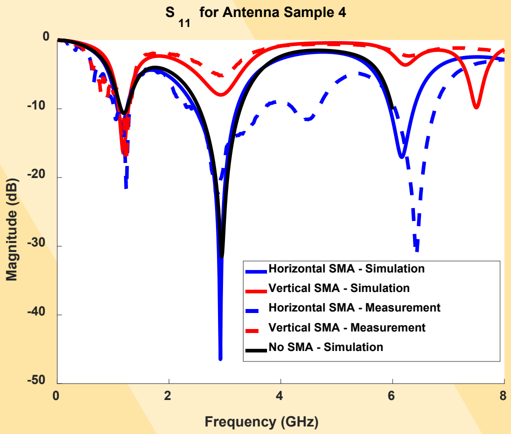
Parameter	Parameter Min	Parameter Max
Patch Length (pl)	15 mm	40 mm
Patch Width (pw)	20 mm	50 mm
Inset Length (il)	500 µm	5 mm
Gap Length (g)	100 µm	600 µm
Feed Width (fw)	150 µm	400 µm
Ground Plane Length (gpl)	10 mm	40 mm
Trace Thickness (t)	500 nm	20 µm
Substrate Height (h)	.5 mils	7 mils
Panel Separation*	15 mm	45 mm
ϵ_r	1.5	6
$tan\delta$	0.001	0.1
σ	5e4 S/m	6e6 S/m
Frequency Range	10 MHz	8 GHz

Measured Results

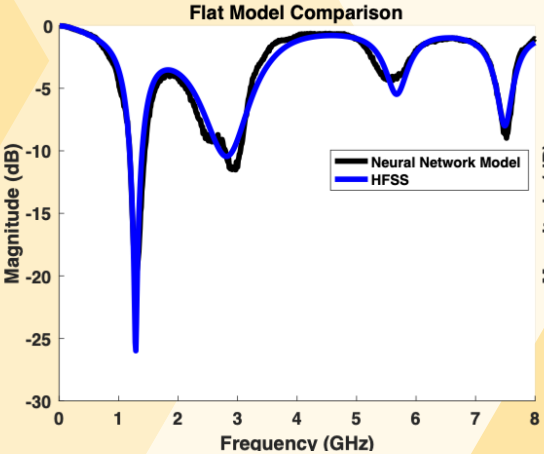
Fabricated Samples and Model Correlation



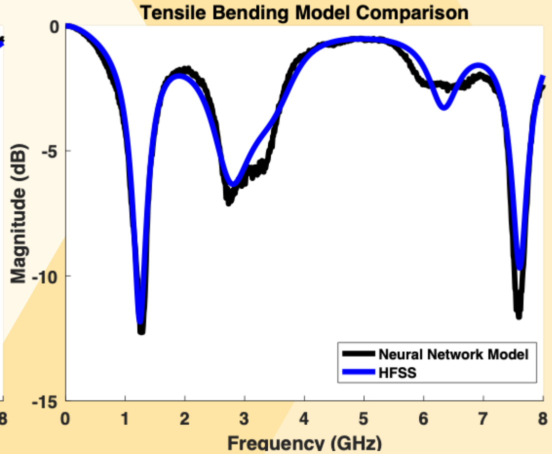
- The resonant frequency increases with increasing panel separation
- Good model correlation was found after including the vertical SMA in the simulations



Parameter	Minimum
Patch Length	28 mm
Patch Width	34 mm
Inset Length	2.5 mm
Gap Length	150 µm
Feed Width	209 µm
Ground Plane Length	30 mm
Trace Thickness	6 µm
ϵ_r	3.5
$tan\delta$	0.0026
σ	2.75e6



Parameter	FOM
Real	97.6868
Imaginary	98.0389
Magnitude	96.4451



Parameter	FOM
Real	98.6093
Imaginary	98.3882
Magnitude	96.2966

- The model exhibits good correlation throughout the sample space and can be seen in this example

Conclusion

- FHE-PDK 1.0 was created by a collaborative team consisting of HPE Labs, Georgia Tech, Stanford, UCSB, WMU, and Cadence
- Project was completed in April 2019 with final review in August 2019
- Includes the components shown in previous slides as well as resistors and capacitors
- Currently works with multiple software platforms from Cadence and Mentor Graphics
- The framework used to create the inductor, transmission lines, and antennas will be critical for moving forward to include other components
    - RF couplers, antenna arrays, etc.